Научном већу Института за физику у Београду

Предмет: Молба за покретање поступка за избор у звање
научни саветник

Молим Научно веће Института за физику у Београду да у складу са Правилником о поступку и начину вредновања и квантитативном исказивању научно-истраживачких резултата истраживача, покрене поступак за мој избор у звање научни саветник.

У прилогу достављам:

1. Мишљење руководиоца пројекта са предлогом чланова комисије за избор у звање
2. Образложење за превремено покретање избора у звање
3. Стручну биографију
4. Преглед научне активности
5. Елементе за квалитативну оцену научног доприноса
6. Елементе за квантитативну оцену научног доприноса
7. Списак објављених научних радова и њихове копије
8. Податке о цитираности радова
9. Фотокопија решења о избору у претходно звање
10. Додатке

Београд 28.11. 2018

Са поштовањем,

др. Срећковић Владимир
виши научни сарадник
Институт за физику у Београду

Научном већу Института за физику у Београду

Предмет: Мишљење руководиоца пројекта о избору др. Срећковић Владимира у звање научни саветник

Др Владимир Срећковић је запослен на Институту за физику у Београду у Лабораторији за астрофизику и физику јоносфере и ангажован је на пројектима Министарства просвете, науке и технолошког развоја Републике Србије ИИИ44002 „Астроинформатика: Примена ИТ у астрономији и сродним пољима истраживања“ и ОИ176002 „Утицај сударних процеса на астрофизичку плазму“. Др. Срећковић Владимир је један од водећих истраживача на поменутим пројектима где ради на темама везаним за проучавање атомских и молекулских процеса у астрофизици. Предлажем Научном већу Института за физику да покрене поступак за избор др Срећковић Владимира у звање научни саветник јер задовољава све потребне услове предвиђене Правилником о поступку и начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача.

За избор др. Срећковић Владимира у звање научни саветник предлажем следећу комисију:

- др Љубинко Игњатовић, Научни саветник Института за физику
- др Братислав Маринковић, Научни саветник Института за физику
- др Дарко Јевремовић, научни саветник Астрономске опсерваторије
- проф. др Срђан Буквић, Редовнои професор Физичког факултета

У Београду, 28. 11. 2018.

Руководилац пројекта ИИИ44002

др Дарко Јевремовић,

научни саветник

Научном већу Института за физику у Београду

Предмет: Образложење предлога за избор др Владимира Срећковића у звање научни саветник

Др Владимир Срећковић је запослен од 2003 у Институту за физику у Београду. Као виши научни сарадник је сада ангажован на пројектима Министарства за науку и технолошки развој Републике Србије 176002 и ИИИ4402. Др Владимир Срећковић тренутно има звање виши научни сарадник од 28.10.2015 године. Избор у звање научни саветник покреће нешто раније из више разлога који су сумирани у даљем тексту.

Бројни, разноврсни и значајни научни резултати које је остварио у свом истраживачком раду представљају основни разлог за убрзано напредовање др. Срећковић Владимира. Како по квантитативним тако и по квалитативним мерилима он је након претходног избора остварио далеко више резултата него што је неопходно за избор у звање научни саветник. Посебно треба истаћи нове доприносе у проучавању атомских процеса у атмосферама разних небеских тела и интерстеларним плазмама тако и експерименталним и лабораториским плазмама.

Др Владимир Срећковић је оснивач и руководилац Лабораторије за астрофизику и физику јоносфере, Института за физику, Универзитета у Београду. Он је вођа тима са Института за физику у Београду и члан Менаџмент комитета COST акције „The multi-messenger physics and astrophysics of neutron stars“ (PHAROS) CA16214. Поред тога, др Владимир Срећковић је и вођа тима са Института за физику у Београду и члан Менаџмент комитета COST акције „Mobilising Data, Policies and Experts in Scientific Collections“ (MOBILISE) CA17106. Др Срећковић Владимир је руководио израдом једне докторске тезе на Београдском универзитету. Развио је живу међународну сарадњу са више појединаца и истраживачких група (Сједињене Америчке државе-Станфорд Унив., Словенија-Инст. Нова Горица, Индија, Бразил). Постао носилац истраживања у оквиру пројекта основних истраживања Министарства науке ОИ141033 (2006-2010), као и у последњем пројектном циклусу систем је носилац пројекта ОН 176002, и III44002.

До сада је објавио 38 (тридесет седам) научних радова од којих 15 од претходног избора у звање и низ саопштења на скуповима међународног значаја. По позиву је одржао већи број предавања на међународним конференцијама и научним школама.

Укупан импакт фактор радова др Срећковића износи 102.406, а у периоду након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања радова укупан импакт фактор је 34.85. Часописи у којима објављује др Срећковић су цењени по свом угледу и водећи у његовим областима рада. Међу поменутим часописима посебно се истичу *Physical Review A, Astronomy & Astrophysics, Astrophysical Journal Supplement Series, Geophysical Research Letters, Monthly Notices of the Royal Astronomical Society, J. Phys. A* итд. Др Срећковић је до сада објавио 8 радова у једном од најугледнијих часописа у области астрофизике Monthly Notices of the Royal Astronomical Society. Рецензент је за часописе *Remote Sensing, Journal of Atmospheric and Solar-Terrestrial Physics, Atmospheric Research, IEEE Transactions on Plasma Science, Publ. Astron. Obs. Belgrade, Atoms, JPCS, Journal of Physics B, Advances in Space Research.*

С обзиром да далеко превазилази све предвиђене квантитативне и квалитативне услове, као и да је у тренутно научно звање виши научни сарадник изабран пре више од три године, у складу са Законом о научноистраживачкој делатности и Правилником о поступку, начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача МПНТР предлажемо да се за колегу др Владимира Срећковића покрене убрзани поступак за избор у звање виши научни сарадник.

У Београду, 28. 11. 2018.

др Љубинко Игњатовић,
Научни саветник Института за физику

др Братислав Маринковић,
Научни саветник Института за физику

др Дарко Јевремовић,
Научни саветник Астрономске опсерваторије

проф. др Срђан Буквић,
Редовнои професор Физичког факултета

1. БИОГРАФСКИ ПОДАЦИ О КАНДИДАТУ

Др Владимир Срећковић је рођен 01.03.1972. године у Београду где је завршио основну школу и Прву београдску гимназију. Студијску групу Физика на Физичком факултету Универзитета у Београду смер теоријска и експериментална физика дипломирао је 17. фебруара 2003. године одбраном дипломског рада "Штарково померење Mg II спектралних линија у плазми аргона и хелијума", урађеног у Лабораторији за спектроскопију плазме Физичког факултета у Београду, под руководством проф. Срђана Буквића, оценом 10. Одмах по дипломирању уписао се на последипломске студије смера Експериментална физика јонизованих гасова на Физичком факултету Универзитета у Београду. Све испите предвиђене наставним планом положио је са оценом 10. Последипломске студије на Физичком факултету кандидат др Владимир Срећковић завршио је 3. фебруара 2006. године одбраном магистарске тезе "Транспортне особине густе јако јонизоване плазме", која је урађена под руководством научног саветника др. Љубинка Игњатовића. Награду за најбоље урађен магистарски рад за 2005/06. годину из фонда "проф. др Љубомир Ћирковић", која се додељује на Физичком факултету, добио је 17. децембра 2006. године. Одбраном докторског рада под називом "Електропроводност и друге транспортне особине неидеалне делимично јонизоване плазме хелијума, неона и аргона" који је урађен под менторством научног саветника др. Љубинка Игњатовића, стекао је звање доктора физичких наука на Физичком факултету Универзитета у Београду дана 09. јула 2010.

Др Владимир Срећковић је запослен од 2003 у Институту за физику у Београду. Као виши научни сарадник је сада запослен на пројектима Министарства за науку и технолошки развој Републике Србије ОН176002 и ИИИ4402.

Др Владимир Срећковић је оснивач и руководилац Лабораторије за астрофизику и физику јоносфере, Института за физику, Универзитета у Београду. Он је вођа тима са Института за физику у Београду и члан Менаџмент комитета COST акције „The multi-messenger physics and astrophysics of neutron stars“ (PHAROS) CA16214. Поред тога, др Владимир Срећковић је и вођа тима са Института за физику у Београду и члан Менаџмент комитета COST акције „Mobilising Data, Policies and Experts in Scientific Collections“ (MOBILISE) CA17106. До сада су под руководством др Срећковића урађена једна докторска дисертација. Такође још једна је у процесу израде.

У својој каријери др Владимир Срећковић је као аутор или коаутор, објавио и презентовао 193 библиографских јединица тј. научних радова, у часописима од међународног значаја, у домаћим часописима, међународним и домаћим конференцијама. Др Срећковић је до сада је објавио 38 (тридесет осам) научних радова са ISI листе од којих 15 од претходног избора у звање и низ саопштења на скуповима међународног значаја. Такође има објављено и поглавље у монографији међународног значаја. По позиву је одржао већи број предавања на међународним конференцијама и научним школама. Био је члан организационог и научног комитета на више међународних конференција. Према бази Google Scholar радови др Срећковића цитирани су 401 пута са h-фактором 12. Према бази ISI Web of Science, радови др Срећковића укупно су цитирани 247 пута, док је број цитата без аутоцитата 125. Према бази Scopus, укупан број цитата је 281, док је број цитата без аутоцитата 113. Према подацима с обе базе (ISI Web of Science и Scopus) Хиршов индекс радова др Срећковића је 11.

Др Срећковић је Едитор а такође и рецензент у реномираним часописима као што су Journal of Physics B, Advances in Space Research, IEEE Transactions on Plasma Science, Atmospheric Research, Remote Sensing, Journal of Atmospheric and Solar-Terrestrial Physics, итд. Према Publons Clarivate Analytics тј. Web of Science сервису који прати, потврђују и приказују рефери доприносе и уредничке доприносе за академске часописе кандидат има преко 30 верификованих рецензија као и 7 уредничких доприноса у тренутку покретања избора.

Истраживачки рада др Владимира Срећковића је усмерен на проучавање сударних атомско/молекулских процеса у слабо-јонизованим лабораторијским и астрофизичким плазмама као и ка проучавању и анализи експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали) и нумеричком моделовању плазми ниске јоносфере и развијању теоријских процедура за опис параметара који је карактеришу. Последњих неколико година активност кандидата усмерена је и на раду везаном за атомске/молекулске базе података у оквиру Европског виртуалног центра за атомске и молекулске податке.

2. ПРЕГЛЕД НАУЧНЕ АКТИВНОСТИ

Истраживачки рада др Владимира Срећковића је усмерен на проучавање сударних атомско/молекулских процеса у слабо-јонизованим астрофизичким и лабораторијским плазмама као и проучавању и анализи експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали) и нумеричком моделовању плазми ниске јоносфере и развијању теоријских процедура за опис параметара који је карактеришу. Научна активност др Владимира Срећковића је у периоду од 2003. до 2010. године везана за истраживања електропроводности и других транспортних особина густе делимично јонизоване неидеалне лабораторијске и астрофизичке плазме водоника и неких инертних гасова, применом модификованог постојећег квантномеханичког метода. Резултати су приказани у радовима:

Srećković, V. A., Ignjatović, Lj .M., Mihajlov, A. A. and Dimitrijević, M. S. (2010) *Electrical conductivity of plasmas of DB white dwarf atmospheres,* Monthly Notices of the Royal Astronomical Society Vol 406 Issue: 1 Pages: 590-596 ISSN: 1365-2966 DOI: 10.1111/j.1365-2966.2010.16702.x (M21)

Srećković, V.A., Adamyan, V.M., Ignjatović, Lj. M. and Mihajlov, A.A. (2010) *The self-consistent determination of HF electroconductivity of strongly coupled plasmas,* Physics Letters A Vol 374 Issue: 5 Pages: 754-760 ISSN: 0375-9601 DOI: 10.1016/j.physleta.2009.11.073 (M21)

Adamyan, V.M., Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Tkachenko, I.M. (2009)
The dynamic conductivity of strongly non-ideal plasmas: is the Drude model valid?
Journal of Physics A: Mathematical and Theoretical Vol 42 Issue: 21 Pages: 214005 ISSN: 1751-8121 DOI: 10.1088/1751-8113/42/21/214005 (M21)

Tkachenko, I.M., Adamyan, V.M., Mihajlov, A.A., Sakan, N.M., Šulić, D. and Srećković, V.A. (2006) *Electrical conductivity of dense non-ideal plasmas in external HF electric field* Journal of Physics A: Mathematical and General Vol 39 Issue: 17 Pages: 4693-4698 ISSN: 0305-4470 DOI: 10.1088/0305-4470/39/17/S58 (M21)

Adamyan, V.M., Grubor, D., Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Tkachenko, I.M. (2006) *Optical HF electrical permeability, refractivity and reflectivity of dense non-ideal plasmas,* Journal of Physics A: Mathematical and General Vol 39 Issue: 17 Pages: 4401-4405 ISSN: 0305-4470 DOI: 10.1088/0305-4470/39/17/014 (M21)

Такође, бавио се и теоријским изучавањем процеса дисоцијативне рекомбинације и асоцијативне јонизације у плазми водоника и хелијума астрофизичких објеката. Резултати ових анализа су објављени у неколико радова у међународним часописима (нпр. Gnedin, Yu. N., Mihajlov, A.A., Ignjatović, Lj. M., Sakan, N.M., Srećković, V.A., Zakharov, M. Yu., Bezuglov, N.N. and Klycharev, A.N. (2009) Rydberg atoms in astrophysics, New Astronomy Reviews Vol 53, 7, 259-265), приказани на бројним домаћим и међународним конференцијама које су праћене саопштењима у целини и у изводу и на основу њих је урађена магистарска теза одбрањена 2006 и докторска теза одбрањена 2010 године на Физичком факултету универзитета у Београду. У току овог периода његов рад је обављен у оквиру пројекта Основних истраживања Министарства за науку Србије 141033. Након 2010. др Владимир Срећковић је рад наставио у оквиру пројекта Основних истраживања Министарства за науку Србије „*Неидеална лабораторијска и јоносферска плазма: особине и примена*“ 141033 и од 2011 године у оквиру пројеката „*Астроинформатика: Примена ИТ у астрономији и сродним пољима истраживања*“ ИИИ 44002 и „*Утицај сударних процеса на астрофизичку плазму*“ ОН 176002.

Након избора у звање виши научни сарадник истраживачки рада др Владимира Срећковића је пре свега усмерен на проучавање сударних атомско/молекулских процеса у слабо-јонизованим астрофизичким и лабораторијским плазмама као и проучавању и анализи експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали) и нумеричком моделовању плазми ниске јоносфере и развијању теоријских процедура за опис параметара који је карактеришу. Последњих неколико година активност кандидата фокусирана је и на раду везаном за атомске/молекулске базе података у оквиру Европског виртуалног центра за атомске и молекулске податке.

У досадашњем раду научне активности др Владимира Срећковића одвијале су се у следећим областима:

2.1 Хеми-јонизациони и хеми-рекомбинациони процеси у слабо-јонизованим астрофизичким/лабораторијским плазмама

У оквиру ове теме др Срећковића се бавио истраживањима једне групе хеми-јонизационих и хеми-рекомбинационих процеса у слабо-јонизованим лабораторијским и астрофизичким плазмама где посматрани процеси играју посебно важну улогу. У случају неона, како експериментално тако и теоријски, анализирани су хеми-јонизациони процеси. Израчунати су одговарајући рејт коефицијенти и резултати упоређени са доступним подацима из литературе. У радовима представљени су основни механизми, критички осврт, као и примена хеми-јонизационих процеса. Затим, испитан је утицај ових процеса на популацију побуђених стања водоникових атома у фотосфери Сунца и атмосфери белих патуљака као и у слабо-јонизованим областима Активних галактичких језгра (AGN). Испитиван је њихов однос са конкурентским електрон-атом и електрон-јон јонизационим/рекомбинационим процесима. Такође, показано је да хеми-јонизациони и хеми-рекомбинациони процеси утичу на облик спектралних линија у звезданим атмосферама. На пример у раду Srećković et al. (2018) циљ је био да се иде дубље у физику AGN -а, да се истраже неки атомски процеси као што су сударни атом -Ридберг атом процеси, тј. хемијонизација/рекомбинација и n-n’-mixing и ревидира њихова улога. Другим речима то значи да сазнамо при којим условима у плазми одређени атомски процеси постају важни, и где могу ови процеси бити од користи за дијагностику, нумеричке симулације и моделовање те да се може објаснити постојање AGN области са таквим карактеристикама. Резултати истраживања приказани су у следећим радовима:

- Srećković VA, Dimitrijević MS, Ignjatović LM (2018) Atom-Rydberg atom chemi-ionization/recombination processes in the hydrogen clouds in Broad Line Region of AGNs Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 4, 11 November 2018, Pages 5078–5083 M21

- Mihajlov Anatolij A, Srećković Vladimir A, Ignjatovic Ljubinko M, Dimitrijevic Milan S (2016) Atom-Rydberg-atom chemi-ionization processes in solar and DB white-dwarf atmospheres in the presence of (n - n')-mixing channels, Monthly Notices of the Royal Astronomical Society, vol. 458, no. 2, p. 2215-2220 M21

- Mihajlov Anatolij A, Srećković Vladimir A,Ignjatovic Ljubinko M, Klyucharev AN, Dimitrijevic Milan S, Sakan Nenad M (2015) Non-Elastic Processes in Atom Rydberg-Atom Collisions: Review of State of Art and Problems, J. Astrophys. Astron., vol. 36, 4, p. 623-634 M23

- Arefieff K.N., Miculis K., Bezuglov N.N., Dimitrijevic Milan S, Klyucharev A.N., Mihajlov Anatolij A., Srećković Vladimir A. (2015) Dynamics Resonances in Atomic States of Astrophysical Relevance, Journal of Astrophysics and Astronomy, vol. 36, no. 4, p. 613-622 M23

- Bezuglov, N. N., Klyucharev, A. N., Mihajlov, A. A. and Srećković, V. A. (2014) *Anomalies in radiation-collisional kinetics of Rydberg atoms induced by the effects of dynamical chaos and the double Stark resonance,* Advances in Space Research Vol 54 Issue: 7 p1159-1163 (M23)

- Srećković, V.A., Mihajlov, A.A., Ignjatović, Lj. M. and Dimitrijević, M.S. (2013) *Excitation and deexcitation processes in atom-Rydberg atom collisions in helium-rich white dwarf atmospheres,* Astronomy & Astrophysics Vol 552 Pages**:** A33, 3 pp. (M21)

- O'Keeffe, P., Bolognesi, P., Avaldi, L., Moise, A., Richter, R., Mihajlov, A.A., Srećković, V.A. and Ignjatović, Lj. M. (2012) *Experimental and theoretical study of the chemi-ionization in thermal collisions of Ne Rydberg atoms,* Physical Review A Vol 85 Issue: 5 p: 052705 (M21)

- Mihajlov, A.A., Srećković, V.A., Ignjatović, Lj. M. and Klyucharev, A.N. (2012) *The Chemi-Ionization Processes in Slow Collisions of Rydberg Atoms with Ground State Atoms: Mechanism and Applications,* Journal of Cluster Science Vol 23 Issue: 1 p. 47-75 (M23)

- Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A and Dimitrijević, M. S (2011) *Chemi-ionization in Solar Photosphere: Influence on the Hydrogen Atom Excited States Population,* The Astrophysical Journal Supplement Series Vol 193 Issue: 1 Pages: 2(7pp) (M21)

- Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A. and Dimitrijević, M. S (2011) *The Influence of Chemi-Ionization and Recombination Processes on Spectral Line Shapes in Stellar Atmospheres,* Baltic Astronomy Vol 20 p. 566-571 (M23)

2.2 Дијагностика плазме јоносферске D области електромагнетним VLF таласима

Циљ истраживања у оквиру ове теме је анализа експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали), нумеричко моделовање плазме ниске јоносфере и развијање теоријских процедура за опис параметара који је карактеришу. Један део ових истраживања је приказан у оквиру дисертације др Александре Нине којој је др Владимир Срећковић био ментор. Резултати ових анализа су објављени у неколико радова у међународним часописима и приказани на бројним међународним конференцијама које су праћене саопштењима у целини и у изводу. У доле наведеним радовима урађено је моделовање просторних и временских расподела електронске концентрације посебно развијеном техником упоређивања регистрованих амплитуда и фаза са одговарајућим вредностима добијеним нумеричким моделовањем простирања *VLF* сигнала. Ова процедура је представљала основу на којој су, као последица добре временске резолуције израчунатих података, даље омогућене анализе других параметара плазме и то на основу података релевантних за конкретно посматрани простор и време. У радовима је развијена метода, у којој се интензивнији поремећаји користе за одређивања карактеристика плазме у периоду њене релаксације након престанка пертурбационог дејства и последично, на основу добијених сатурационих вредности, у периоду мирне јоносфере. Поред тога извршено је поређење реакције *D*-области на интезивирање зрачења у различитим деловима електромагнетног спектра од γ до Lyα. Поређења утицаја који на јонизацију у *D*- области имају повећана зрачења у *X* домену и повећани интензитет водоникове Lyα линије су показала да је први од њих доминантнији, што је, касније, потврђено и од стране других аутора. Значај развијања наведених процедура је у могућности одређивања параметара плазме у конкретном тренутку и конкретном делу *D*-области. Најважнији радови су:

- Ilić, L., Kuzmanoski, M., Kolarž, P., Nina, A., Srećković, V., Mijić, Z., Bajčetić, J., & Andrić, M. (2018). *Changes of atmospheric properties over Belgrade, observed using remote sensing and in situ methods during the partial solar eclipse of 20 March 2015*, Journal of Atmospheric and Solar-Terrestrial Physics, 171 250–259, (M22)

- Šulic Desanka M, Srećković Vladimir A, Mihajlov Anatolij A (2016) *A study of VLF signals variations associated with the changes of ionization level in the D-region in consequence of solar conditions*, Advances in Space Research, vol. 57, br. 4, str. 1029-1043 (M22)

- D. M. Šulić, V. A. Srećković and Anatolij A. Mihajlov *Analysis of the Ionospheric D-Region Disturbances in Response to the Effects of Solar X-Ray Flares*, Chapter 3 in Solar Flares: Investigations and Selected Research Eds: Sarah L. Jones, Nova Science Publishers Inc., New York 2016, p.44-81, ISBN: 978-1-53610-204-8

- Nina Aleksandra, Simic Sasa Z, Srećković Vladimir A, Popovic Luka C (2015) Detection of short-term response of the low ionosphere on gamma ray bursts, Geophysical Research Letters, vol. 42, br. 19, str. 8250-8261. 16.10.2015. (M21a)

- Šulić, D. M. and Srećković, V. A. (2014) *A comparative study of measured amplitude and phase perturbations of VLF and LF radio signals induced by solar flares,* Serbian Astronomical Journal Vol 188 Pages: 45-54 (M23)

- Nina, A., Čadež, V., Šulić, D., Srećković, V.A. and Žigman, V. (2012) *Effective electron recombination coefficient in ionospheric D-region during the relaxation regime after solar flare from February 18, 2011,* Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Vol 279 p: 106-109 (M21)

- Nina, A., Čadež, V., Srećković, V.A. and Šulić, D. (2012) *Altitude distribution of electron concentration in ionospheric D-region in presence of time-varying solar radiation flux,* Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Vol 279 p: 110-113 (M21)

- Nina, A., Čadež, V., Srećković, V.A. and Šulić, D. (2011) *The influence of solar spectral lines on electron concentration in terrestrial ionosphere* Baltic Astronomy Vol 20 p: 609-612 (M23)

2.3 Несиметрични јон-атомски радиативни процеси у астрофизичким плазмама

У оквиру ове теме др Срећковић се бавио истраживањима утицаја јако несиметричних јон-атом радиативних процеса у атмосферама Сунца (мирно Сунце, Сунчеве пеге) и у атмосферама белих патуљака (White dwarf) као и утицај ових процеса у лабораторијским и стеларним плазмама. Главни циљ је био указивање на чињеницу да су испитивани процеси важни и незаобилазни приликом описивање оптичких својстава посматраних плазми. Резултати ових истраживања су презентовани у неколико публикација од којих издвајамо:

- Ignjatović, Lj. M., Mihajlov, A. A., Srećković, V. A. and Dimitrijević, M. S. (2014) *The ion–atom absorption processes as one of the factors of the influence on the sunspot opacity,* Monthly Notices of the Royal Astronomical Society Vol 441 Issue: 2 p1504-1512 (M21)

- Srećković, V. A., Mihajlov, A. A., Ignjatović, Lj M. and Dimitrijević, M. S. (2014) *Ion-atom radiative processes in the solar atmosphere: quiet Sun and sunspots,* Advances in Space Research Vol 54 Issue: 7 p 1264-1271 (M23)

- Ignjatović, Lj. M., Srećković, V. A., Mihajlov, A. A. and Dimitrijević, M. S. (2014) *Absorption non-symmetric ion–atom processes in helium-rich white dwarf atmospheres,* Monthly Notices of the Royal Astronomical Society Vol: 439 Issue: 3 p 2342-2350 (M21)

- Mihajlov, A. A., Ignjatović, Lj. M., Srećković, V. A., Dimitrijević, M. S. and Metropoulos, A. (2013) *The non-symmetric ion–atom radiative processes in the stellar atmospheres,* Monthly Notices of the Royal Astronomical Society Vol 431 Issue: 1 p 589-599 (M21)

2.4 Атомски сударни и радиативни процеси VAMDC

Последњих неколико година активност кандидата усмерена је и на раду везаном за атомске/молекулске базе података (http://servo.aob.rs/mold/) у оквиру Европског виртуалног центра за атомске и молекулске податке (http://vamdc.org; https://portal.vamdc.eu/vamdc_portal/nodes.seam). Сама проблематика је од стратешког значаја за Европску унију и широку научну заједницу како итиче *European Strategy Forum on Research Infrastructures* (ESFRI) у свом извештају *Strategy Report and Roadmap 2018*. Др Срећковић са екипом колега је и сам произвођач тих теоријско/експерименталних података. Резултати ових истраживања приказани су на неколико конференција и радионица као и у следећим радовима:

- Bratislav P. Marinković, Darko Jevremović, Vladimir A. Srećković, Veljko Vujčić, Ljubinko M. Ignjatović, Milan S. Dimitrijević and Nigel J. Mason (2017), BEAMDB and MolD – databases for atomic and molecular collisional and radiative processes: Belgrade nodes of VAMDC, The European Physical Journal D vol.71, issue 6, 158(9) M23

- Vujcic Veljko, Jevremovic Darko M, Mihajlov Anatolij A, Ignjatovic Ljubinko M, Srećković Vladimir A, Dimitrijevic Milan S, Malovic Miodrag (2015) MOL-D: A Collisional Database and Web Service within the Virtual Atomic and Molecular Data Center, Journal of Astrophysics and Astronomy, vol. 36, no. 4, p. 693-703 M23

Техничка решења у организовању велике количине података тј. MolD базе података (http://servo.aob.rs/mold/) приказани су и у и два техничка решења РБ 1612 и РБ 1764 http://www.mpn.gov.rs/wp-content/uploads/2016/04/TEHNICKA-RESENJA-2011-2015-10-april.xls

2.5 Моделирање континуалне апсорпције електромагнетног зрачења у густој лабораторијској и астрофизичкој плазми

У оквиру ове теме, др Срећковић се бавио истраживања процеса континуалне апсорпције у области од делимично до јако јонизованих плазми у опсегу електронских концентрација од 10^{14} cm^{-3} па до 10^{20} cm^{-3} и температура 6000 K до 300 000 K. Главни циљ је био постављање новог модела за прорачун процеса континуалне апсорпције електромагнетног зрачења. Он је примењен и проверен за ЕМ спектар таласних дужина 10 nm < λ < 3000 nm у опсегу електронских концентрација до 10^{19} cm^{-3} и температура око > 6000 K. Приказани резултати имају примену како на опис лабораторијских, тако и на плазме у атмосферама звезда. Резултати су представљени у неколико радова као и на неколико конференција:

- Srećković V. A., Sakan N., Šulić D., Jevremović D., Ignjatović Lj. M. and Dimitrijević M. S. (2018) Free–free absorption coefficients and Gaunt factors for dense hydrogen-like stellar plasma Monthly Notices of the Royal Astronomical Society, 475 (1), 1131-1136 (M21)

- M. S. Dimitrijević , V. A. Srećković, N. M. Sakan, N. N. Bezuglov, A. N. Klyucharev (2018)

Free-Free Absorption in Solar Atmosphere, Geomagnetism and Aeronomy, 2018, Vol. 58, No. 8, pp. 1067–1072, DOI: 10.1134/S0016793218080054 (M23)

- Mihajlov Anatolij A, Srećković Vladimir A,Sakan Nenad M (2015) Inverse Bremsstrahlung in Astrophysical Plasmas: The Absorption Coefficients and Gaunt Factors, J. Astrophys. Astron., 36, 4, p. 635-642 (M23)

- Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Vitel, Y. (2011) *Modeling of continuous absorption of electromagnetic radiation in dense partially ionized plasmas*, Journal of Physics A: Mathematical and Theoretical Vol: 44 Issue: 9 p (M21)

- Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Vitel, Y. (2011) *Modeling of the Continuous Absorption of Electromagnetic Radiation in Dense Hydrogen Plasma* Baltic Astronomy, Vol 20 p 604-608 (M23)

3. ЕЛЕМЕНТИ ЗА КВАЛИТАТИВНУ ОЦЕНУ РАДА КАНДИДАТА

3.1. Квалитет научних резултата

3.1.1 Научни ниво и значај резултата, утицај научних радова

У својој каријери др Владимир Срећковић је као аутор или коаутор, објавио и презентовао 193 библиографских јединица тј. научних радова, у часописима од међународног значаја, у домаћим часописима, међународним и домаћим конференцијама. До сада је објавио 38 (тридесет осам) научних радова са ISI листе од којих 15 од одлуке Научног већа о предлогу за стицање претходног научног звања као и поглавље у монографији међународног значаја. Укупан импакт фактор радова др Срећковића износи 102.406, а у периоду након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања радова укупан импакт фактор је 34.85. Часописи у којима објављује др Срећковић (3 категорије М21а, 15 категорије М21, 6 категорије М22 и 14 категорије М23) су цењени по свом угледу и водећи у његовим областима рада. Међу поменутим часописима посебно се истичу *Physical Review A*, *Astronomy & Astrophysics, Astrophysical Journal Supplement Series, Geophysical Research Letters, Monthly Notices of the Royal Astronomical Society, J. Phys. A* итд. Др Срећковић је до сада објавио 8 радова у једном од најугледнијих часописа у области астрофизике Monthly Notices of the Royal Astronomical Society (средњи ИФ=5.2).

Као пет најзначајнијих радова др Срећковића могуће је издвојити:

<u>1. Srećković, V. A.</u>, Ignjatović, Lj .M., Mihajlov, A. A. and Dimitrijević, M. S. (2010)
Electrical conductivity of plasmas of DB white dwarf atmospheres, Monthly Notices of the Royal

Astronomical Society Vol 406 Issue: 1 Pages: 590-596 ISSN: 1365-2966
http://dx.doi.org/10.1111/j.1365-2966.2010.16702.x **(M21) (IF=5.185)**

2. Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A and Dimitrijević, M. S (2011)
Chemi-ionization in Solar Photosphere: Influence on the Hydrogen Atom Excited States Population, The Astrophysical Journal Supplement Series Vol 193 Issue: 1 Pages: 2(7pp) ISSN: 0067-0049
http://dx.doi.org/10.1088/0067-0049/193/1/2 (**M21a**) (**IF=15.206**)

3. Mihajlov Anatolij A, Srećković Vladimir A, Ignjatovic Ljubinko M, Dimitrijevic Milan S (2016)
Atom-Rydberg-atom chemi-ionization processes in solar and DB white-dwarf atmospheres in the presence of (n - n')-mixing channels, Monthly Notices of the Royal Astronomical Society, vol. 458, br. 2, str. 2215-2220 **M21 (5.107)** http://dx.doi.org/10.1093/mnras/stw308

4. Srećković V. A., Sakan N., Šulić D., Jevremović D., Ignjatović Lj. M. and Dimitrijević M. S. (2018) *Free–free absorption coefficients and Gaunt factors for dense hydrogen-like stellar plasma* Monthly Notices of the Royal Astronomical Society, 475 (1), 1131-1136 **M21 (5.194)**
http://dx.doi.org/10.1093/mnras/stx3237

5. Srećković VA, Dimitrijević MS, Ignjatović LM (2018) *Atom-Rydberg atom chemi-ionization/ recombination processes in the hydrogen clouds in Broad Line Region of AGNs* Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 4, 11 November 2018, Pages 5078–5083 **M21 (5.194)**
https://doi.org/10.1093/mnras/sty2256

У првом раду кандидат долази до идеје и испитује статичку електропроводност делимично јонизоване густе плазме хелијума у широкој области плазма параметара: 10^4 K $\leq T \leq$ 10^5 K и масених густина 10^{-6} g/cm$^3 \leq \rho \leq 2\ 10^{-3}$ g/cm^3 где је израчуната електропроводност од интереса за атмосфере звезда типа DB белих патуљака са ефективним температурама 10^3 K $\leq T_{\mathrm{eff}} \leq$ $3{\cdot}10^3$ K. Модификовањем и адаптацијом постојеће RPA методе урачунат је утицај атомске компоненте на електропроводност. Добијени резултати су показали очекивани ток електропроводности а најважније, у раду је показано да атомска компонента има значајан допринос у посматраном случају те се обавезно мора урачунавати при одређивању осталих транспортних коефицијената. Ови резултати су веома важни и могу се користити како у моделовању термалне еволуције звезда тако и у проналажењу других планета у близини звезда.

У другом и трећем раду, кандидат је дао кључан допринос у добијању, обради и тумачењу резултата при проучавању групе хеми-јонизационих и хеми-рекомбинационих процеса у слабо-јонизованим астрофизичким и лабораторијским плазмама где посматрани процеси играју посебно важну улогу. У овим радовима анализиран је утицај ових ових сударних атомских/молекулских процеса на популацију побуђених стања водоникових атома у фотосфери и џромосфери Сунца и атмосфери белих патуљака и испитан њихов однос са конкурентским електрон-атом и електрон-јон јонизационим/рекомбинационим процесима. Показано је да хеми-јонизациони и хеми-рекомбинациони процеси утичу на облик спектралних линија у звезданим атмосферама. Кандидат је резултате ових радова представио кроз три предавања по позиву, као и на другим предавањима која је одржао на престижним конференцијама у овој области.

У четвтом раду дата је студија посвећена одређивању коефицијента апсорпције за процесе инверзног bremsstrahlung-а и одговарајућих Gaunt фактора за густе водоничне стеларне и лабораторијске плазме где се концентрација електрона и температура мењају у широком опсегу. Кандидат је дао кључан допринос у развијању модела, добијању, обради и тумачењу резултата као и у предавањима која је одржао на престижним конференцијама.

Други, трећи и пети рад третирају комплементарне теме. У петом раду кандидат долази до идеје и испитује утицај групе хеми-јонизационих и хеми-рекомбинационих процеса у слабо-јонизованим областима Активних галактичких језгра. Као закључак се намеће констатација да наведени процеси могу да играју значајну улогу тј. могу бити корисни за дијагностику, моделирање, и потврду постојања или непостојања веома густих слабонизованих подручја у широколинијским областима активних галактичких језгара.

Имајући у виду горенаведено јасно је да се ради о научним резултатима високог нивоа, који су имали јасан значај и утицај на истраживачку и ширу заједницу.

3.1.2 Позитивна цитираност научних радова кандидата

Према подацима на дан 28. 10. 2018 према бази Google Scholar радови др Срећковића цитирани су 401 пута са h-фактором 12. Према бази ISI Web of Science, радови др Срећковића укупно су цитирани 247 пута, док је број цитата без аутоцитата 125. Према бази Scopus, укупан број цитата је 281, док је број цитата без аутоцитата 113 (Scopus Author ID: 12805196400). Према подацима с обе базе (ISI Web of Science и Scopus) Хиршов индекс радова др Срећковића је 11 (ResearcherID: S-5724-2018). Orcid ID: 0000-0001-7938-5748 . (У прилогу су подаци о цитираности из ових база).

3.1.3 Параметри квалитета часописа

До сада је објавио 38 (тридесет осам) научних радова са ISI листе од којих 15 од одлуке Научног већа о предлогу за стицање претходног научног звања као и поглавље у истакнутој монографији међународног значаја. Укупан импакт фактор радова др Срећковића износи 102.406, а у периоду након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања радова укупан импакт фактор је 34.851. Часописи у којима објављује др Срећковић (3 категорије M21a, 15 категорије M21, 6 категорије M22 и 14 категорије M23) при чему су подвучени импакт-фактори часописа у којима су публиковани радови након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања:

• 1 рад у *Astrophysical Journal Supplement Series* (ИФ 15.206)

• 1 рад у *Astronomy & Astrophysics* (ИФ 5.084)

• 8 рада у часопису *Monthly Notices of the Royal Astronomical Society* (ИФ 5.185 за један рад, ИФ 5.521 за 3 рада, 5.107 за 1 рад и 5.194 за 3 рада)

• 1 рад у часопису *Geophysical Research Letters* (ИФ 4.456)

• 1 рад у часопису *Physical Review A* (ИФ 3.042)

• 1 рад у часопису *Physics Letters A* (ИФ 2.174)

• 1 рад у часопису *Journal of Quantitative Spectroscopy and Radiative Transfer* (ИФ 1.972)

• 4 рада у часопису *Journal of Physics. A: Mathematical and General* (ИФ 1.577 за два рада, ИФ 1.641 за један ради и ИФ 1.680 за један рад)

• 1 рад у часопису *Journal of Atmospheric and Solar-Terrestrial Physics* (ИФ 1.492)

• 3 рада у часопису *Advances in Space Research* (ИФ 1.409 за један рад и ИФ 1.358 за два рада)

• 2 рада у часопису *European Physical Journal D* (ИФ 1.393)

• 1 рад у часопису *New Astronomy Reviews* (ИФ 1.299)

• 2 рада у часопису *Nuclear Instruments and Methods in Physics Research. Section B* (ИФ 1.266)

• 1 рад у часопису *Journal of Cluster Science* (ИФ 1.111)

• 1 рад у часопису *Serbian Astronomical Journal* (ИФ 1.100)

• 3 рада у часопису *Balt Astron* (ИФ 1.032)

• 4 рада у часопису *Journal of Astrophysics and Astronomy* (ИФ 0.711)

• 1 рад у часопису *Nuclear Technology & Radiation Protection* (ИФ 0.620)

• 1 рад у часопису *Geomagnetism and Aeronomy* (ИФ 0.555)

Додатни библиометријски показатељи, за радове од претходног избора, према Упутству о начину писања извештаја о изборима у звања које је усвојио Матични научни одбор за физику приказани су у следећој табели:

	ИФ	**М**	**СНИП**
Укупно	34.851	76	13.463
Усредњено по чланку	2.3234	5.067	0.898
Усредњено по аутору	8.7	18.346	3.218

3.1.4 Степен самосталности и степен учешћа у реализацији радова у научним центрима у земљи и иностранству

У својој досадашњој каријери, кандидат је показао самосталност у решавању сложених проблема који са собом носи рад како у експерименталној тако и у теоријској физици. Учествовао је у стварању Лабораторије за астрофизику и физику јоносфере у Институту за физику у Београду. Заједно са другим сарадницима у лабораторији отворио нову област истраживања у самом Институту за физику и широј научној заједници у Србији и то у областима астрофизике и физике јоносфере. Ипак, пуну самосталност у истраживањима достигао је након докторирања, када је покренуо више праваца истраживања која се раније нису спроводила на Институту за физику и у Србији.

Први покренути правац рада је проучавање и анализа експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали), нумеричко моделовање плазме ниске јоносфере и развијање теоријских процедура за опис параметара који је карактеришу. У оквиру те теме, успео је да оствари интезивну међународну сарадњу, кроз билатералне пројекте нпр. са Словенијом. Такође, један је од покретача сарадње са VLF групом Универзитета Станфорд у оквиру AWESOME Global Collaborative for VLF Research. Развио је међународну сарадњу са више истраживачких група и појединаца.

Други покренути правац рада подразумева сарадњу са Групом за астрономску спектроскопију са Астрономске опсерваторије у Београду. Допринос др Срећковића у заједничким радовима се огледа у нумеричким прорачунима брзина реакција атомских сударних процеса тј. групе хеми-јонизационих и хеми-рекомбинационих процеса у слабо-јонизованим астрофизичким плазмама које постоје у фотосфери Сунца, атмосфери белих патуљака и у неким областима у Активним галактичким језгрима. При изради поменутих публикација, поред писања самих текстова радова, др Срећковић је учествовао у анализи и дискусији резултата где је већином и први аутор. Развио је међународну сарадњу пре свега са колегама са Катедре за оптику физичког факултета Универзитета у Ст. Петербургу, Русија.

Трећи покренути правац рада подразумева сарадњу са проф. Др. Братиславом Маринковићем из Лабораторије за физику атомских сударних процеса са Института за физику и Групом за астрономску спектроскопију са Астрономске опсерваторије у Београду на стварању и прикључењу Београдског Нода (BEAMDB и MOLD базе података атомских/молекулских процеса) у оквире Европског виртуалног центра за атомске и молекулске податке VAMDC (http://vamdc.org), Париз. Др. Срећковић не само да је учествовао у стварању Београдског Нода и укључењу Србије у ову организацију него активно учествује у раду VAMDC-а. Сама проблематика је од стратешког значаја за Европску унију и широку научну заједницу како истиче *European Strategy Forum on Research Infrastructures* (ESFRI) у свом извештају *Strategy Report and Roadmap 2018*. Непосредно из овог правца рада проистекло је више публикација у међународним часописима као и техничка решења на којима је др Срећковић дао значајан тј. кључан допринос.

У периоду након одлуке Научног већа о предлогу за стицање претходног научног звања др Срећковић је од објављених М20 и М30 публикација први аутор на 32 рада.

3.1.5 Награде и признања за научни рад

Награду за најбоље урађен магистарски рад за 2005/06. годину из фонда "проф. др Љубомир Ћирковић", која се додељује на Физичком факултету Универзитета у Београду кандидат је добио 17. децембра 2006. године (видети прилог).

Рад објављен у међународном часопису Geophysical Research Letters изабран за „ Research Spotlight" (best accepted articles for the broad Earth and space science Community) и публиковано је саопштење за штампу везано за тај рад https://eos.org/research-spotlights/gamma-ray-bursts-leave-their-mark-in-the-low-ionosphere Nina Aleksandra, Simic Sasa Z, Srećković Vladimir A, Popovic Luka C (2015) *Detection of short-term response of the low ionosphere on gamma ray bursts*, vol. 42, no. 19, p. 8250-8261. 16.10.2015 (видети линк и прилог).

3.2. Ангажованост у развоју услова за научни рад, образовању и формирању научних кадрова

Др Владимир Срећковић је био ментор при изради једне докторске тезе под називом „Дијагностика плазме јоносферске D области електромагнетним VLF таласима" (др Александра Нина) одбрањене 15. априла 2014 на Физичком факултету Универзитета у Београду (видети прилог). Тренутно, под руководством др Срећковића је у току израда једне докторске дисертације (Златка Мајлингера) на Природословно-математичком факултет у Загребу, Хрватска.

Такође је био више пута члан различитих комисија, и то за одбрану (Милке Поледице, мастер рада на Физичком факултету Универзитета у Београду) и за изборе у звања (др. Александре Нине, др. Ненада Сакана, др. Михаила Мартиновића).

3.3 Нормирање броја коауторских радова, патената и техничких решења

Од избора претходно звање кандидат има 15 публикованих радова са са ISI листе. Теоријски радови др Срећковића објављени у периоду након одлуке Научног већа о предлогу за стицање претходног научног звања су базирани на аналитичким прорачунима и комплексним нумеричким симулацијама и имају већином пет или мање аутора док експериментални радови подразумевају шире колаборације. Бодови за ове радове су нормирани по формули датој у правилнику, и нормирани број М поена је приказан у табели у прегледу квантитативних резултата. Нормирањем се укупан број бодова М20 радова смањио веома мало, што не мења на битан начин процену резултата кандидата.

3.4. Руковођење пројектима, потпројектима и пројектним задацима

Кандидат је:

- Руководилац и оснивач Лабораторије за астрофизику и физику јоносфере, Института за физику, Универзитета у Београду (документовано у прилогу). http://www.ipb.ac.rs/istrazivanja/laboratorije/laboratorija-za-astrofiziku-i-fiziku-jonosfere/

- Руководилац тима са Института за физику у Београду и члан Управног одбора (енг. Managing Committee - MC) COST акције „The multi-messenger physics and astrophysics of neutron stars“ (PHAROS) CA16214. https://www.cost.eu/actions/CA16214#tabs|Name:management-committee

- Руководилац тима са Института за физику у Београду и члан Управног одбора (MC) COST акције „Mobilising Data, Policies and Experts in Scientific Collections“ (MOBILISE) CA17106. Руковођења овим пројектима, су документована у прилозима. Прилог копија званичне интернет странице COST акције. https://www.cost.eu/actions/CA17106#tabs|Name:management-committee

- Руководилац потпројекта *Утицај нееластичних атом-Ридберг атом сударних процеса на кинетику слабо јонизоване плазме Сунца и белих патуљака*, у оквиру пројеката Министарства просвете, науке и технолоког развоја ОН 176002 *Утицај судара на спектре астрофизичке плазме*.

Све наведене активности су документоване у прилозима и линковима.

3.5. Активност у научним и научно-стручним друштвима

Од 2017. члан је редакције тј. Уређивачког одбора часописа Васиона, који издаје друштво астр. Руђер Бошковић у сврху популаризације астрофизике.

• Владимир Срећковић је члан Уређивачког одбора (енг. Editor Board) међународног часописа *Data* (Open Access Journal of ‘Data in Science’, ESCI - Web of Science indexed) (https://www.mdpi.com/journal/data) и члан Advisory Board часописа *Sci* (https://www.mdpi.com/journal/sci) који издаје MDPI (Multidisciplinary Digital Publishing Institute) .

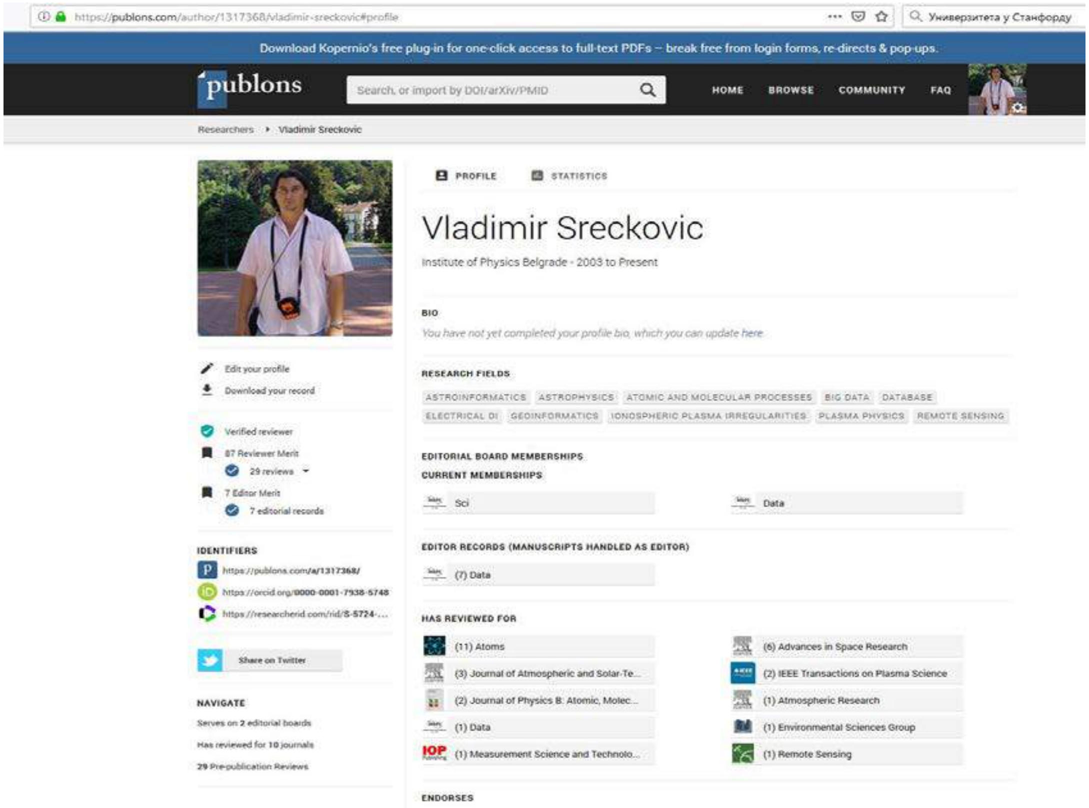
• Владимир Срећковић је био један од Уредника (Guest Ed.) посебних издања међународних часописа:

- Special Issue in Atoms[1] (Scopus and ESCI - Web of Science indexed): *Atomic and Ionic Collisions with Formation of Quasimolecules* Guest Eds.: Dr. Vladimir A. Srećković, Prof. Dr. Milan S. Dimitrijević, Dr. Nikolai N. Bezuglov, Deadline for manuscript submissions: 31 March 2019 https://www.mdpi.com/journal/atoms/special_issues/Atomic_ionic_collisions_formation_quasimolecules

- Special Issue in Data: *Data in Astrophysics & Geophysics: Research and Applications* Guest Eds.: Dr. Vladimir A. Srećković, Dr. Aleksandra Nina https://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Све наведене активности су документоване линковима као и у прилозима, такође видети и едитор профил на https://publons.com/author/1317368/vladimir-Srećković#profile) Publons ID a/1317368 . Publons је Clarivate Analytics тј. Web of Science сервис за истраживаче који прати, потврђују и приказују рефери доприносе и **уредничке доприносе** за академске часописе.

[1] У часопису Atoms иначе су публиковани и изабрани радови са једне од наших највећих међународних конференција SPIG2018 https://www.mdpi.com/journal/atoms/special_issues/SPIG2018



3.5.1. Рецензије научних радова

• Има више од 40 рецензензија научних радова међу којима и у водећим међународним часописима као што су:

Journal of Atmospheric and Solar-Terrestrial Physics у издању Elsevier,

Atmospheric Research у издању Elsevier,

IEEE Transactions on Plasma Science издавач IEEE,

Remote Sensing у издању MDPI,

Publ. Astron. Obs. Belgrade издавач AOB,

Atoms у издању MDPI,

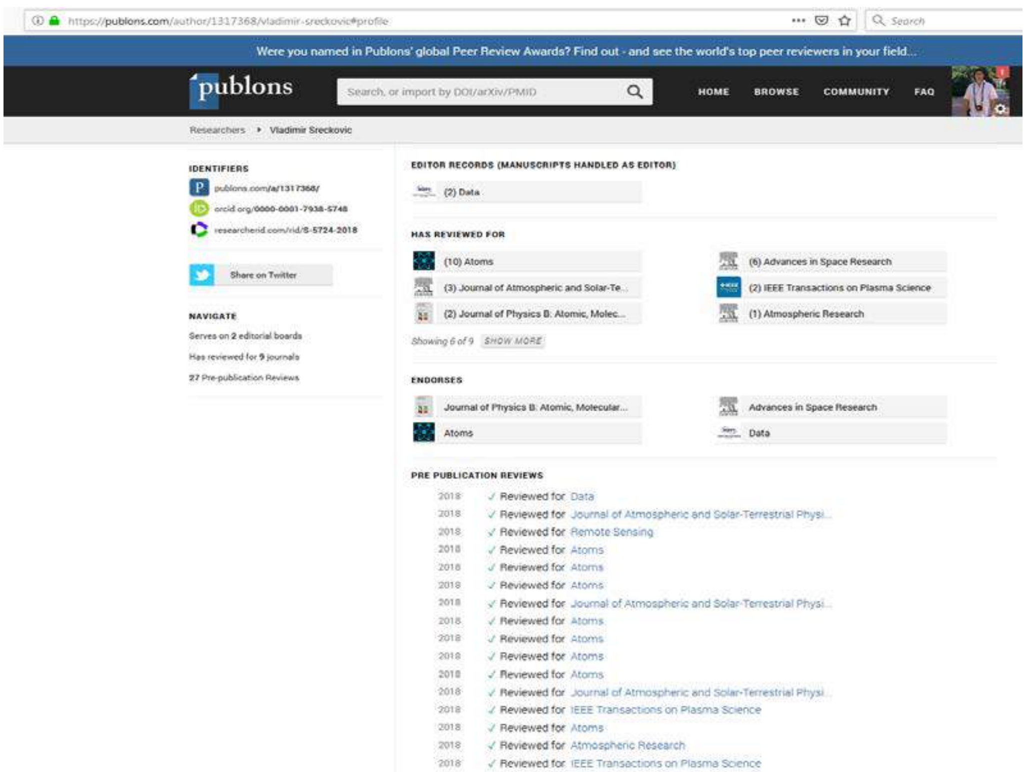
Data у издању MDPI,

JPCS у издању IOP Publishing,

Journal of Physics B у издању IOP Publishing, Advances in Space Research у издању Elsevier.

итд.

Од тога Др. Срећковић је урадио 18 рецензија само у 2018 години (видети рефери профил на https://publons.com/author/1317368/vladimir-Srećković#profile) Publons ID a/1317368/ и на дан 26.новембар 2018 заузима 32 место на листи рецензената из Србије. Publons је Clarivate Analytics тј. Web of Science сервис за истраживаче који прати, потврђују и приказују рефери доприносе и уредничке доприносе за академске часописе.



Све наведене активности су документоване у прилозима (због обимности приказане су само неке рецензије, већину можете видети на Publons профилу) .

3.5.2. Организација научних скупова

• Др Владимир Срећковић је био члан Орагизационог и Научног комитета више међународних конференција.

-Члан Организационог комитета „II Workshop on Astrophysical spectroscopy“ која је одржана 9 - 13, Oct. 2013, Vrujci, Serbia link

-Члан Организационог комитета међународне конференције "Big data in sky and Earth Observations" која је одржана у Београду 30-31 March 2015, link

-Члан Организационог комитета међународне конференције "LSST@Europe 2" која је одржана у Београду 20-24 June, 2016.

-Члан Научног и Организационог комитета међународне конференције X-SBAC која је одржана у Београду 30 May - 3 June, 2016, Serbia. link

-Члан Организационог комитета међународне конференције 11th SCSLSA Conference on Spectral Line Shapes in Astrophysics која је одржана у Шабцу, 20-25, August 2017, Serbia. link

-Члан Научног комитета међународне конференције XI BSAC Conference која је одржана 14 - 18 May, 2018, Belogradchik, Bulgaria. link

-Члан Научног комитета међународне конференције 12th SCSLSA Conference on Spectral Line Shapes in Astrophysics Vrdnik, Serbia, која се одржава Jun 3-7, 2019 link

• Поред тога, кандидат је члан Одсека за Астрономију и Астрофизику Друштва физичара Србије. У пратећој документацији је списак представника у Одељењима Друштва физичара Србије за научна истраживања и високо образовање.

Члан је Међународне Астрономске Уније (International Astronomical Union - IAU), Еуро-Азијског астрономског друштва, Друштва астронома Србије, итд.

Све наведене активности су документоване линковима и прилозима.

3.6. Утицајност научних резултата

Утицај научних резултата кандидата се огледа у броју цитата који су наведени у тачки 3.1.2 овог прилога као и у прилогу о цитираности. Значај резултата кандидата је такође описан у тачки 3.1 (У прилогу је списак радова и цитата).

Такође радови: **1)** Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A and Dimitrijević, M. S (2011) *Chemi-ionization in Solar Photosphere: Influence on the Hydrogen Atom Excited States Population*, The Astrophysical Journal Supplement Series 193, 1, 7pp и **2)** Gnedin, Yu. N., Mihajlov, A.A., Ignjatović, Lj. M., Sakan, N.M., Srećković, V.A., Zakharov, M. Yu., Bezuglov, N.N. and Klycharev, A.N. (2009) *Rydberg atoms in astrophysics*, New Astronomy Reviews, 53, 7, 259-265 су наведени као референце на Википедији под појмом Chemi-ionization (https://en.wikipedia.org/wiki/Chemi-ionization) и појмом Rydberg atom (https://en.wikipedia.org/wiki/Rydberg_atom).

3.7. Конкретан допринос кандидата у реализацији радова у научним центрима у земљи и иностранству

Др Срећковић је значајно допринео сваком раду у чијој припреми је учествовао. Од укупно 38 тј. 15 радова са ISI листе објављених у периоду након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања, сви радови су урађени у сарадњи с колегама из земље и иностранства.

Конкретно, кандидат је током израде ових публикација био покретач истраживања, учествовао је у прорачунима/аквизицији и вршио обраду података, а при писању већине радова је био у комуникацији тј. кореспонденцији са уредником часописа при слању. Интензивним праћењем литературе др Срећковић је, међу коауторима, примарно допринео развијању метода за анализу добијених резултата.

Др Срећковић је покренуо правце истраживања који се нису раније изучавали у Србији:

Први правац рада је проучавање и анализа експериментално забележених података релевантних за електромагнетне сигнале врло ниских фреквенција (VLF сигнали), нумеричко моделовање плазме ниске јоносфере и развијање теоријских процедура за опис параметара који је карактеришу. У оквиру те теме, успео је да оствари интезивну међународну сарадњу, кроз билатералне пројекте нпр. са Словенијом. Такође, један је од покретача сарадње са VLF групом Станфорд Универзитета у оквиру AWESOME Global Collaborative for VLF Research. Развио је међународну сарадњу са више истраживачких група и појединаца.

Други покренути правац рада подразумева сарадњу са *Групом за астрономску спектроскопију са Астрономске опсерваторије* у Београду. Допринос др Срећковића у заједничким радовима се огледа у нумеричким прорачунима брзина реакција атомских/молекулских процеса тј. групе хеми-јонизационих и хеми-рекомбинационих процеса у слабо-јонизованим астрофизичким плазмама које постоје у фотосфери Сунца, атмосфери белих патуљака и у неким областима у Активним галактичким језгрима. При изради поменутих публикација, поред писања самих текстова радова, др Срећковић је учествовао у анализи и дискусији резултата где је већином и први аутор.

Трећи покренути правац рада подразумева сарадњу са проф. Др. Братиславом Маринковићем из *Лабораторије за физику атомских сударних процеса* са Института за физику и

Групом за астрономску спектроскопију са Астрономске опсерваторије у Београду на стварању и прикључењу Београдског Нода (BEAMDB и MolD базе података атомских/молекулских процеса) у оквире Европског виртуалног центра за атомске и молекулске податке VAMDC (http://vamdc.org), Париз. Др. Срећковић не само да је учествовао у стварању Београдског Нода и укључењу Србије у ову организацију него активно учествује у раду VAMDC-а. Сама проблематика је од стратешког значаја за Европску унију и широку научну заједницу како итиче *European Strategy Forum on Research Infrastructures* (ESFRI) у свом извештају *Strategy Report and Roadmap 2018*. Непосредно из овог правца рада проистекло је више радова у међународним часописима и два техничка решења на којима је др Срећковић дао значајан тј. кључан допринос.

3.8. Уводна предавања на конференцијама и друга предавања

У периоду након одлуке Научног већа о предлогу за стицање претходног научног звања др Срећковић је одржао следећа предавања по позиву:

1* *VLF Remote Sensing of the Lower Ionospheric Disturbance Caused by Intense Solar Radiation*, International conference X SCSLSA, 15 - 19 June 2015, Srebrno Jezero, Serbia. link

2* *Non-elastic processes in atom - Rydberg atom collisions: Review of state of art and problems*, International conference X SCSLSA, 15 - 19 June 2015, Srebrno Jezero, Serbia. link

3. *Atom-Rydberg atom processes in the stellar atmospheres: dwarf atmospheres, quiet sun and sunspots*, International conference XSBAC, 30 May - 3 June, 2016, Belgrade, Serbia link

4. *VLF Data Acquisition and database storing,* BigSkyEarth Workshop, with the topic "Research Matchmaking – Building Bridges Between Disciplines ", in Brno, Czech Republic, on April 14-16, 2016.

5. *MolD a Database and a Web Service within the SerVO and the VAMDC*, BigSkyEarth Second workshop, with the topic "Big Data processing and management concepts for new platforms" in Sopron, Hungary, on February 23-24, 2017. link

6. *Atom-Atom and Ion-Atom collisional processes: Modeling of stellar atmospheres,* International conference 11th SCSLSA Šabac, Serbia, August 21-25, 2017. link

7. *Radiative and collisional atomic/molecular data for astrophysics,* Conference XVIII SAC 17-21 October 2017, Belgrade, Serbia. link

8. *Chemi-ionization/recombination Atomic Processes in the AGNs Broad-Line,* XI BSAC International Astronomical Conference 14 - 18 May, 2018, Belogradchik, Bulgaria. link

9. *Influence of strong solar X-ray flares and its negative effects* International conference Natural hazards Lessons from the past and contemporary challenges, 5-7th October 2018, Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Serbia.

10. *Examination of the solar activity, low ionospheric perturbations and natural hazards* International

conference Natural hazards Lessons from the past and contemporary challenges, 5-7th October 2018, Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Serbia.

11. *Atom-Rydberg Atom Processes in the Broad Line Region of AGNs,* 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, Serbia, 28-31 August 2018. link

Сва горенаведена предавања је одржао Др Срећковић. Кандидат је био коаутор и на већем броју предавања по позиву на међународним конференцијама чија се комплетна листа налази у списку радова. Ова предавања су бодована са категоријама М33 и М34.

Све наведене активности су документоване линковима и прилозима.

Пре претходног избора у звање др Срећковић је одржао следећа предавања по позиву:

1. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S. *The Non-Symmetric Ion-Atom Absorption Processes in the Helium Rich White Dwarf Atmospheres in UV and EUV Region* SPIG 2014 International Symposium on the Physics of Ionized Gases; 2014; Belgrade, *Journal of Physics: Conference Series* Volume 565 012022(12) 10.1088/1742-6596/565/1/012022.

2. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *The manifestations of the non-symmetric ion–atom absorption processes in the solar atmospheres in UV and VUV region* (VIII SBAC) Astronomical Conference, Leskovac, Serbia, May 8-12, 2012, (Eds M S Dimitrijević and M K Tsvetkov) PASP, No 12, 2013, 333-337.

3. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *The quasi-molecular absorption bands in UV and EUV region caused by the non-symmetric ion-atom processes in the helium rich white dwarf atmospheres* II Workshop on Astrophysical Spectroscopy 2013; Vrujci, Serbia. Book of abstracts (Edited by Milan S. Dimitrijević and Zoran Simić) p.15.

4. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *Absorption quasi-molecular bands as factors of the solar photosphere opacity above sunspots* IX SCSLSA, Conference on spectral line shapes in astrophysics, May 13-17, 2013, Banja Koviljaca, Serbia, Book of abstracts, (Eds Luka Č Popović, Milan S Dimitrijević, Zoran Simić and Marko Stalevski) 2013. p. 49.

5. Srećković V., Šulić D., Nina A., Mihajlov A., Ignjatović L. *VLF data acquisition and central database storing* Vamdc Regional Workshop on Atomic and Molecular Data; 2012; Belgrade, Serbia. Book of abstracts (Edited by Milan S. Dimitrijević) p.20

6. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *Radiative ion-atom collisions in stellar atmospheres* I Workshop on Astrophysical Spectroscopy; 2011; Orašac, Serbia Program and book of abstracts (Edited by Milan S. Dimitrijević) p.10.

7. Mihajlov A.A., Ignjatović L.M., Srećković V.A., Dimitrijević M.S. *Chemi-ionization/recombination processes as factors of the influence on the spectral line shapes in stellar atmospheres* VIII SCSLSA, Conference on spectral line shapes in astrophysics 6-10 June 2011, Divcibare, Serbia Book of Abstracts, (Eds L ·C Popovic, D Jevremovic and D Ilic) Astronomical Observatory Belgrade, 2011. p. 38.

4. ЕЛЕМЕНТИ ЗА КВАНТИТАТИВНУ ОЦЕНУ НАУЧНОГ ДОПРИНОСА КАНДИДАТА

У својој каријери др Владимир Срећковић је као аутор или коаутор, објавио и презентовао 192 библиографских јединица тј. научних радова, у часописима од међународног значаја, у домаћим часописима, међународним и домаћим конференцијама. Др Срећковић Владимир је до сада је објавио 38 (тридесет осам) научних радова са ISI листе од којих 15 од одлуке Научног већа о предлогу за стицање претходног научног звања као и поглавље у истакнутој монографији међународног значаја. Укупан импакт фактор радова др Срећковића је 102.406, а у периоду након одлуке Научног већа Института за физику о предлогу за стицање претходног научног звања радова укупан импакт фактор је 34.85. Часописи у којима је објавио др Срећковић су 3 категорије M21a, 15 категорије M21, 6 категорије M22 и 14 категорије M23. Према бази Google Scholar радови др Срећковића цитирани су 401 пут са h-фактором 12. Према бази ISI Web of Science, радови др Срећковића укупно су цитирани 236 пута, док је број цитата без аутоцитата 114. Према бази Scopus, укупан број цитата је 281, док је број цитата без аутоцитата 113. Према подацима с обе базе (ISI Web of Science и Scopus) Хиршов индекс је 11.

Остварени резултати након одлуке Научног већа о предлогу за стицање претходног научног звања:

Diferencijalni uslov - od prvog zbora u prethodno zvanje do izbora u zvanje	Potrebno je da kandidat ima najmanje XX poena, koji treba da pripadaju sledećim kategorijama:		
		Neophodno Услов - 150% минималног броја бодова*	Ostvareno
Naučni saradnik	Ukupno	16	
Obavezni (1)	M10+M20+M31+M32+M33+M41+M42	10	
Obavezni (2)	M11+M12+M21+M22+M23	6	
Viši naučni saradnik	Ukupno	50	
Obavezni (1)	M10+M20+M31+M32+M33+M41+M42+M90	40	
Obavezni (2)	M11+M12+M21+M22+ M23	30	
Naučni savetnik	Ukupno	70 (105)*	185.7(175.903)**
Obavezni (1)	M10+M20+M31+M32+M33+M41+M42+M90	50 (75)*	123.0 (115.522)**
Obavezni (2)	M11+M12+M21+M22+M23	35 (52.5)*	76 (70.763)**

* Услов - 150% минималног броја бодова*;   ** нормирани бодови

Категорија	М бодова по раду	Број радова	Укупно М бодова
М14	4	1	4
М18	2	1	2
М21а	10	1	10
М21	8	4	32 (30.667)
М22	5	2	10(9.167)
М23	3	8	24(20.929)
М31	3.5	2	7.0
М32	1.5	8	12.0
М33	1	22	22(19.759)
М34	0.5	33	16.5(15.719)
М51	2.0	21	42.0(39.537)
М62	1.0	1	1.0
М64	0.2	6	1.2(1.125)
М86	1.0	2	4.0
UKUPNO			185.7(175.903)

Остварени резултати од почетка каријере:

Категорија	М бодова по раду	Број радова	Укупно М бодова
М14	4	1	4
М18	2	1	2
М21а	10	3	30
М21	8	15	120
М22	5	6	30
М23	3	14	42
М31	3.5	4	14

M32	1.5	13	19.5
M33	1	33	33
M34	0.5	63	31.5
M51	2.0	31	62
M62	1.0	1	1.0
M64	0.2	5	1.0
M86	1.0	2	2.0
UKUPNO			392.0

СПИСАК РАДОВА ДР СРЕЋКОВИЋ ВЛАДИМИРА

МОНОГРАФИЈЕ, МОНОГРАФСКЕ СТУДИЈЕ, ТЕМАТСКИ ЗБОРНИЦИ, ЛЕСКИКОГРАФСКЕ И КАРТОГРАФСКЕ ПУБЛИКАЦИЈЕ МЕЂУНАРОДНОГ ЗНАЧАЈА (М10)

М14 (Монографска студија/поглавље у књизи М12 или рад у тематском зборнику међународног значаја)

Objavljeni nakon prethodnog izbora u zvanje (1x4.0=4.0):

Поглавље у књизи: D.M. Šulić, V. A. Srećković and Anatolij A. Mihajlov 2016 *Analysis of the Ionospheric D-Region Disturbances in Response to the Effects of Solar X-Ray Flares*, Chapter 3 in Solar Flares: Investigations and Selected Research Eds: Sarah L. Jones, Nova Science Publishers Inc., New York 2016, p.44-81, ISBN: 978-1-53610-204-8
http://www.novapublishers.org/catalog/product_info.php?products_id=59907

Уређивање тематског зборника, лексикографске или картографске публикације међународног значаја (М18=2.0)

Након претходног избора у звање (1x2.0=4.0):

1. Urednik Tematskog zbornika radova: Special Issue in Atoms[2]: *Atomic and Ionic Collisions with Formation of Quasimolecules* Guest Eds.: Dr. Vladimir A. Srećković, Prof. Dr. Milan S. Dimitrijević, Dr. Nikolai N. Bezuglov, Deadline for manuscript submissions: 31 March 2019, mdpi.com/si/18683 (Scopus

[2] У часопису Atoms иначе су публиковани и изабрани радови са једне од наших највећих међународних конференција SPIG2018 https://www.mdpi.com/journal/atoms/special_issues/SPIG2018

and ESCI - Web of Science indexed) otvoren broj
https://www.mdpi.com/journal/atoms/special_issues/Atomic_ionic_collisions_formation_quasimolecules

2. Urednik Tematskog zbornika radova: Special Issue in Data: *Data in Astrophysics & Geophysics: Research and Applications* Guest Eds.: Dr. Vladimir A. Srećković, Dr. Aleksandra Nina, mdpi.com/si/13896 https://www.mdpi.com/journal/data/special_issues/Astro_Geophy broj zatvoren

РАДОВИ ОБЈАВЉЕНИ У НАУЧНИМ ЧАСОПИСИМА МЕЂУНАРОДНОГ ЗНАЧАЈА (М21-М23)

М 21а Радови у међународни часопис изузетних вредности

Радови објављени након претходног избора у звање (1x10.0=10.0):

1.[3] Nina Aleksandra, Simic Sasa Z, Srećković Vladimir A, Popovic Luka C (2015)
Detection of short-term response of the low ionosphere on gamma ray bursts, Geophysical Research Letters, vol. 42, br. 19, str. 8250-8261. 16.10.2015. **(IF 4.456)** doi: http://dx.doi.org/10.1002/2015GL065726

Радови објављени пре претходног избора у звање:

1. O'Keeffe, P., Bolognesi, P., Avaldi, L., Moise, A., Richter, R., Mihajlov, A.A., Srećković, V.A. and Ignjatović, Lj. M. (2012)
Experimental and theoretical study of the chemi-ionization in thermal collisions of Ne Rydberg atoms, Physical Review A Vol 85 Issue: 5 Pages: 052705 ISSN: 1050-2947 DOI: 10.1103/PhysRevA.85.052705 **(M21a) (IF=3.042)**

2. Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A and Dimitrijević, M. S (2011)
Chemi-ionization in Solar Photosphere: Influence on the Hydrogen Atom Excited States Population, The Astrophysical Journal Supplement Series Vol 193 Issue: 1 Pages: 2(7pp) ISSN: 0067-0049 DOI: 10.1088/0067-0049/193/1/2 **(M21a) (IF=15.206)**

М 21 Радови у врхунским међународним часописима

Радови објављени након претходног избора у звање (4x8.0=32.0):

1. Mihajlov Anatolij A, Srećković Vladimir A, Ignjatovic Ljubinko M, Dimitrijevic Milan S (2016)
Atom-Rydberg-atom chemi-ionization processes in solar and DB white-dwarf atmospheres in the presence of (n - n')-mixing channels, Monthly Notices of the Royal Astronomical Society, vol. 458, br. 2, str. 2215-2220 **(IF=5.107)** http://dx.doi.org/10.1093/mnras/stw308

2. Srećković V. A., Sakan N., Šulić D., Jevremović D., Ignjatović Lj. M. and Dimitrijević M. S. (2018)
Free–free absorption coefficients and Gaunt factors for dense hydrogen-like stellar plasma

[3] Рад објављен након одлуке научног већа за избор у претходно звање

Monthly Notices of the Royal Astronomical Society, 475 (1), 1131-1136 **(IF=5.194)**
http://dx.doi.org/10.1093/mnras/stx3237

3. Srećković V.A., Dimitrijević M.S., Ignjatović L.M. (2018)
Atom-Rydberg atom chemi-ionization/recombination processes in the hydrogen clouds in Broad Line Region of AGNs Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 4, 11 November 2018, Pages 5078–5083 **(IF=5.194)** https://doi.org/10.1093/mnras/sty2256

4. Ignjatović L.M., Srećković V.A., Dimitrijević M.S., (2019)
The collisional atomic processes of Rydberg alkali atoms in Geo-cosmical plasmas Monthly Notices of the Royal Astronomical Society, Volume 482, 8p. **(IF=5.194)** https://doi.org/10.1093/mnras/sty3294

Радови објављени пре претходног избора у звање:

1. Ignjatović, Lj.M. , Srećković, V.A., Mihajlov, A.A. and Dimitrijević, M.S. (2014)
Absorption non-symmetric ion–atom processes in helium-rich white dwarf atmospheres,
Monthly Notices of the Royal Astronomical Society Vol: 439 Issue: 3 Pages: 2342-2350 ISSN: 0035-8711 DOI: 10.1093/mnras/stu058 **(M21) (ImpaktFaktor=5.521)**

2. Ignjatović, Lj.M., Mihajlov, A.A., Srećković, V.A. and Dimitrijević, M.S. (2014)
The ion–atom absorption processes as one of the factors of the influence on the sunspot opacity,
Monthly Notices of the Royal Astronomical Society Vol 441 Issue: 2 Pages: 1504-1512 ISSN: 0035-8711 DOI: 10.1093/mnras/stu638 **(M21) (IF=5.521)**

3. Srećković, V.A., Mihajlov, A.A., Ignjatović, Lj. M. and Dimitrijević, M.S. (2013)
Excitation and deexcitation processes in atom-Rydberg atom collisions in helium-rich white dwarf atmospheres, Astronomy & Astrophysics Vol 552 Pages**:** A33, 3 pp. ISSN: 0004-6361 DOI: 10.1051/0004-6361/201220699 **(M21) (IF=4.422)**

4. Mihajlov, A.A., Ignjatović, Lj. M., Srećković, V.A., Dimitrijević, M.S. and Metropoulos, A. (2013)
The non-symmetric ion–atom radiative processes in the stellar atmospheres, Monthly Notices of the Royal Astronomical Society Vol 431 Issue: 1 Pages: 589-599 ISSN: 0035-8711 DOI: 10.1093/mnras/stt187 **(M21) (IF=5.521)**

5. Nina, A., Čadež, V., Šulić, D., Srećković, V.A. and Žigman, V. (2012)
Effective electron recombination coefficient in ionospheric D-region during the relaxation regime after solar flare from February 18, 2011, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Vol 279 Pages: 106-109 ISSN: 0168-583X DOI: 10.1016/j.nimb.2011.10.026 **(M21) (IF=1.266)**

6. Nina, A., Čadež, V., Srećković, V.A. and Šulić, D. (2012)
Altitude distribution of electron concentration in ionospheric D-region in presence of time-varying solar radiation flux, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Vol 279 Pages: 110-113 ISSN: 0168-583X DOI: 10.1016/j.nimb.2011.10.019 **(M21) (IF=1.266)**

7. Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Vitel, Y. (2011)
Modeling of continuous absorption of electromagnetic radiation in dense partially ionized plasmas, Journal of Physics A: Mathematical and Theoretical Vol: 44 Issue: 9 Pages: 095502 ISSN: 1751-8121 DOI: 10.1088/1751-8113/44/9/095502 **(M21) (IF=1.641)**

8. Srećković, V. A., Ignjatović, Lj .M., Mihajlov, A. A. and Dimitrijević, M. S. (2010) *Electrical conductivity of plasmas of DB white dwarf atmospheres,* Monthly Notices of the Royal Astronomical Society Vol 406 Issue: 1 Pages: 590-596 ISSN: 1365-2966 DOI: 10.1111/j.1365-2966.2010.16702.x **(M21) (IF=5.185)**

9. Srećković, V.A., Adamyan, V.M., Ignjatović, Lj. M. and Mihajlov, A.A. (2010) *The self-consistent determination of HF electroconductivity of strongly coupled plasmas,* Physics Letters A Vol 374 Issue: 5 Pages: 754-760 ISSN: 0375-9601 DOI: 10.1016/j.physleta.2009.11.073 **(M21) (IF: 2.174)**

10. Tkachenko, I.M., Adamyan, V.M., Mihajlov, A.A., Sakan, N.M., Šulić, D. and Srećković, V.A. (2006) *Electrical conductivity of dense non-ideal plasmas in external HF electric field* Journal of Physics A: Mathematical and General Vol 39 Issue: 17 Pages: 4693-4698 ISSN: 0305-4470 DOI: 10.1088/0305-4470/39/17/S58 **(M21) (IF: 1.577)**

11. Adamyan, V.M., Grubor, D., Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Tkachenko, I.M. (2006) *Optical HF electrical permeability, refractivity and reflectivity of dense non-ideal plasmas,* Journal of Physics A: Mathematical and General Vol 39 Issue: 17 Pages: 4401-4405 ISSN: 0305-4470 DOI: 10.1088/0305-4470/39/17/014 **(M21) (IF: 1.577)**

M 22 Радови у истакнутим међународним часописима

Радови објављени након претходног избора у звање (2x5.0=10.0):

1. Šulic Desanka M, Srećković Vladimir A,Mihajlov Anatolij A (2016) *A study of VLF signals variations associated with the changes of ionization level in the D-region in consequence of solar conditions*, Advances in Space Research, vol. 57, br. 4, str. 1029-1043 (IF=1.409) doi: http://dx.doi.org/10.1016/j.asr.2015.12.025

2. Ilić, L., Kuzmanoski, M., Kolarž, P., Nina, A., Srećković, V., Mijić, Z., Bajčetić, J., & Andrić, M. (2018). *Changes of atmospheric properties over Belgrade, observed using remote sensing and in situ methods during the partial solar eclipse of 20 March 2015*, Journal of Atmospheric and Solar-Terrestrial Physics, 171 250–259, (IF=1.492) https://doi.org/10.1016/j.jastp.2017.10.001 .

Радови објављени пре претходног избора у звање:

1. Bezuglov, N. N., Klyucharev, A. N., Mihajlov, A. A. and Srećković, V. A. (2014) *Anomalies in radiation-collisional kinetics of Rydberg atoms induced by the effects of dynamical chaos and the double Stark resonance,* Advances in Space Research Vol 54 Issue: 7 Pages: 1159-1163 ISSN: 0273-1177 DOI: 10.1016/j.asr.2013.08.028 **(M22)(ImpaktFaktor: 1.238)**

2. Srećković, V. A., Mihajlov, A. A., Ignjatović, Lj M. and Dimitrijević, M. S. (2014) *Ion-atom radiative processes in the solar atmosphere: quiet Sun and sunspots,* Advances in Space Research Vol 54 Issue: 7 Pages: 1264-1271 ISSN: 0273-1177 DOI: 10.1016/j.asr.2013.11.017 **(M22) (IF: 1.238)**

3. Adamyan, V.M., Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Tkachenko, I.M. (2009)
The dynamic conductivity of strongly non-ideal plasmas: is the Drude model valid?
Journal of Physics A: Mathematical and Theoretical Vol 42 Issue: 21 Pages: 214005 ISSN: 1751-8121 DOI: 10.1088/1751-8113/42/21/214005 **(M22) (IF: 1.680)**

4. Mihajlov, A.A., Ignjatović, Lj. M., Srećković, V.A. and Djurić, Z. (2008)
The influence of (n-n')-mixing processes in He(n)+ He (1s2) collisions on He*(n) atoms' populations in weakly ionized helium plasmas*, Journal of Quantitative Spectroscopy and Radiative Transfer Vol 109 Issue: 5 Pages: 853-862 ISSN: 0022-4073 DOI: 10.1016/j.jqsrt.2007.09.005 **(M22) (IF: 1.972)**

М 23 Радови у међународним часописима

Радови објављени након претходног избора у звање (8x3.0=24.0):

1. Arefieff K.N., Miculis K., Bezuglov N.N., Dimitrijevic Milan S, Klyucharev A.N., Mihajlov Anatolij A., Srećković Vladimir A. (2015)
Dynamics Resonances in Atomic States of Astrophysical Relevance, Journal of Astrophysics and Astronomy, December 2015, vol. 36, no. 4, p. 613-622 (IF=0.711) http://dx.doi.org/10.1007/s12036-015-9358-5

2. Mihajlov Anatolij A, Srećković Vladimir A,Sakan Nenad M (2015)
Inverse Bremsstrahlung in Astrophysical Plasmas: The Absorption Coefficients and Gaunt Factors, J. Astrophys. Astron., December 2015, 36, 4, p. 635-642 (IF=0.711) http://dx.doi.org/10.1007/s12036-015-9350-0

3. Vujcic Veljko, Jevremovic Darko M, Mihajlov Anatolij A, Ignjatovic Ljubinko M, Srećković Vladimir A, Dimitrijevic Milan S, Malovic Miodrag (2015)
MOL-D: A Collisional Database and Web Service within the Virtual Atomic and Molecular Data Center, Journal of Astrophysics and Astronomy, December 2015, vol. 36, no. 4, p. 693-703 (IF=0.711) http://dx.doi.org/10.1007/s12036-015-9344-y

4. Mihajlov Anatolij A, Srećković Vladimir A, Ignjatovic Ljubinko M, Klyucharev AN, Dimitrijevic Milan S, Sakan Nenad M (2015)
Non-Elastic Processes in Atom Rydberg-Atom Collisions: Review of State of Art and Problems, J. Astrophys. Astron., December 2015, vol. 36, 4, p. 623-634 (IF=0.711) http://dx.doi.org/10.1007/s12036-015-9364-7

5. Bratislav P. Marinković, Darko Jevremović, Vladimir A. Srećković, Veljko Vujčić, Ljubinko M. Ignjatović, Milan S. Dimitrijević and Nigel J. Mason (2017),
BEAMDB and MolD – databases for atomic and molecular collisional and radiative processes: Belgrade nodes of VAMDC, The European Physical Journal D vol.71, issue 6, 158(9) (IF=1.393) DOI: http://doi.org/10.1140/epjd/e2017-70814-6

6. Nina A., Čadež V., Popovic L. Č., Srećković Vladimir A (2017)
Diagnostics of plasma in the ionospheric D-region: detection and study of different ionospheric disturbance types, EPJD vol.71, issue 7, 189(12), (IF=1.393) DOI: http://doi.org/10.1140/epjd/e2017-70747-0

7. Srećković, V. A., Šulic D., A. A., Ignjatović, Lj M. and Dimitrijević, M. S. (2017)

A study of high-frequency properties of plasma and the influence of electromagnetic radiation from IR to XUV, Nuclear Technology & Radiation Protection, Vol. 32, No. 3 September 2017, 222-228, (IF=0.620) doi: http://doi.org/10.2298/NTRP1703222S

8. M. S. Dimitrijević, V. A. Srećković, N. M. Sakan, N. N. Bezuglov, A. N. Klyucharev (2018) *Free-Free Absorption in Solar Atmosphere,* Geomagnetism and Aeronomy, 2018, Vol. 58, No. 8, pp. 1067–1072, (IF=0.555) DOI: 10.1134/S0016793218080054

Радови објављени пре претходног избора у звање:

1. Šulić, D. M. and Srećković, V. A. (2014)
A comparative study of measured amplitude and phase perturbations of VLF and LF radio signals induced by solar flares, Serbian Astronomical Journal Vol 188 Pages: 45-54 ISSN: 1450-698X DOI: 10.2298/saj1488045s **(M23) (IF: 1.100)**

2. Mihajlov, A.A., Srećković, V.A., Ignjatović, Lj. M. and Klyucharev, A.N. (2012)
The Chemi-Ionization Processes in Slow Collisions of Rydberg Atoms with Ground State Atoms: Mechanism and Applications, Journal of Cluster Science Vol 23 Issue: 1 Pages: 47-75 ISSN: 1040-7278 DOI: 10.1007/s10876-011-0438-7 **(M23) (IF: 1.111)**

3. Nina, A., Čadež, V., Srećković, V.A. and Šulić, D. (2011)
The influence of solar spectral lines on electron concentration in terrestrial ionosphere
Baltic Astronomy Vol 20 Pages: 609-612 ISSN: 1392-0049 **(M23) (IF: 1.032)**

4. Mihajlov, A.A., Sakan, N.M., Srećković, V.A. and Vitel, Y. (2011)
Modeling of the Continuous Absorption of Electromagnetic Radiation in Dense Hydrogen Plasma
Baltic Astronomy, Vol 20 Pages: 604-608 ISSN: 1392-0049 **(M23) (IF: 1.032)**

5. Mihajlov, A.A, Ignjatović, Lj. M, Srećković, V. A. and Dimitrijević, M. S (2011)
The Influence of Chemi-Ionization and Recombination Processes on Spectral Line Shapes in Stellar Atmospheres, Baltic Astronomy Vol 20 Pages: 566-571 ISSN: 1392-0049 **(M23) (IF: 1.032)**

6. Gnedin, Yu. N., Mihajlov, A.A., Ignjatović, Lj. M., Sakan, N.M., Srećković, V.A., Zakharov, M. Yu., Bezuglov, N.N. and Klycharev, A.N. (2009)
Rydberg atoms in astrophysics, New Astronomy Reviews Vol 53 Issue: 7 Pages: 259-265 ISSN: 1387-6473 DOI: 10.1016/j.newar.2009.07.003 **(M23)(IF: 1.299)**

M31 Предавање по позиву са међународног скупа штампано у целини (M31-3.5 poena)

Након претходног избора у звање (2x3.5=7.0):

1. V. A. Srećković, A. A. Mihajlov, Lj. M. Ignjatović and Milan S. Dimitrijević: *Atom-Rydberg atom processes in the stellar atmospheres: dwarf atmospheres, quiet sun and sunspots*, XSBAC Astronomical Conference, 30 May - 3 June, 2016, Belgrade, Serbia, Eds. M. S. Dimitrijević and M. K. Tsvetkov, Astronomical and Astrophysical Transactions, 2018, Vol. 30, Issue 3, pp. 281/290, ISSN 1055-6796

2. V. Srećković, M. Dimitrijević, Lj. Ignjatović – *Chemi-ionization/recombination Atomic Processes in*

the AGNs Broad-Line Region 2018 XI BSAC Astronomical Conference 14 - 18 May, 2018, Belogradchik, Bulgaria http://www.astro.bas.bg/XIBSAC/program.php Proceedings of the XI BSAC Belogradchik, Bulgaria, May 14-18, 2018 Edrs: Milcho K. Tsvetkov, Milan S. Dimitrijević and Momchil Dechev, PASRB No 18, 2018, 135-138 ISBN 978-86-89035-11-7

Пре претходног избора у звање:

1. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S. *The Non-Symmetric Ion-Atom Absorption Processes in the Helium Rich White Dwarf Atmospheres in UV and EUV Region* (PR) SPIG 2014 International Symposium on the Physics of Ionized Gases; 2014; Belgrade, *Journal of Physics: Conference Series* Volume 565 012022(12) 10.1088/1742-6596/565/1/012022.

2. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *The manifestations of the non-symmetric ion–atom absorption processes in the solar atmospheres in UV and VUV region* (PR) (VIII SBAC) Astronomical Conference, Leskovac, Serbia, May 8-12, 2012, (Eds M S Dimitrijević and M K Tsvetkov) PASP, No 12, 2013, 333-337.

M32 Предавање по позиву са међународног скупа штампано у изводу (M32-1.5 poena)

након претходног избора у звање (8x1.5=12.0):

1.* Vladimir A. Srećković, A. A. Mihajlov, D. M. Sulic, A.Nina and Lj. M. Ignjatović, *VLF Remote Sensing of the Lower Ionospheric Disturbance Caused by Intense Solar Radiation,* The book of abstracts 10th SCSLSA June, 15-19 2015, Srebrno jezero Eds. L.C.Popović, M.S.Dimitrijević, Sasa Simić, pp.66, ISBN 978-86-80019-70-3 http://www.scslsa.matf.bg.ac.rs/program10.html

2.* A. A. Mihajlov, Vladimir A. Srećković, M. S. Dimitrijević and A. N. Kljucharev, *Non-elastic processes in atom - Rydberg atom collisions: Review of state of art and problems*, The book of abstracts 10th SCSLSA June 15-19 2015, Srebrno jezero Eds. L.C.Popović, M.S. Dimitrijević, Sasa Simić, pp.50, ISBN 978-86-80019-70-3 http://www.scslsa.matf.bg.ac.rs/program10.html

3. Vladimir Srećković *VLF Data Acquisition and database storing*, BigSkyEarth Workshop, with the topic "Research Matchmaking – Building Bridges Between Disciplines ", in Brno, Czech Republic, on April 14-16, 2016. https://bigskyearth.eu/wp-content/uploads/2016/04/BRNO_Book_of_Abstracts.pdf

4. Vladimir A. Srećković **"***MolD a Database and a Web Service within the SerVO and the VAMDC*" BigSkyEarth Second workshop, with the topic "Big Data processing and management concepts for new platforms", in Sopron, Hungary, on February 23-24, 2017. http://bigskyearth.eu/bigskyearth-workshop-in-sopron/

5. Vladimir Srećković, Lj. M. Ignjatovic, M. S. Dimitrijevic *Atom-Atom and Ion-Atom collisional processes: Modeling of stellar atmospheres*, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts (Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić), ISBN 978-86-80019-82-6, p.21 http://servo.aob.rs/scslsa11/program11.html

6. Vladimir A. Srećković, Milan S. Dimitrijević and Ljubinko M. Ignjatović
Atom-Rydberg Atom Processes in the Broad Line Region of AGNs, 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, 28-31 August 2018, Eds. G. Poparić, B. Obradović, D. Borka and M. Rajković, ISBN 978-86-7306-146-7, p. 278, http://spig2018.ipb.ac.rs/SPIG2018-book-online.pdf

7. Srećković V. A., Šulić D. M. *Influence of strong solar X-ray flares and its negative effects* The book of abstracts of International conference Natural hazards Lessons from the past and contemporary challenges, 5-7th October 2018, Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Serbia, Eds. S.B. Marković, M. Hrvojević and L. Lazić, ISBN:978-86-7031-498-6, p.17

8. Srećković V. A., Jevremović D., Vujčić V.
Examination of the solar activity, low ionospheric perturbations and natural hazards, The book of abstracts of International conference Natural hazards Lessons from the past and contemporary challenges, 5-7th October 2018, Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Serbia, Eds. S.B. Marković, M. Hrvojević and L. Lazić, ISBN:978-86-7031-498-6, p.26-27

пре претходног избора у звање:

1. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *The quasi-molecular absorption bands in UV and EUV region caused by the non-symmetric ion-atom processes in the helium rich white dwarf atmospheres* (IL) II Workshop on Astrophysical Spectroscopy 2013; Vrujci, Serbia. Book of abstracts (Edited by Milan S. Dimitrijević and Zoran Simić) p.15.

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3. Srećković V., Šulić D., Nina A., Mihajlov A., Ignjatović L. *VLF data acquisition and central database storing* (PR) Vamdc Regional Workshop on Atomic and Molecular Data; 2012; Belgrade, Serbia. Book of abstracts (Edited by Milan S. Dimitrijević) p.20.

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Саопштења са међународних скупова штампана у целини (М33-1 poen)

Радови објављени након претходног избора у звање (22x1.0 =22.0; норм=19.134):

1* A. Nina, V. M. Čadež, L. Č. Popović, D. Jevremović, M. Radovanović, A. Kolarski, V. A. Srećković,

J. Bajčetić, B. Milovanović, A. Kovačević, “Low ionospheric perturbations and natural hazards” Proceedings of The International Conference "Natural disasters - links between science and practice", 23-24. April 2015, Saransk, Russia, ISBN 978-5-7103-3078-4, УДК 502.1:001.4 ББК Б1 pp: 2013-2018 **норм. 0.625**

2. Vinković, D.; Gritsevich, M.; Srećković, V.; Pečnik, B.; Szabó, G.; Debattista, V.; Škoda, P.; Mahabal, A.; Peltoniemi, J.; Mönkölä, S.; Mickaelian, A.; Turunen, E.; Kákona, J.; Koskinen, J.; Grokhovsky, V. *Big data era in meteor science*, Proceedings of the International Meteor Conference, Egmond, the Netherlands, 2-5 June 2016, Eds.: Roggemans, A.; Roggemans, P., ISBN 978-2-87355-030-1, pp. 319-329 **норм 0.385**

3. D. Jevremović, V. Vujčič, A. A. Mihajlov, V. A. Srećković, Lj. M. Ignjatović, M. S. Dimitrijević, S. Erkapić and N. Milovanović *MOL-D: Database for Specific Collisional Processes and Web Service Within the Serbian Virtual Observatory and the Virtual Atomic and Molecular Data Center Consortium*, 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić) p. 397-401 ISBN 978-86-84539-14-6 http://spig2016.ipb.ac.rs/spig2016-book-online.pdf **норм. 0.833**

4. A. A. Mihajlov, V. A. Srećković, Lj. M. Ignjatović, Z. Simić and M. S. Dimitrijević *Atom Rydberg-Atom Processes in the Stellar Atmospheres*, 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić) p. 413-416 ISBN 978-86-84539-14-6 http://spig2016.ipb.ac.rs/spig2016-book-online.pdf

5. A. Nina, S. Simić, V. A. Srećković, A. Djulaković and L. Č. Popović *Short-Term Disturbances of the Low Ionosphere Induced by γ-Ray Bursts*, 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić) p. 421-424 ISBN 978-86-84539-14-6 http://spig2016.ipb.ac.rs/spig2016-book-online.pdf

6. N. M. Sakan, V. A. Srećković, Lj. M. Ignjatović and A. A. Mihajlov *Bond - Bound State Transitions in the Frame of Coulomb Cut-Off Model Potential*, 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić) p. 425-428 ISBN 978-86-84539-14-6 http://spig2016.ipb.ac.rs/spig2016-book-online.pdf

7. Zoran Simić, Milan S. Dimitrijević and Vladimir Srećković *Stark Broadening of Bismuth IV Spectral Lines in A Type Stellar Atmospheres*, 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić), p. 433-436 ISBN 978-86-84539-14-6 http://spig2016.ipb.ac.rs/spig2016-book-online.pdf

8. A A Mihajlov, V A Srećković, N M Sakan, Lj M Ignjatovic, Z Simic and M S Dimitrijevic *The inverse bremsstrahlung absorption coefficients and Gaunt factors in astrophysical plasmas* 23rd ICSLS, Torun, 2017 Journal of Physics: Conference Series, Volume 810, Number 1 012058(4pp), doi:10.1088/1742-6596/810/1/012059 **норм. 0.833**

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Conference Series (Vol. 810, No. 1, p. 012058). IOP Publishing. doi:10.1088/1742-6596/810/1/012058

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12. Vladimir A. Srećković *The effects of solar activity on the terrestrial lower ionosphere*, Proceedings of the Astronomical Conference (XI BSAC) Belogradchik, Bulgaria, May 14-18, 2018 Eds: Milcho K. Tsvetkov, Milan S. Dimitrijević and Momchil Dechev PASRB No 18, 2018, p. 239-243, ISBN 978-86-89035-11-7

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14. Bratislav P. Marinković, Vladimir A. Srećković, Darko Jevremović,Veljko Vujčić, Ljubinko M. Ignjatović, Milan S. Dimitrijević, Stefan Ivanović, Nebojša Uskoković, Milutin Nešić and Nigel J. Mason *BEAMDB and MolD – Collisional and Radiative Databases at the Serbian Virtual Observatory*, 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, 28-31 August 2018, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds G. Poparić, B. Obradović, D. Borka and M. Rajković) p. 23-26, ISBN 978-86-7306-146-7, http://spig2018.ipb.ac.rs/SPIG2018-book-online.pdf **норм. 0.625**

15. Nenad M. Sakan, Vladimir A. Srećković, Zoran J. Simić and Milan S. Dimitrijević *Photoabsorption Cross Section of a Dense Hydrogen Plasma, Model Method*, 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, August 2018, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds G. Poparić, B. Obradović, D. Borka and M. Rajković), p. 297-300, ISBN 978-86-7306-146-7, http://spig2018.ipb.ac.rs/SPIG2018-book-online.pdf

16. V. A. Srećković, Lj. M. Ignjatović, M. S. Dimitrijević, N. N. Bezuglov and A. N. Klyucharev *Rate Coefficients for the Chemi-Ionization in Alkali Geocosmical Plasmas*, 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, August 2018, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds G. Poparić, B. Obradović, D. Borka and M. Rajković) p. 305-308, ISBN 978-86-7306-146-7, http://spig2018.ipb.ac.rs/SPIG2018-book-online.pdf

17. V. A. Srećković and D. M. Šulić *Strong Solar X-ray Radiation: Influence on the Plasma in the Ionospheric D- Region*, 29 Summer School and International Symposium on the Physics of Ionized Gases: SPIG, Belgrade, August 2018, Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds G. Poparić, B. Obradović, D. Borka and M. Rajković) p. 309-312, ISBN 978-86-7306-146-7, http://spig2018.ipb.ac.rs/SPIG2018-book-online.pdf

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The work on inclusion of the bound-bound optical transition process within the frame of the cut-off coulomb potential model – main numerical error sources, August 2018, Conference XII PDP: Belgrade, Serbia 27-31 August 2018, p.75-78, ISBN: 978-86-84539-21-4

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21. Vladimir A. Srećković, Milan S. Dimitrijević, Ljubinko M. Ignjatović, Nikolai N. Bezuglov and Andrei N. Klycharev *The rate coefficients of the slow atom-Rydberg atom collisions: alkali case* Volume: 2, p.523-526 (2018) Proceedings of the XXII international conference on Gas discharges and their applications, 2nd -7th September 2018, Novi Sad, Serbia http://gd2018.ipb.ac.rs/index.php/proceedings/ ISBN 978-86-7025-782-5

22. Dimitrijević, M.S.; Srećković, V.A.; Ignjatović, L.M. (2018) *Chemi-ionization processes in Narrow-Line Seyfert 1 Galaxies. In Proceedings of the Revisiting Narrow-Line Seyfert 1 Galaxies and Their Place in the Universe*. PoS, 049 (1–4) https://pos.sissa.it/328/049/pdf

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2. Nina A., Čadež V.M., Popović L.Č., Srećković V.A., Simić S. *Application of terrestrial low ionospheric plasma diagnostic for detection astrophysical phenomena* (PR) X PDP Symposium on Physics and Diagnostics of Laboratory and Astrophysical Plasmas; 2014; Belgrade. Proceedings (Eds. M.M.Kuraica, B.M.Obradovic and N.Cvetanovic) p. 66-69.

3. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. *The non-symmetric ion-atom absorption processes in the stelar atmospheres*. 26th SPIG August 27th -31st, 2012, Zrenjanin Serbia 2012. Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports, (Eds: M. Kuraica and Z. Mijatović), Contributed Paper, pp. 383-387.

4. Novović I., Marković D.M., Vilotić D., Ignjatović L., Srećković V. *Determination of Fe, Mn and Pb in tree-rings and bark of linden (tilia platyphyllos scop.) from locations Zemun and Obrenovac*. 9th International Conference on Fundamental and Applied Aspects of Physical Chemistry, Belgrade,Serbia, 2008, p. 428-432; ISBN 978-86-82475-16-3.

5. Marković D.M., Novović I., Vilotić D., Ignjatović L., Srećković V. *Determination of Pb and Mn in tree-rings and bark of linden (tilia platyphyllos scop.) by U-shaped dc-arc* . 9th International Conference on Fundamental and Applied Aspects of Physical Chemistry; 2008; Belgrade, Serbia p. 458-462, ISBN 978-86-82475-16-3.

6. Tkachenko I.M., Adamyan V.M., Sakan N.M., Mihajlov A.A., Srećković V., *The HF characteristics of strongly non ideal plasma in an external HF electric field*. PDP Symposium on Physics and Diagnostic of Laboratory and Astrophysical Plasma; 2008; Minsk, Belorusia

7. Sakan N.M., Srećković V.A., Adamyan V.M., Tkachenko I.M., Mihajlov A.A. *The Methods for Determination of HF Characteristics of Non-ideal Plasma*. PDP Symp. on Phys. and Diagn. of Lab. & Astrophys. Plasma, Belgrade, Serbia, 22 - 25 August 2006 (Eds. M Ćuk, MS Dimitrijević, J Purić, N Milovanović) Publ Astron Obs Belgrade No 82 (2007), p. 171-181 2007.

8. Mihajlov A.A., Sakan N.M., Srećković V.A., *The modeling of the continuous emission spectrum of a dense non-ideal plasma in optical region*. AIP Conference Proceedings(VI SCSLSA, Conference on Spectral Line Shapes in Astrophysics) 2007, vol 938 p. 262-267

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11. Sakan N.M., Srećković V.A., Mihajlov A.A. *The application of the cut-off coulomb potential for the calculation of a continuous spectra of dense hydrogen plasma* (PR) SCSLSA 2005, V Conference on Spectral Line Shapes; 2005; Vrsac, Serbia: MmSAI (Memorie della Societa Astronomica Italiana Supplement), v.7, p.221 (2005).

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Саопштења са међународних скупова штампана у изводу (М34-0.5)

Радови објављени након претходног избора у звање (33x0.5=16.5; норм=15.719):

1.* A. A. Mihajlov, N. M. Sakan and V. A. Srećković, *The Inverse bremsstrahlung in astrophysical plasmas: the absorption coefficients and Gaunt factors,* The book of abstracts 10th SCSLSA, June 15-19, Srebrno jezero, 2015, Eds. L.C. Popović, M.S. Dimitrijević,Sasa Simić, p.49, ISBN 978-86-80019-70-3

2.* D. Jevremović, A. A. Mihajlov, V. A. Srećković, L. M. Ignjatović, M. S. Dimitrijević, and V. Vujcic, *MOL-D a Collisional Database Repository and Web Service Within the Virtual Atomic and Molecular Data Centre*, The book of abstracts 10th SCSLSA June 15-19, 2015 Srebrno jezero, Eds. L.C. Popović, M.S. Dimitrijević, Sasa Simić, p.39, ISBN 978-86-80019-70-3

3. * A. A. Mihajlov, L. M. Ignjatović, V. A. Srećković, M. S. Dimitrievié, D. Jevremović, *Ion-Atom and Atom-Atom Collisional Processes and Modeling of Stellar Atmospheres* The conference "Astronomy from Our Cosmic Neighborhood to Deepest Cosmology", and XIIth General Meeting of the Eurasian Astronomical Society (EAAS), May 25–30, 2015, Moscow, at P.K. Sternberg Astronomical Institute of M.V. Lomonosov Moscow State University. The book of abstracts Editors - prof. N.N. Samus, V.L. Shtaerman, p.66

4.* D. Jevremović, A. A. Mihajlov, V. A. Srećković, L. M. Ignjatović, M. S. Dimitrijević, and V. Vujcic, *MOL-D A database for photo-dissociation cross-sections for individual ro-vibrational states of diatomic molecular ions*, The book of abstracts of The Twenty-fourth Colloquium on High Resolution Molecular Spectroscopy, August 24 – 28, 2015 Universit´e Bourgogne Franche-Comte Dijon – FRANCE, Eds Vincent BOUDON, p.277

5.* A. A. Mihajlov, V. A. Srećković and M. S. Dimitrijević, *Chemi-ionization processes caused by the creation of quasi molecular complexes in atom - Rydberg atom collisions* The book of abstracts of The Twenty-fourth Colloquium on High Resolution Molecular Spectroscopy, August 24 – 28, 2015 Universit´e Bourgogne Franche-Comte Dijon – FRANCE , Eds Vincent BOUDON p.278

6. A. Nina, V. M. Čadež, L. Č. Popović and V. A. Srećković, *Diagnostics of Plasma in Ionospheric D-Region by VLF Radio Waves*. 28th SPIG 2016 International Symposium on the Physics of Ionized Gases 2016, Belgrade Book of Contributed Papers & Abstracts of Invited Lectures and Progress Reports (Eds. Dragana Marić, Aleksandar R. Milosavljević, Bratislav Obradović and Goran Poparić) p. 378. http://spig2016.ipb.ac.rs/invited.html ISBN 978-86-84539-14-6

7. K. N. Arefieff, N. N. Bezuglov, M. S. Dimitrijević, A. N. Klyucharev, A. A. Mihajlov and V. A. Srećković: *On the anomalous low spontaneous emission rates for p-series of sodium due to the effect of natural Förster resonance*, p 56, XSBAC, 30 May - 3 June, 2016, Belgrade, Serbia, The book of abstracts of XSBAC Eds. Milan S. Dimitrijević and Milcho K. Tsvetkov, ISBN 978-86-80019-73-4 **норм. 0.417**

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21. Lj. M. Ignjatovic and V. A. Srećković *The screening characteristics of the astrophysical plasmas: three-component systems*, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić, p. 71, ISBN 978-86-80019-82-6

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model potential for the calculation of bound - bound state transitions, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić, ISBN 978-86-80019-82-6, p. 79

23. V.A. Srećković, M.S. Dimitrijevic, Z. Simic and N.M. Sakan *The cross sections and the rate coefficients of the free-free absorption processes in stellar atmospheres*, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić, p. 80, ISBN 978-86-80019-82-6

24.V.A. Srećković and D.M. Sulic *Solar X ray flares and their impact on the ionosphere*, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić, p.82, ISBN 978-86-80019-82-6

25. V.A. Srećković, Lj.M. Ignjatovic, D. Jevremovic, V. Vujcic and M.S. Dimitrijevic *Radiative and collisional molecular data and virtual laboratory astrophysics: state of advancement and perspectives*, 11th SCSLSA Šabac, Serbia, August 21-25, 2017, The book of abstracts Eds. Luka Č. Popović, Andjelka Kovačević and Saša Simić, p. 81, ISBN 978-86-80019-82-6

26. N. M. Sakan, V. A. Srećković, Z. Simić, M. S. Dimitrijević, *Free-free absorption coefficients in white dwarf atmosphere*, International Conference Strongly Coupled Coulomb Systems 30 July – 4 August 2017, Kiel, Germany, The book of abstracts p.133

27. V. A. Srećković, N. M. Sakan, Z. Simić, Lj. M. Ignjatović, M. S. Dimitrijević, *HF electric properties of the astrophysical plasmas under extreme conditions*, International Conference Strongly Coupled Coulomb Systems 30 July – 4 August 2017, Kiel, Germany, The book of abstracts p.134

28. Milan S. Dimitrijević, Vladimir A. Srećković, and Ljubinko M. Ignjatović : *Chemi-ionization/ recombination processes in the AGNs Broad-Line Region* 2018 SerbChin 2018. Astronomical Scientific Meeting: Physics and Nature of Active Galactic Nuclei April 16 - 19, 2018 Belgrade, Faculty of Mechanical Engineering, Book of abstracts Eds. Maša Lakićević, Edi Bon and Luka Č. Popović, p.6 http://servo.aob.rs/serbchin/ ISBN 978-86-80019-88-8

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30. M. S. Dimitrijević, V. A. Srećković, Lj. M. Ignjatović *Rate coefficients for symmetric and non-symmetric ion-atom and atom-atom processes in stellar atmospheres*, EWAS European Week of Astronomy and Space Science 3-6 April 2018- Liverpool, UK SS4.05

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http://www.sctm.mk/conferences/25Congress-Book%20of%20abstracts-draft.pdf

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норм. 0.25

Радови објављени пре претходног избора у звање:

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2. Nina A, Čadež V.M., Popović L.Č., Srećković V.A., Simić S. *Differences in detection of D-region perturbations induced by UV, X and γ radiation from outer space using VLF signals* (IL) (IX BSACA) Astronomical Conference: Astroinformatics 2014; 1-4 July, 2014, SOFIA, Bulgaria, Book of abs. p.

3. Nina A., Cadez V.M., Popovic L.C., Srećković V.A., Simic S. *Detection of terrestrial ionospheric perturbations caused by different astrophysical phenomena*. (PR) XVII NKAS; Belgrade, Serbia 2014. Book of abstracts, (eds. S. ·Segan, S. Ninkovic, A. Kovacevic and B. Novakovic) p. 94. ISBN:978-86-7589-089-0

4. Mihajlov A.A., Ignjatović L.M. , Srećković V.A., Dimitrijević M.S., *Sunspots opacity: the ion-atom absorption processes*, XVII NKAS; Belgrade, Serbia 2014. Book of abstracts, (eds. S. ·Segan, S. Ninkovic, A. Kovacevic and B. Novakovic) p. 81. ISBN:978-86-7589-089-0

5. Srećković V.A. and Šulić D.M., *Untypical perturbations on VLF radio signals during solar flares*, XVII NKAS; Belgrade, Serbia 2014. Book of abstracts, (eds. S. ·Segan, S. Ninkovic, A. Kovacevic and B. Novakovic) p. 87. ISBN:978-86-7589-089-0

6. Srećković V.A., Nina A., Šulić D, Mihajlov A.A. *Perturbations of the lower ionosphere due to the γ, X and UV stellar radiatio*n. IX SCSLSA, 2013, Banja Koviljaca, Serbia, (Eds. Luka Č. Popović, Milan S. Dimitrijević, Zoran Simić and Marko Stalevski), p. 75. ISBN 978-86-80019-60-4**.**

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(Eds LC Popovic, D Jevremovic and D Ilic) Astronomical Observatory Belgrade, 2011. p. 62. ISBN 978-86-80019-44-4 (AO)

10. Šulić D., Nina A., Žigman V., Srećković V. *Study of Electron Density Changes Derived From Perturbed VLF Signals During Solar Flares,*. Indo-US Workshop on Advancing VLF Science through the Global AWESOME Networ; Neelams The Grand Goa, India 2011. p 25.

11. Šulić D, Nina A, Srećković V, Žigman V. *Distrubution of electron density in the D-region in presence of LEP eventa obtained from VLF radio measurements,*. Indo-US Workshop on Advancing VLF Science through the Global AWESOME Network 2011; Goa India. p 3.

12. Šulić D, Nina A, Srećković V, Čadež V. *Statistical analysis of D-region electron density during solar flares from VLF radio measurements*. XVI NKAS; 2011; Belgrade, Serbia. p.54 ISBN 978-86-80019-60-3

13. Srećković V.A., Mihajlov A.A., Ignjatović L.M., Dimitrijević M.S. *The influence of the radiative non-symmetric ion-atom collisions on the stellar atmospheres in VUV region*. EWASS2011 "European Week of Astronomy and Space Science 2011" JENAM; 2011; St. Petersburg, Russia. p.233

14. Nina A, Čadež V, Šulić D, Srećković V, Žigman V. *Effective electron recombination coefficient in the ionospheric D-region during the relaxation regime following a solar flare on February 18, 2011* CEPAS 2011 5th Conference on Elementary Processes in Atomic Systems 2011; Belgrade, Serbia.p.60 ISBN 978-86-82441-32-8.

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17. Ignjatović L.M., Mihajlov A.A., Srećković V.A., Dimitrijević M.S., Metropoulos A. *The influence of the radiative non-symmetric ion-atom collisions in the stellar atmospheres in UV and VUV regions*. I Workshop on Astrophysical Spectroscopy; 2011; Orašac, Serbia,
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20. Ignjatović L.M., Mihajlov A.A., Sakan N.M., Srećković V.A., Dimitrijević M.S., Jevremović D., *The chemi-ionization processes in the solar photosphere* (IL) VII SCSLSA 2009, Conference on spectral line shapes in astrophysics; 2009; Zrenjanin, Serbia. Book of Abstracts (Eds L ·C Popovic, D Jevremovic and

D Ilic) p.18.

21. Šulić D, Srećković V. *VLF Measurements of LEPs and their effects on D-region Electron Density Profiles*,. The First IHY International Workshop on Advancing VLF science through the global AWESOME network, 30-May to 01-Jun 2009, Tunis, Tunnisia; 2009.

22. Sakan N.M., Mihajlov A.A., Ignjatovic L.M., Srećković V.A. *The modeling of the continuous absorption spectra of the dense hydrogen plasma on the base of the cut-of Coulomb potential*. XIII International Conference on Physics of Non-Ideal Plasmas (PNP13); 2009; Chernogolovka, Russia, Book of Abstracts p. 61.

23. Šulić Desanka, Davorka Grubor, Vida Žigman and Vladimir Srećković: Numerical simulation of LEP events observed n recorded VLF signals at Belgrade station 3rd VERSIM Workshop, 15th -20th September 2008, Tihany Hungary, Book of Abstracts p. 39

24. Srećković V.A., Tkachenko I.M., Adamyan V.M., Sakan N.M., Šulic D., Mihajlov A.A. *Electrical conductivity of strongly non-ideal plasma in external HF electric field*. SCCS2008, International Conference on Strongly Coupled Coulomb Systems; 2008; Camerino Italy, Book of Abstracts p.15

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26. Ignjatović L.M., Dimitrijević M.S., Mihajlov A.A., Srećković V.A. *The processes of (n-n')-mixing in atom-rydberg atom collisions in stellar atmospheres*. VI SBAC, 2008. Book of Abstracts p. 17 (Eds: M. S. Dimitrijević, M. K. Tsvetkov l.C. Popovic and Valeri Golev).

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30. Adamyan V.M., Grubor D., Mihajlov A.A., Sakan N.M., Srećković V.A., Tkachenko I.M. *Optical HF electrical permeability, refractivity and reflectivity of dense non-ideal plasmas*. International Conference on Strongly Coupled Coulomb Systems; 2005; Moscow, Russia. Book of Abstracts, p28

Рад у водећем часопису националног значаја М51

Радови објављени након претходног избора у звање (21x2.0=42.0; 39.537):

1*. Mihajlov, A., Ignjatović, L. M., Srećković, V., Dimitrijević, M. & Jevremović, D. (2015) *Ion-Atom and Atom-Atom Collisional Processes and Modeling of Stellar Atmospheres*. Astronomicheskij

Tsirkulyar, Septembar 2015, vol. 1626, 1-13.

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8. V. A. Srećković and D. M. Šulić (2017) *Untypical perturbations on lf radio signals during solar flares* Publ AOB, No. 96, p. 229-232, http://publications.aob.rs/96/pdf/229-232.pdf

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15. N. M. Sakan, V. A. Srećković, Z. Simić and M. S. Dimitrijević (2018) *The spectral coefficients of absorption processes in dense strongly ionized astrophysical plasmas* Publ. Astron. Obs. Belgrade No. 98, p. 325-328 http://publications.aob.rs/98/pdf/325-328.pdf

16. V. A. Srećković and D. M. Šulić (2018), *Strong solar X-ray flares: influence on the ionosphere* Publ. Astron. Obs. Belgrade No. 98 p. 337-340 http://publications.aob.rs/98/pdf/337-340.pdf

17. D. Jevremovic, V. Vujcic, V.A. Srećković, A.A. Mihajlov, Lj.M. Ignjatovic, M.S. Dimitrijevic (2018), *The MOL-D database VAMDC node for molecular collisional and radiative processes* Astronomical and Astrophysical Transactions (AApTr), ISSN: 10556796, Vol. 30, Issue 3, pages 337 – 342

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20. A.A. Mihajlov, V.A. Srećković, N.M. Sakan, M.S. Dimitrijevic (2018) *Inverse bremsstrahlung in dwarf atmospheres: the absorption coefficients and Gaunt factors* Astronomical and Astrophysical Transactions (AApTr) ISSN: 10556796 Vol. 30, Issue 3, pages 291 – 298

21. V.A. Srećković; A.A. Mihajlov, Lj.M. Ignjatovic, M.S. Dimitrijevic (2018) *Atom-Rydberg atom processes in the stellar atmospheres: DB white-dwarf atmospheres and solar atmosphere*. Astronomical and Astrophysical Transactions (AApTr) ISSN: 10556796Vol. 30, Issue 3, pages 281 - 290

Радови објављени пре претходног избора у звање:

1. Srećković, V. A., Mihajlov, A.A., Ignjatović, Lj.M. and Dimitrijević, M.S. (2013) *The infuence of the radiative non-symmetric ion-atom collisions on the stellar atmospheres in VUV region*, Astronomical and Astrophysical Transactions (AApTr) Vol 28 Issue: 1 Pages: 73-79 ISSN: 1055-6796

2. Mihajlov A.A., Srećković V.A., Ignjatović L.M., Dimitrijević M.S., Metropoulos A. (2012) *The quasi-molecular absorption bands in UV region caused by the non-symmetric ion-atom radiative processes in the solar photospher*e. (21st ICSLS, International Conference on Spectral Line Shapes St Petersburg,

Russia,June 3–9, 2012); Journal of Physics: Conference Series. v 397 no.1 p. 012054(4) 2012.

3. Šulic D., Nina A., Srećković V. (2010) *Numerical Simulations Of The Effect Of Localised Ionospheric Perturbations On Subionospheric VLF Propagation*., Physics of ionized gases summer school and international symposium 25th (SPIG 2010) Serbia (Eds. Luka Č. Popović and Milorad M. Kuraica) Publications of the Astronomical Observatory of Belgrade, 89, p. 391-395,

4. Srećković V.A., Ignjatović L.M., Mihajlov A.A., Dimitrijević M.S. (2010) *Electrical Conductivity Of Plasmas In Db White Dwarf Atmospheres*. Physics of ionized gases summer school and international symposium 25th (SPIG 2010) Serbia (Eds. Luka Č. Popović and Milorad M. Kuraica) Publications of the Astronomical Observatory of Belgrade, 89, p. 383-386,

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9. Sakan, N.M., Srećković, V.A. and Mihajlov, A.A. (2005) *The application of the cut-off Coulomb potential for the calculation of a continuous spectra of dense hydrogen plasma*, Memorie della Societa Astronomica Italiana Supplementi Vol 7 Pages: 221 ISSN: 0037-8720

Предавање по позиву са скупа националног значаја штампано у изводу М62

Радови објављени након претходног избора у звање (1x1.0=1.0):

1. V. A. Srećković, Lj. M. Ignjatovic, D. Jevremovic, V. Vujcic and M. S. Dimitrijevic Radiative and collisional atomic/molecular data for astrophysics, XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L.C. Popovic, D. Urosevic and R. Pavlovic Astr. Obs. and Faculty of Mathematics, Belgrade, 2017, p.55, ISBN 978-86-80019-85-7 http://sac18.aob.rs/Program.html

Саопштења са скупова националног знацаја штампано у целини (М63- 1.0)

Радови објављени након претходног избора у звање (0x1.5=0.0):

Саопштења са скупова националног знацаја штампано у изводу (М64- 0.2)

Радови објављени након претходног избора у звање (6x0.2=1.2; норм. 1,193):

1. A. Nina, V. M. Cadez, L. C. Popovic, V. A. Srećković, J. Bajcetic, S. T. Mitrovic, M. Radovanovic, M. Todorovic Drakul, A. Kolarski and S. Simic, *Low ionospheric response to astro-geo-phenomena - recent research*, XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L. ·C. Popovic, D. Urosevic and R. Pavlovic Astronomical Observatory and Faculty of Mathematics, Belgrade, 2017 p.89, ISBN 978-86-80019-85-7 **норм. 0.125**

2. N. M. Sakan, V. A. Srećković, Z. Simic and M. S. Dimitrijevic, *The spectral coefficients of absorption processes in dense strongly ionized astrophysical plasmas* XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L. ·C. Popovic, D. Urosevic and R. Pavlovic Astronomical Observatory and Faculty of Mathematics, Belgrade, 2017, p.95, ISBN 978-86-80019-85-7

3. N. M. Sakan, V. A. Srećković, Z. Simic and M. S. Dimitrijevic, *The optical characteristics of dense, strongly ionized hydrogene plasma, applicable in astrophysical objects*, XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L. ·C. Popovic, D. Urosevic and R. Pavlovic Astronomical Observatory and Faculty of Mathematics, Belgrade, 2017, p.96, ISBN 978-86-80019-85-7

4. V. A. Srećković, Lj. M. Ignjatovic, A. Nina and M. S. Dimitrijevic, *The new model method of the electrostatic screening of the astrophysical plasmas: multi-component systems*, XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L. ·C. Popovic, D. Urosevic and R. Pavlovic Astronomical Observatory and Faculty of Mathematics, Belgrade, 2017, p.99, ISBN 978-86-80019-85-7

5. V. A. Srećković and D. M. Šulic *Strong solar X ray flares: influence on the ionosphere*, XVIII SAC 17-21 October 2017, Belgrade, Serbia Book of abstracts, eds. L. ·C. Popovic, D. Urosevic and R. Pavlovic Astronomical Observatory and Faculty of Mathematics, Belgrade, 2017, p.100, ISBN 978-86-80019-85-7

6. M. S. Dimitrijevic, A.Bajić, V. A. Srećković *On the astronomical symbols on greek and roman coins*, II SRPAC Timişoara, November 16-17 2018, Conf. Abstracts Ed. Marc FRINCU p2S5

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1. Срећковић В.А., Михајлов А.А., Игњатовић Љ.М., Димитријевић М.С. *Ексцитациони и деексцитациони процеси у атом-Rydberg атом сударима у атмосферама белих патуљака богатим хелијумом*. XII Конгрес физичара Србије; 2013; Vrnjacka Banja. (Eds. J. Labat, N. Cvetanović and I. Dojčinović) p.400-403.

2. Нина А, Чадеж В.М., Поповић Л.Ч., Срећковић В.А., Јевремовић Д., Симић С. *Дијагностика пертурбација плазме ниске јоносфере VLF радио таласима*. XII Конгрес физичара Србије; 2013; Vrnjacka Banja. (Eds. J. Labat, N. Cvetanović and I. Dojčinović) p. 388-391

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7. МАГИСТАРСКЕ И ДОКТОРСКЕ ТЕЗЕ (М 70)

М 71
Докторска дисертација: ***" ЕЛЕКТРОПРОВОДНОСТ И ДРУГЕ ТРАНСПОРТНЕ ОСОБИНЕ НЕИДЕАЛНЕ ДЕЛИМИЧНО ЈОНИЗОВАНЕ ПЛАЗМЕ ХЕЛИЈУМА, НЕОНА И АРГОНА ",*** Физички Факултет Универзитета у Београду
Ментор: Проф. др Љ.М. Игњатовић

М 72
Magistarska teza: ***" ТРАНСПОРТНЕ ОСОБИНЕ ГУСТЕ ЈАКО ЈОНИЗОВАНЕ ПЛАЗМЕ "*** Физички Факултет Универзитета у Београду
Ментор: Проф. др Љ.М. Игњатовић

8. ТЕХНИЧКА И РАЗВОЈНА РЕШЕЊА (М 80)

М 86 *објављени након претходног избора у звање (2x1.0=2.0):*

1. Veljko Vujčić, Vladimir Srećković, Darko Jevremović, Sanja Erkapić, Decembar 2015, ***BEAMDB*** **(РБ 1612) M86**
MNTRS link: http://www.mpn.gov.rs/wp-content/uploads/2016/04/TEHNICKA-RESENJA-2011-2015-10-april.xls

2. Anatolij Mihajlov, Veljko Vujčić, Vladimir Srećković, Darko Jevremović, Milan Dimitrijević, Sanja Erkapić, Decembar 2015, ***MOLD*** **(РБ 1764) M86**
MNTRS link: http://www.mpn.gov.rs/wp-content/uploads/2016/04/TEHNICKA-RESENJA-2011-2015-10-april.xls

J. Astrophys. Astr., Vol. 36, No. 4, December 2015, pp. 693–703

MOL-D: A Collisional Database and Web Service within the Virtual Atomic and Molecular Data Center

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Abstract. MOL-D database is a collection of cross-sections and rate coefficients for specific collisional processes and a web service within the Serbian Virtual Observatory (SerVO) and the Virtual Atomic and Molecular Data Center (VAMDC). This database contains photo-dissociation cross-sections for the individual ro-vibrational states of the diatomic molecular ions and rate coefficients for the atom-Rydberg atom chemi-ionization and inverse electron–ion–atom chemi-recombination processes. At the moment it contains data for photodissociation cross-sections of hydrogen H_2^+ and helium He_2^+ molecular ions and the corresponding averaged thermal photodissociation cross-sections. The ro-vibrational energy states and the corresponding dipole matrix elements are provided as well. Hydrogen and helium molecular ion data are important for calculation of solar and stellar atmosphere models and for radiative transport, as well as for kinetics of other astrophysical and laboratory plasma (i.e. early Universe).

Key words. Atomic and molecular processes: photodissociation/association—chemi-ionization/recombination—astronomical databases: miscellaneous—plasmas—spectral line profiles.

1. Introduction

Mihajlov and coworkers have demonstrated that ion–atom radiative processes, the photodissociation of the diatomic molecular ion in the symmetric and non-symmetric cases, could be important in specific stellar atmosphere layers and they should be included in chemical models (Mihajlov & Dimitrijevic 1986; Mihajlov *et al.* 1993, 2007; Ignjatović *et al.* 2009, 2014b; Srećković *et al.* 2014). In the symmetric case, we consider the processes of molecular ion photodissociation (bound-free) and ion–atom photoassociation (free-bound):

$$h\nu + A_2^+ \Longleftrightarrow A + A^+, \tag{1}$$

and the corresponding free–free absorption and emission processes:

$$h\nu + A + A^+ \Longleftrightarrow A^+ + A, \tag{2}$$

where A and A^+ are atom and ion in their ground states, and A_2^+ is molecular-ion in the ground electronic state.

In the non-symmetric case, the similar processes of photodissociation/photoassociation are

$$h\nu + AX^+ \Longleftrightarrow A^+ + X, \tag{3}$$

and the corresponding absorption/emission processes

$$h\nu + A + X^+ \Longleftrightarrow A^+ + X. \tag{4}$$

The processes of stimulated photoassociation, characteristic for the non-symmetric case are

$$\varepsilon_\lambda + A + X^+ \Longleftrightarrow (AX^+)^*, \tag{5}$$

where X is an atom whose ionization potential is less than the corresponding value for atom A. AX^+ is also molecular-ion in the ground electronic state and $(AX^+)^*$ molecular-ion in the first excited electronic state.

In the general case, molecular ion A_2^+ or AX^+ can be in one of the states from the group which contains the ground electronic state. Similarly, the excited molecular ion $(AX^+)^*$ can exist in one of the states from the group which contains the first excited electronic state of the considered molecular ion.

For the solar atmosphere, A usually denotes atom H(1s) and X one of the relevant metal atoms (Mg, Si, Ca, Na,...) (Mihajlov & Dimitrijevic 1986; Mihajlov *et al.* 1993, 2007; Ignjatović *et al.* 2014b; Srećković *et al.* 2014), but there are cases where A = He and X = H, Mg, Si, Ca, Na. For the helium-rich white dwarf atmospheres, A denotes He(1s^2) and X denotes H(1s), and eventually C, O (Mihajlov & Dimitrijevic 1992; Mihajlov *et al.* 2013; Ignjatović *et al.* 2014a).

Our results show the importance of including the symmetric processes with A =H(1s) in the stellar atmosphere models (see e.g. Fontenla *et al.* 2009) and for the early Universe investigation (see Coppola *et al.* 2013). Also, our results for A =He(1s^2) have been used for modeling the DB white dwarf atmospheres (Koester 2015). Such data are also of interest for research on the corresponding weakly ionized laboratory plasmas.

The processes mentioned above are closely connected to several groups of inelastic atomic collision processes. The first few groups consist of the chemi-ionization processes in symmetric and non-symmetric atom/Rydberg-atom collisions, including the processes of associative ionization as well as the corresponding inverse electron–ion–atom chemi-recombination processes:

$$A^*(n) + A \Longleftrightarrow A_2^+ + e, \tag{6}$$

$$A^*(n) + A \Longleftrightarrow A + A^+ + e, \tag{7}$$

$$A^*(n) + X \Longleftrightarrow A_2^+ + e, \tag{8}$$

$$A^*(n) + X \Longleftrightarrow A + X^+ + e. \tag{9}$$

$A^*(n)$ is an atom in one of the highly excited (Rydberg) states with the principal quantum number $n \gg 1$, e is a free electron and A, $A^+A_2^+$, X have the same meaning as in the previous cases. The ionization potential of the atom X is lower than that of the atom A. The considered radiative processes are allowed by the dipole selection rules.

The other groups of processes consist of excitation and deexcitation processes known also as the $(n - n')$-mixing processes:

$$A^*(n) + A \Longrightarrow \begin{cases} A^*(n') + A, \\ A + A^*(n'), \end{cases} \quad 1 \ll n < n' \tag{10}$$

and

$$A^*(n) + A \Longrightarrow \begin{cases} A^*(n') + A, \\ A + A^*(n'), \end{cases} \quad 1 \ll n' < n. \tag{11}$$

A^* has the same meaning as in the case of chemi-ionization/chemi-recombination processes.

Chemi-ionization/chemi-recombination and $(n - n')$-mixing processes are such that system passes through the phase where it can be treated in the form:

$$(A + A^+)^{\text{in,fin}}_{\text{q.-m.}} + e_{\text{out}}, \tag{12}$$

or

$$(A + X^+)^{\text{in,fin}}_{\text{q.-m.}} + e_{\text{out}}. \tag{13}$$

$(A + A^+)^{\text{in,fin}}_{\text{q.-m.}}$ and $(A + X^+)^{\text{in,fin}}_{\text{q.-m.}}$ denote a quasi-molecular ion-atom complex in the corresponding (initial or final) electronic state, and e_{out} denotes a free electron in weakly bound or free state.

The connection of these processes with the above described radiative processes is in the following chemi-ionization/chemi-recombination and $(n - n')$-mixing transitions:

$$(A + A^+)^{\text{in}}_{\text{q.-m.}} \longrightarrow (A + A^+)^{\text{fin}}_{\text{q.-m.}} \tag{14}$$

or

$$(A + X^+)^{\text{in}}_{\text{q.-m.}} \longrightarrow (A + X^+)^{\text{fin}}_{\text{q.-m.}}. \tag{15}$$

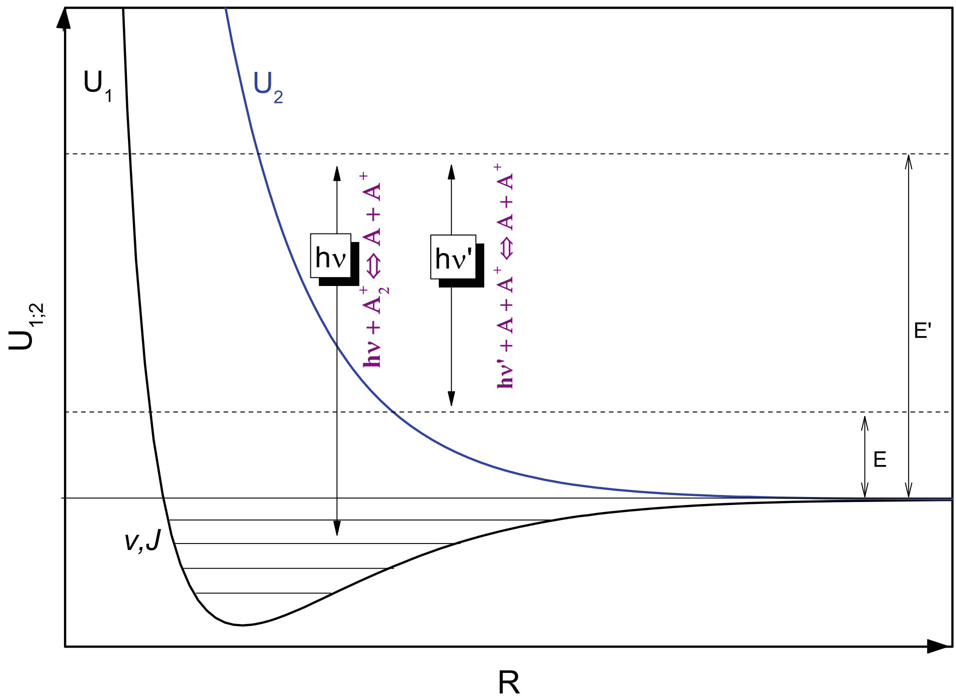

Figure 1. The schematic presentation of the photo-dissociation/association processes (equation (1)) and free–free processes (equation (2)): R is the internuclear distance, $U_1(R)$ and $U_2(R)$ are the potential energy curves of the initial(lower) and final(upper) electronic state of molecular ion A_2^+, J and v are individual ro-vibrational states, E and E' are the total energies of the system $A + A^+$, $h\nu$ and $h\nu'$ are the photon energies.

The processes described above (equations (1)–(11)) are schematically illustrated in Figures 1–6.

The results obtained during the investigation of the processes mentioned in the present section are presented in MOL-D database which will be described in the next section. The first version of this database is available online and can be accessed directly through http://servo.aob.rs/mold or through VAMDC node within the Serbian Virtual Observatory (SerVO – http://servo.aob.rs, Jevremović *et al.* 2009), and the Virtual Atomic and Molecular Data Center (VAMDC – http://www.vamdc.org, Dubernet *et al.* 2010; Rixon *et al.* 2011).

2. Content of MOL-D e-service

The MOL-D is an e-service which exposes our results to the wider community. In particular, we provide:

- the cross-sections for the photodissociation of individual ro-vibrational states of the considered molecular ions as well as the cross sections for the inverse ion–atom photoassociation (equations (1) and (3)), in a wide region of photon wavelengths λ,

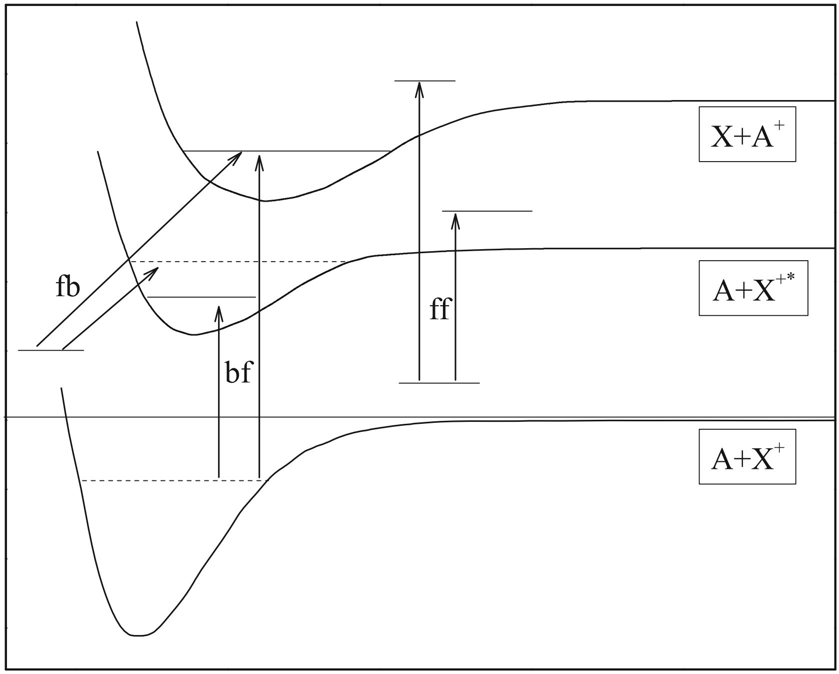

Figure 2. The schematic presentation of the processes (equations (3)–(5)) for the case of the molecular ion AX^+ and ion–atom system $A^+ + X$.

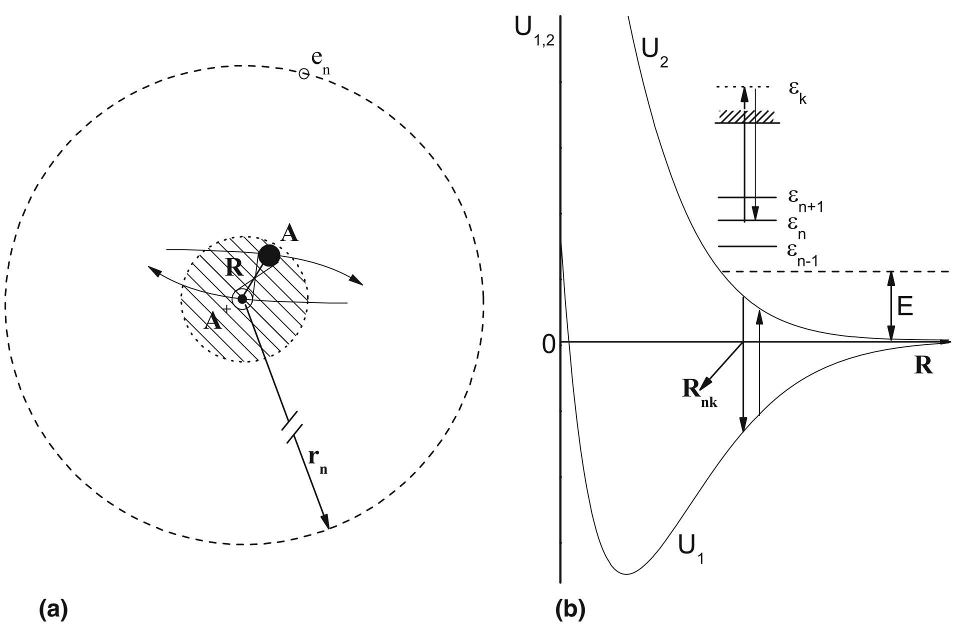

Figure 3 (a), (b). The schematic presentation of the chemi-ionization/recombination processes (equations (6)–(9)): n is the principal quantum number of the Rydberg state, ϵ_k is the energy of the free electron.

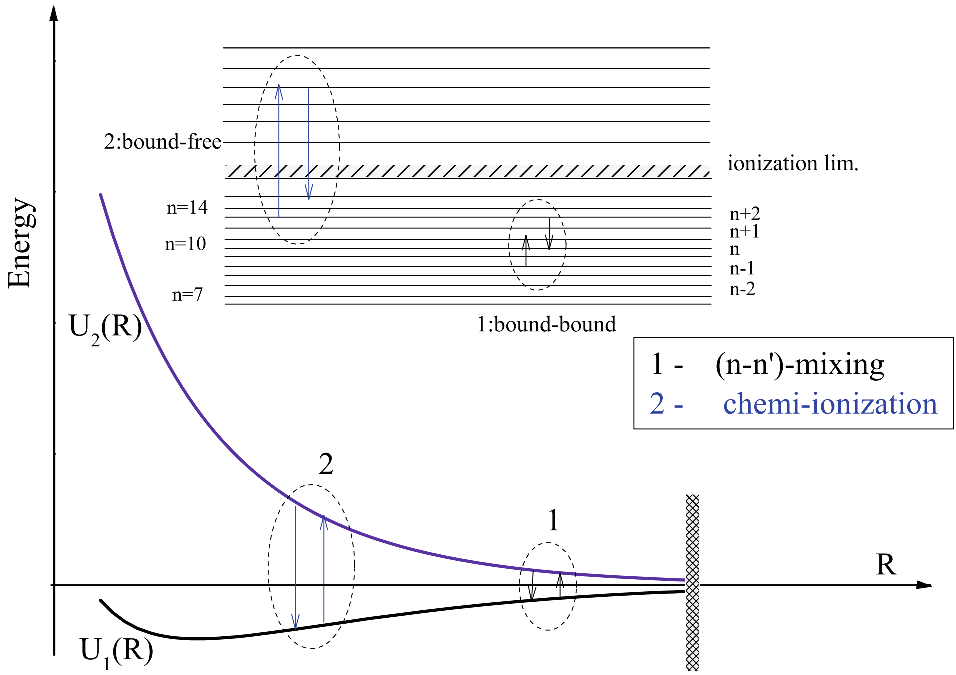

Figure 4. The schematic presentation of the chemi-ionization and $(n - n')$-mixing processes (equations (7) and (10)): n and n' are the principal quantum numbers of the considered Rydberg states.

- the averaged thermal cross sections for the considered molecular ion photodissociation and for the reverse process, ion–atom photoassociation (equations (1) and (3)), in a wide region of λ and temperature T,
- the rate coefficients and the corresponding averaged thermal cross sections for the ion–atom absorption processes and inverse emission processes (equations (2) and (4)), as well as for the non-symmetric ion–atom photoassociation in equation (5) in a wide region of λ and T,
- visualization of the wavelength dependance of the averaged thermal cross sections for a given temperature input.

MOL-D is available online from the end of 2014 and for the moment it contains the data for the photodissociation processes (equation (1)) with $A =$ H(1s)and $A =$ He(1s^2). In the near future, we intend to include the relevant data for some other non-symmetric photodissociation processes (equation (3)).

The cross-sections for the photodissociation of individual ro-vibrational state of the considered molecular ions are determined in the dipole approximation:

$$\sigma_{J,v}(\lambda) = \frac{8\pi^3}{3\lambda}\left[\frac{(J+1)|D_{E,J+1;v,J}|^2 + J|D_{E,J-1;v,J}|^2}{2J+1}\right], \tag{16}$$

and the corresponding averaged thermal cross sections are given by

$$\sigma_{\mathrm{ph}}(\lambda, T) = \frac{1}{Z}\sum_J\sum_v g_{J;v}(2J+1)\mathrm{e}^{-\frac{E_{J,v}-E_{0,0}}{k_{\mathrm{B}}T}}\sigma_{J,v}(\lambda). \tag{17}$$

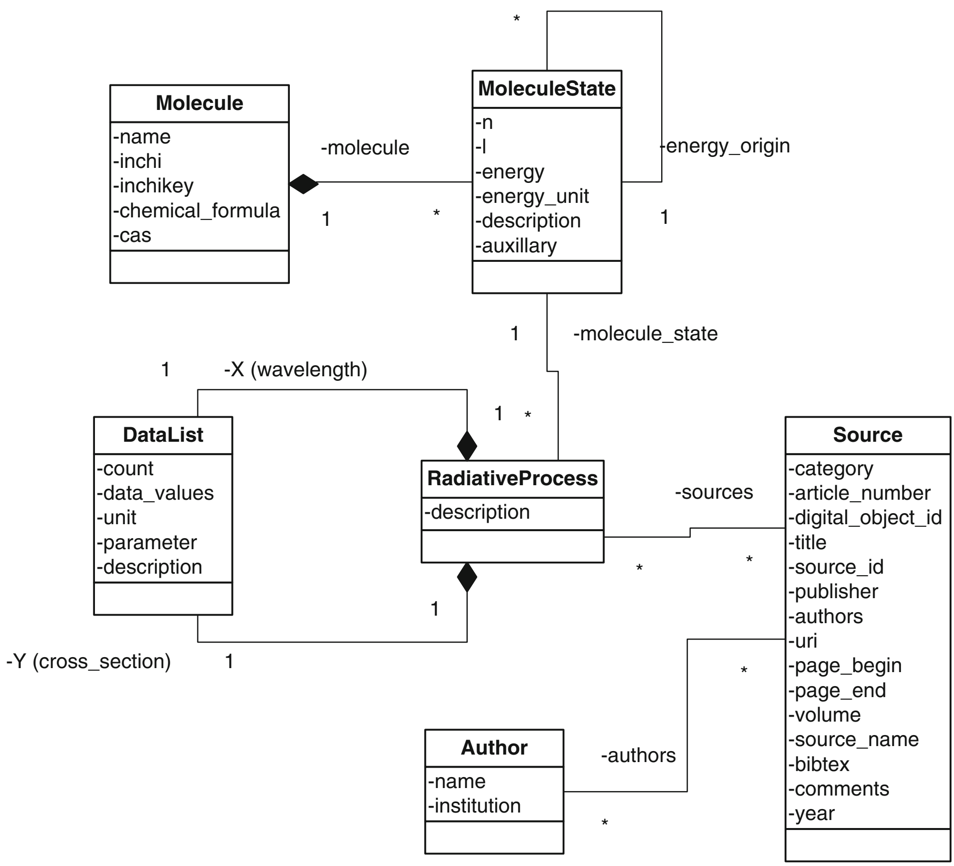

Figure 5. Static structure of the MOL-D database. Relationships between entities are shown by connected lines with designated cardinalities ('1' and '*' denote one and many, respectively), i.e. a molecule can have multiple states.

$D_{E,J+1;v,J}$ is the relevant dipole matrix element, $E_{J,v}$ is the energy of the individual states with the angular and vibrational quantum numbers J and v respectively, and Z is the partition function

$$Z = \sum_{J}\sum_{v} g_{J;v}(2J+1)\mathrm{e}^{-\frac{E_{J,v}-E_{0,0}}{k_{\mathrm{B}}T}}. \tag{18}$$

In this expression, the product $g_{J;v}\cdot(2J+1)$ is the statistical weight of the considered state and the coefficient $g_{J;v}$ depends on the 'the spin of the nuclei'.

We also plan to include the rate coefficients for the chemi-ionization/recombination and $(n-n')$ mixing (equations (6)–(11)). The values of the rate coefficients will be determined in the semi-classical approach (see e.g. Mihajlov *et al.* 2011), but using a significantly improved numerical procedure with respect to the previous papers (Mihajlov *et al.* 2003, 2004, 2005, 2008, 2011; Srećković *et al.* 2013).

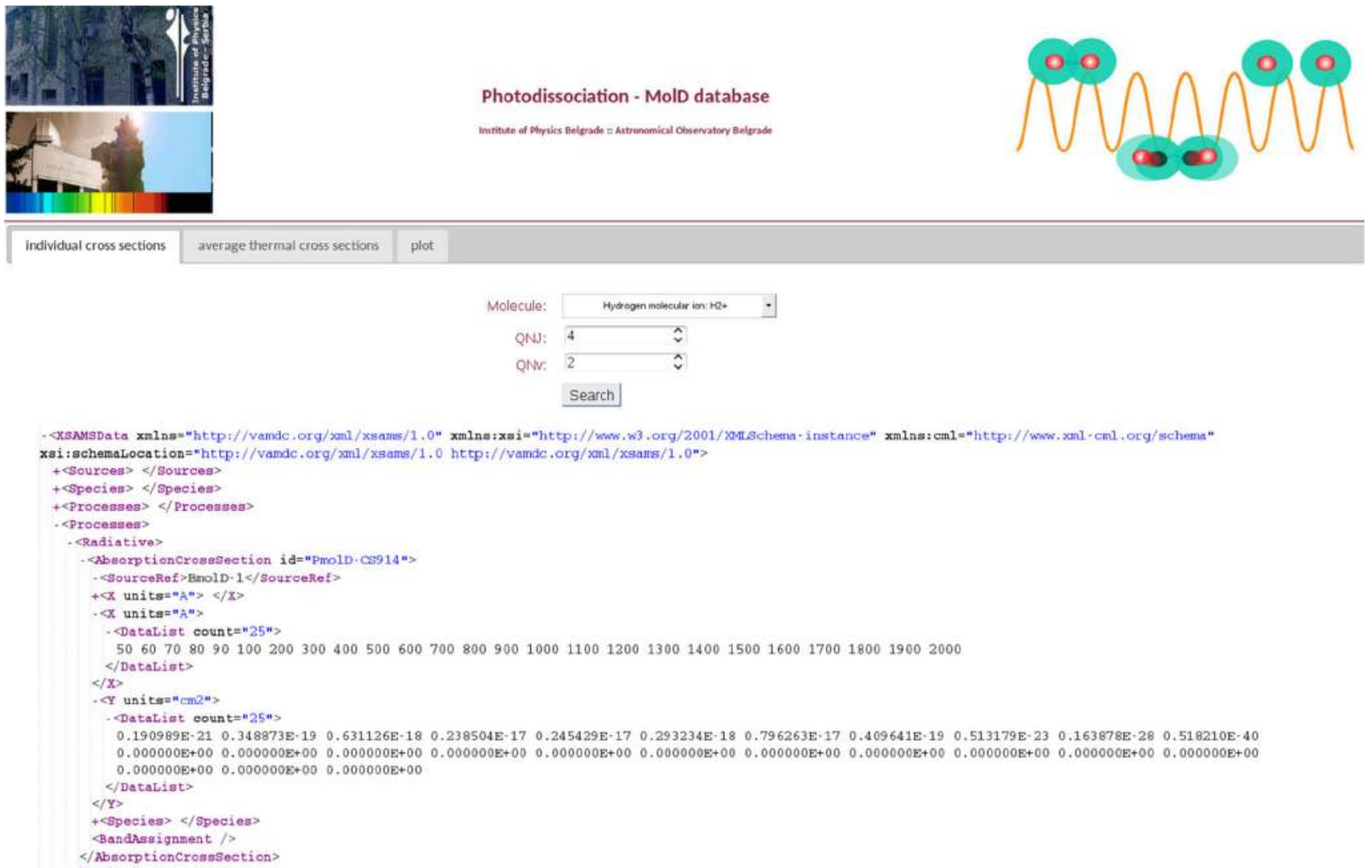

Figure 6. Some screen shots of the MOL-D node at the Belgrade server station.

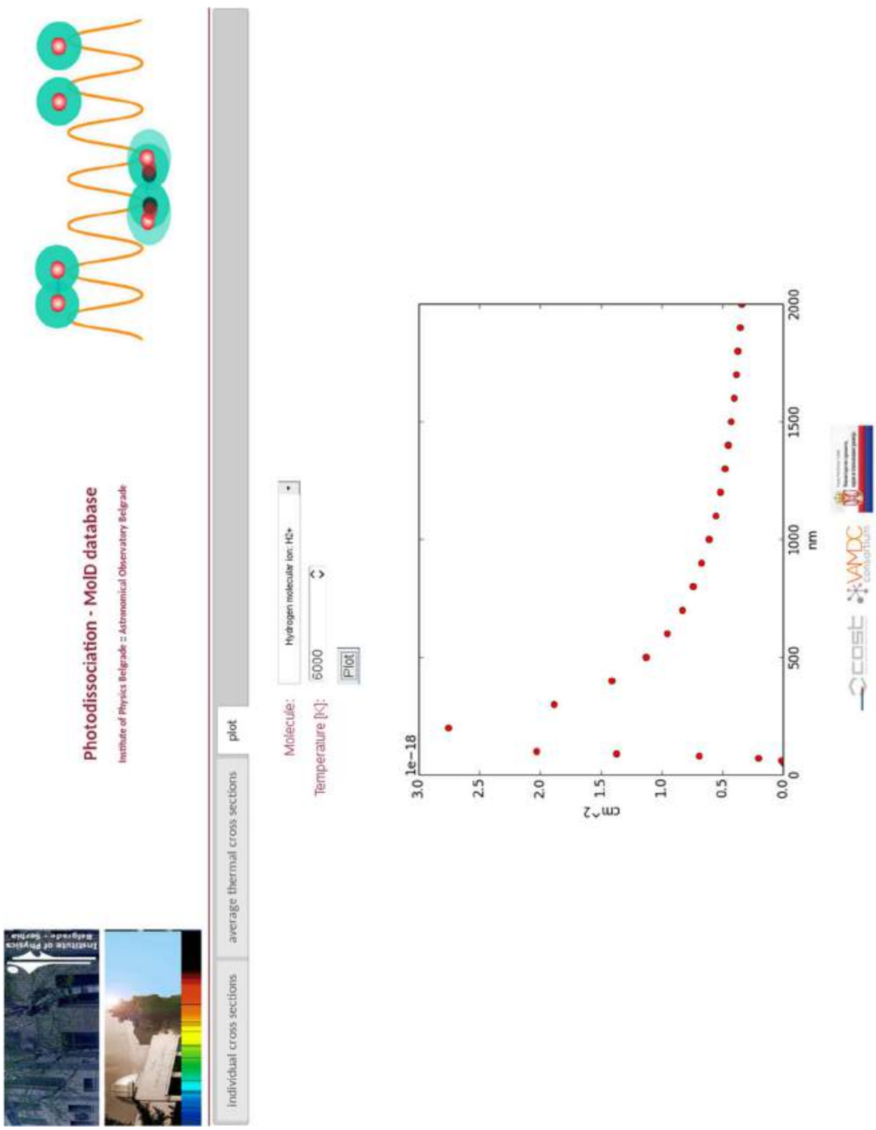

Figure 6. *(continued).*

3. Technical characteristics of MOL-D database

The principal structure of the Belgrade MOL-D database is shown schematically in Figure 5 using UML notation.

MOL-D data are exposed as a web form and a web service accesible according to VAMDC specification[1]. VAMDC (Dubernet *et al.* 2010) standards define VAMDC-TAP RESTful web-service request using VSS2 query language and results formatted as a XSAMS (XML Schema for atoms, molecules and solids) document[2]. Such approach enables accessing multiple databases in a single query.

Software is built on top of Django, a web-based Python framework, and represents an adaptation and extension of VAMDC Node Software. User interface is AJAX-enabled, using JQuery javascript framework and plots are generated by pyplot (matplotlib).

Besides acting as a VAMDC-compliant web service, accessible through VAMDC portal and other tools implemented on VAMDC standards, MOL-D offers on-site services such as

- user can make a selection based on molecule and quantum number J (QNJ) or quantum number v (QNv)
- calculate averaged thermal cross section based on the temperature for a specific molecule and wavelength
- make a plot of averaged thermal cross sections along all (discrete) wavelengths for a given temperature

A screens shot of MOL-D database at Belgrade server station[3] is shown in Figure 6. An example of the visualization of a data set that represents the averaged cross section versus wavelength is shown in the right panel of Figure 6.

4. Future development and perspectives

In the near future, we plan to add the results of the rate coefficients for the ion–atom absorption processes and inverse emission processes. We will also include data for the non-symmetric ion–atom photoassociation. Our plans also consist of including the rate coefficients for chemi-ionization in atom-Rydberg atom collisions (including the processes of associative and Penning type ionization) and corresponding inverse chemi-recombination processes in electron–ion–atom collisions. Finally, we intend to include the rate coefficients for the excitation and deexcitation $(n - n')$-mixing processes in the relevant region of the principal quantum number n and T.

We plan to calculate and include new data about processes which involve species such as HeH^+, LiH^+, NaH^+, SiH^+ which are important for the early Universe chemistry and for the modeling of stellar and solar atmospheres. The MOL-D database will be regularly updated with new results.

[1] http://vamdc-standards.readthedocs.org/en/latest/dataAccessProtocol/vamdctap.html
[2] http://vamdc.eu/documents/standards/dataModel/vamdcxsams/index.html
[3] http://servo.aob.rs/mold

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Atom–Rydberg atom chemi-ionization/recombination processes in the hydrogen clouds in broad-line region of AGNs

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ABSTRACT

The possibility that the chemi-ionization processes in atom–Rydberg atom collisions, as well as the corresponding chemi-recombination processes, may be useful for the diagnostics, modelling, and confirmation of existence or non-existence of very dense weakly ionized domains in clouds in broad-line region of active galactic nuclei, has been considered. The obtained results demonstrate the fact that the considered chemi-ionization/recombination processes, which influence on the ionization level and atom excited-state populations, must have a very significant influence on the optical properties of the weakly ionized regions where the neutral hydrogen densities are larger than $10^{12}\,\mathrm{cm}^{-3}$ since in such conditions they dominate over the relevant concurrent electron–atom collision processes. This can be used as a diagnostic method to find out if the domains with such densities exist or not. Additionally, our previous results obtained for principal quantum number $2 \le n \le 8$ and $4000\,\mathrm{K} \le T \le 10\,000\,\mathrm{K}$ are extended for principal quantum number $9 \le n \le 20$ and $10\,000\,\mathrm{K} < T \le 20\,000\,\mathrm{K}$ and also for low-temperature region ($T < 4000$ K) for $2 \le n \le 20$.

Key words: atomic processes – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

In order to develop and improve diagnostic methods needed for the estimation of the physical conditions in the particular parts of active galactic nuclei (AGNs), the investigation of the influence of various relevant atomic and molecular collisional processes is needed (Netzer 1990; Jogee 2006; Osterbrock & Ferland 2006). For example in Crosas & Weisheit (1993), 18 different atomic and molecular collisional processes, including the associative chemi-ionization, were included in the investigation of hydrogen molecule formation in quasar's broad-line region (BLR) clouds. Using the more or less approximate estimates and hydrogen densities 10^4–10^{10} cm^{-3}, they concluded that the influence of the associative chemi-ionization processes

$$H^*(n = 2) + H(n = 1) \Rightarrow H_2^+ + e, \quad (1)$$

and

$$H^*(n = 3) + H(n = 1) \Rightarrow H_2^+ + e, \quad (2)$$

is negligible in BLR clouds. However, for example in Marziani et al. (2011), Negrete et al. (2012) and Marziani et al. (2015), hydrogen atom density $7.00 \le \log n_{\mathrm{H}} \le 14.00$ has been used for various simulations in BLR with the code CLOUDY (Ferland et al. 2013). On the other hand, the illuminated surface of the BLR clouds is highly ionized, but if they are sufficiently large the temperature may decrease to the much lower values, e.g. up to around 2000 K, as was taken in Crosas & Weisheit (1993), where gas is weakly ionized with large amount of hydrogen molecules (Crosas & Weisheit 1993). If very dense weakly ionized regions exist, these and other chemi-ionization/recombination processes could be important and could change the optical characteristics. This fact can be used for the investigation if such regions exist in BLR clouds. The aim of this work is to find out at what plasma conditions (neutral hydrogen and electron densities) such processes become important and could be used for numerical simulations and modelling and the confirmation of existence of regions with such characteristics. This topic is very current because of existence of uncertainties on the rate coefficients due to hydrogen collisions (Barklem 2007), and the need for accurate ones in order to be properly included in modern codes like Ferland et al. (1998, 2013, 2017).

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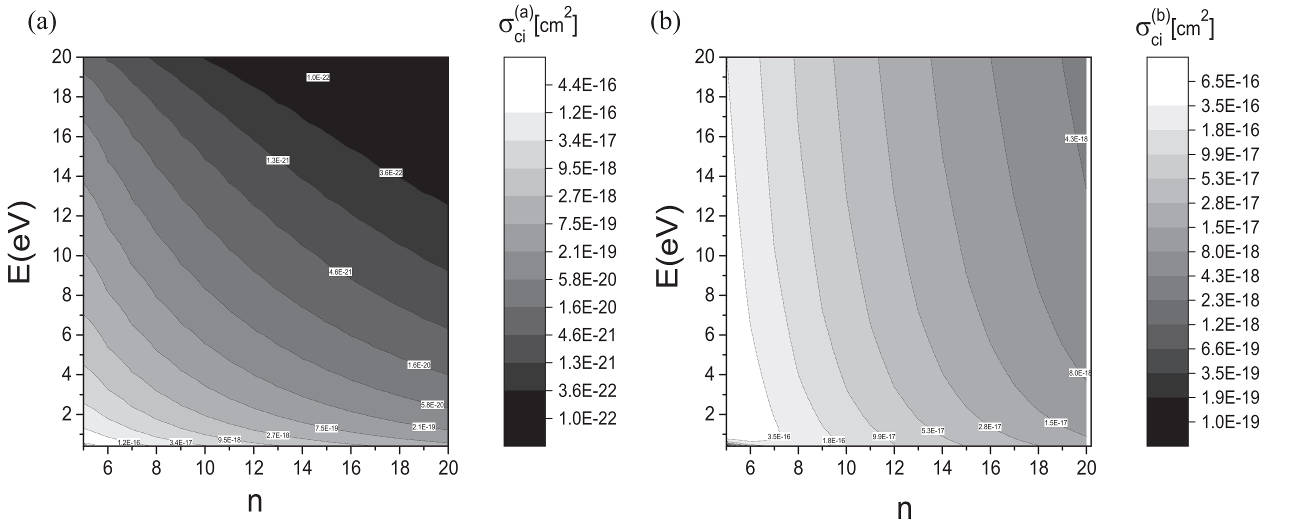

Figure 1. (a) The surface plot of the partial cross-section $\sigma_{\rm ci}^{(a)}(n, E)$ equation (10) of the chemi-ionization processes (3), i.e. associative ionization channel. (b) The surface plot of the partial cross-sections $\sigma_{\rm ci}^{(b)}(n, E)$ equation (10) of the chemi-ionization processes (4), i.e. non-associative ionization channel.

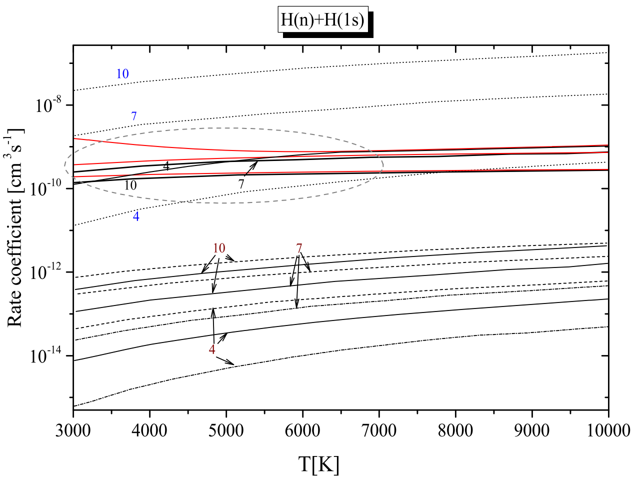

Figure 2. Plot of collisional ionization H(n) + H(1s) rate coefficients for selected excited states (n = 4, 7, 10). The black lines are the data analysed in Barklem (2007) for non-associative channel (4), where A = H. The data from Mihajlov and coworkers based on the same mechanism as here are plotted as thick full lines. The calculated data of Soon (1992) are presented with full lines and the dot–dashed line (see Barklem 2007 for detailed explanation). The data of Drawin (1968, 1969) are presented with dotted lines, and the results of the analytic formula from Soon with dashed lines. The red lines are summary rate coefficients for associative (3) and non-associative (4) channels (this work).

2 THE CHEMI-IONIZATION/ RECOMBINATION PROCESSES

An atom $A^*(n)$ excited into a Rydberg state, with large principal quantum number n, is very sensitive even to inelastic thermal collisions that are often enough energetic to produce ionization reactions. They represent chemi-ionization reactions that can be divided in accordance with the products of the reaction. Such symmetric reactions are for example the processes of associative ionization:

$$A^*(n) + A \Rightarrow A_2^+ + e, \qquad (3)$$

and the non-associative ionization channel

$$A^*(n) + A \Rightarrow A + A^+ + e, \qquad (4)$$

where e is a free electron. The reactions such as $A^*(n) + B \rightarrow B^+ + A + e$, where B is an atom or molecule with the ionization potential less than the internal energy of $A^*(n)$, are called Penning ionization. However, $A^*(n)$ Rydberg atom in the equation (4) does not have the energy needed to ionize the atom A, so that a part of the energy necessary for ionization should come from the collision process. Because of this fact, we will denote the process given by equation (4) as collisional ionization. Both the process of associative ionization and the inverse one, called dissociative recombination, are less studied than the Penning ionization but an extensive literature exists for them as well.

For the investigation of chemi-ionization processes, the dipole resonant mechanism is used here, described in detail in Mihajlov et al. (2012).

The chemi-ionization processes (3) and (4) as well as the inverse chemi-recombination processes

$$A_2^+ + e \Rightarrow A^*(n) + A, \qquad (5)$$

and

$$A + A^+ + e \Rightarrow A^*(n) + A. \qquad (6)$$

The cases A = H(1s) and He(1s^2) have been analysed in Mihajlov, Dimitrijević & Djurić (1996) and Mihajlov et al. (1997b) with the emphasis on their influence on the populations of excited atoms in the weakly ionized H and He plasmas. In order to investigate the efficiency of these processes, they should be compared with the processes

$$A^*(n) + e \Rightarrow A^+ + 2e, \qquad (7)$$

$$A^+ + 2e \Rightarrow A^*(n) + e, \qquad (8)$$

$$A^+ + e \Rightarrow A^*(n) + \varepsilon_\lambda, \qquad (9)$$

where A = H(1s) or He(1s^2) and ε_λ is the energy of a photon with wavelength λ. The rate coefficients for chemi-ionization and chemi-recombination processes have been determined theoretically in Mihajlov et al. (1996, 1997b). On the basis of obtained results, it

Table 1. Calculated Values of Coefficient K_{ci}[cm^3 s^{-1}] as a function of n and T. A portion is shown here for guidance regarding its form and content.

T/n	10	11	12	13	14	15	16	17	18	19	20
3000	1.92E-10	1.51E-10	1.19E-10	9.44E-11	7.56E-11	6.11E-11	4.98E-11	4.09E-11	3.39E-11	2.82E-11	2.37E-11
4000	2.17E-10	1.68E-10	1.31E-10	1.03E-10	8.19E-11	6.57E-11	5.32E-11	4.35E-11	3.58E-11	2.97E-11	2.49E-11
5000	2.36E-10	1.81E-10	1.40E-10	1.09E-10	8.62E-11	6.88E-11	5.55E-11	4.52E-11	3.72E-11	3.08E-11	2.57E-11
6000	2.51E-10	1.90E-10	1.46E-10	1.14E-10	8.94E-11	7.12E-11	5.73E-11	4.65E-11	3.82E-11	3.16E-11	2.63E-11
7000	2.62E-10	1.98E-10	1.51E-10	1.17E-10	9.20E-11	7.30E-11	5.86E-11	4.76E-11	3.89E-11	3.22E-11	2.68E-11
8000	2.71E-10	2.04E-10	1.55E-10	1.20E-10	9.40E-11	7.45E-11	5.97E-11	4.84E-11	3.96E-11	3.26E-11	2.72E-11
9000	2.79E-10	2.09E-10	1.59E-10	1.22E-10	9.57E-11	7.57E-11	6.06E-11	4.90E-11	4.01E-11	3.30E-11	2.75E-11
10000	2.85E-10	2.13E-10	1.62E-10	1.24E-10	9.71E-11	7.67E-11	6.14E-11	4.96E-11	4.05E-11	3.34E-11	2.77E-11
11000	2.91E-10	2.17E-10	1.64E-10	1.26E-10	9.83E-11	7.76E-11	6.20E-11	5.01E-11	4.09E-11	3.36E-11	2.79E-11
12000	2.96E-10	2.20E-10	1.66E-10	1.28E-10	9.93E-11	7.83E-11	6.25E-11	5.05E-11	4.12E-11	3.39E-11	2.81E-11
13000	3.00E-10	2.23E-10	1.68E-10	1.29E-10	1.00E-10	7.90E-11	6.30E-11	5.09E-11	4.14E-11	3.41E-11	2.83E-11
14000	3.04E-10	2.25E-10	1.70E-10	1.30E-10	1.01E-10	7.96E-11	6.35E-11	5.12E-11	4.17E-11	3.43E-11	2.84E-11
15000	3.08E-10	2.28E-10	1.71E-10	1.31E-10	1.02E-10	8.01E-11	6.38E-11	5.15E-11	4.19E-11	3.44E-11	2.86E-11
16000	3.11E-10	2.30E-10	1.73E-10	1.32E-10	1.02E-10	8.06E-11	6.42E-11	5.17E-11	4.21E-11	3.46E-11	2.87E-11
17000	3.14E-10	2.31E-10	1.74E-10	1.33E-10	1.03E-10	8.10E-11	6.45E-11	5.19E-11	4.23E-11	3.47E-11	2.88E-11
18000	3.16E-10	2.33E-10	1.75E-10	1.34E-10	1.04E-10	8.14E-11	6.48E-11	5.21E-11	4.24E-11	3.48E-11	2.89E-11
19000	3.19E-10	2.35E-10	1.76E-10	1.34E-10	1.04E-10	8.17E-11	6.50E-11	5.23E-11	4.26E-11	3.50E-11	2.90E-11
20000	3.21E-10	2.36E-10	1.77E-10	1.35E-10	1.04E-10	8.20E-11	6.52E-11	5.25E-11	4.27E-11	3.51E-11	2.90E-11

Table 2. The fits of the equation (13) to the rate coefficients.

n	k_1	k_2	k_3
4	19.91758	– 15.14785	1.98009
5	– 20.60455	5.21174	– 0.57122
6	– 17.85054	3.94548	– 0.43315
7	– 16.16158	3.1383	– 0.34519
8	– 15.03989	2.57737	– 0.28382
9	– 14.20649	2.14118	– 0.23553
10	– 13.64156	1.82851	– 0.20101
11	– 13.26126	1.60326	– 0.17639
12	– 12.96479	1.41629	– 0.1557
13	– 12.75919	1.27432	– 0.14016
14	– 12.62833	1.1705	– 0.12912
15	– 12.4765	1.05481	– 0.11608
16	– 12.37305	0.96497	– 0.10616
17	– 12.31258	0.89712	– 0.09875
18	– 12.24943	0.82884	– 0.09113
19	– 12.19548	0.76602	– 0.08407
20	– 12.16014	0.71392	– 0.07827

has been concluded that the influence on excited-atom populations of these processes is dominant or comparable to the influence of electron–atom and electron–ion processes for $n \leq 8$ and the ionization degree of the considered plasma $\leq 10^{-3}$.

These results, as well as the papers Mihajlov & Dimitrijević (1986, 1992) etc., with the analysis of radiation ion–atom processes, suggested that the chemi-ionization processes (3) and (4) and the chemi-recombination processes (5) and (6) may have a significant influence on excited-atom populations in the weakly ionized plasma of stellar atmospheres. The importance of the hydrogen case for the corresponding layers in solar photosphere is examined and demonstrated in Mihajlov et al. (1997a, 2011, 2016), and for the helium case in the atmospheres of DB white dwarfs with $T_{\rm eff} = 12000-18000$K) in Mihajlov et al. (2003a, 2015, 2016). We note as well that in Mihajlov et al. (2003b, 2007), the chemi-ionization processes with $A = $ H(1s) have been included *ab initio* in the PHOENIX code (see Baron & Hauschildt 1998), in order to investigate their influence on the excited H atom populations, the electron density, and the profiles of H lines in the atmosphere of an M red dwarf with the effective temperature $T_{\rm eff} = 3800$ K. It has been shown that these processes with $n \leq 8$ have a strong influence on the population of excited states in H atom as well as to the electron density. Due to the change of electron density, the significant change of the profiles of H α, H δ, H ε, and Pa ε has been found.

3 THE CALCULATED QUANTITIES

3.1 The partial cross-sections, the rate coefficients, and branch coefficients of the chemi-ionization/ recombination processes

The partial cross-sections $\sigma_{ci}^{(a,b)}(n; E)$ of the chemi-ionization processes (3) and (4), i.e. associative and non-associative ionization channel are determined as in Mihajlov et al. (2011):

$$\sigma_{ci}^{(a,b)}(n, E) = 2\pi \int_0^{\rho_{max}^{(a,b)}(E)} P_{ci}^{(a,b)}(n, \rho, E)\rho \mathrm{d}\rho, \qquad (10)$$

where $\rho_{(1a,b)}^{max}(E)$ is the upper limit of the values of impact parameter ρ, and $P_{ci}^{(a,b)}(n, \rho, E)$ is the ionization probabilities explained in details in Mihajlov et al. (2011).

With the help of cross-sections $\sigma_{ci}^{(a,b)}(n; E)$, one can obtain the corresponding partial rate coefficients of the chemi-ionization processes (3) and (4), denoted here with $K_{ci}^{(a,b)}(n; T)$, where T is the temperature of the considered plasma. The partial rate coefficients of the inverse chemi-recombination processes (5) and (6) are denoted as $K_{cr}^{(a,b)}(n; T)$.

Using the partial, one can determine the total rate coefficients as

$$K_{ci,cr}(n, T) = K_{ci,cr}^{(a)}(n, T) + K_{ci,cr}^{(b)}(n, T), \qquad (11)$$

characterizing the efficiency of both considered processes together.

In Mihajlov et al. (2011), the processes (3), (4), (5), and (6) with $A = $ H have been considered for $2 \leq n \leq 8$. However, Netzer (1990) in section 4.3.2 underlined that in the broad-line clouds in AGN, many atoms are in excited states due to the high density and large optical depth. Also, it has been mentioned that in BLR clouds exist hydrogen atoms with $n \geq 10$, collisionally coupled to the continuum. Wills, Netzer & Wills (1985) and Dietrich et al. (2003) assumed for example, that higher order Balmer lines, are merging to a pseudocontinuum in QSO. Modelling the pseudocontinuum spectra in type 1 AGNs, Kovačević, Popović & Kollatschny (2014)

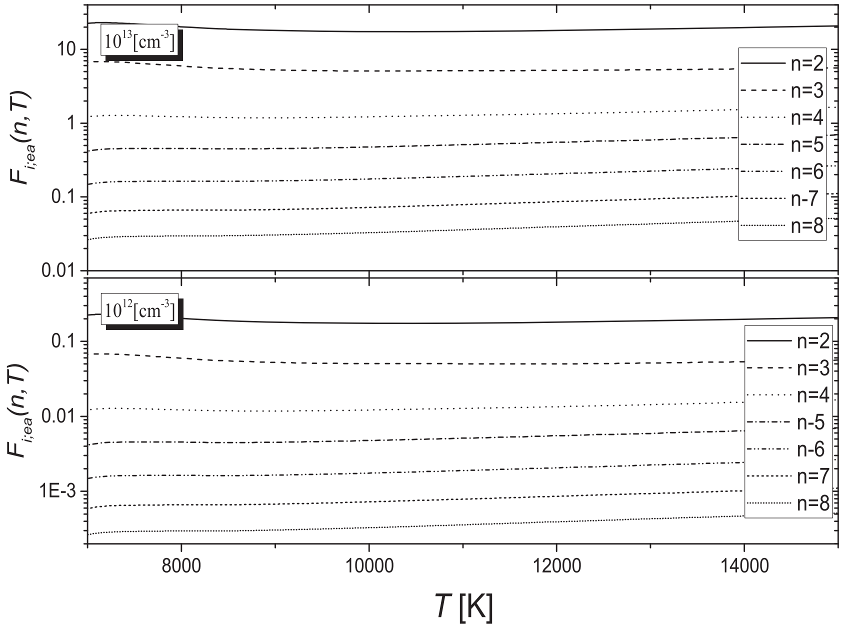

Figure 3. The plot of the quantity $F_{\rm i;ea}^{\rm (ab)}(n)$ equation (16), as a function of T and n, for the neutral hydrogen atom in the ground state densities $N_1 = 10^{12}$ and 10^{13} cm^{-3} and the electron density of 0.01 N_1.

have taken into account Balmer lines with the principal quantum number of the upper level up to 400. Consequently, in order to provide all relevant data for the investigation and modelling of BLR clouds, the above-mentioned processes will be considered here for n up to 20. The H atoms with $5 \le n \le 20$ and $2 \le n \le 4$ will be considered separately as in Mihajlov et al. (2011), due to the behaviour of the adiabatic potential curves of atom-atom systems $H^*(n) + H(1s)$. In fact, within the first region the atom-atom curves are for any R above the adiabatic curve of the ion-ion system $H^+ + H^-(1s^2)$ so that the dipole resonant mechanism is without any exceptions applicable for $n \ge 5$, so that for $n \ge 5$ the rate coefficients of these processes will be determined as in the previous papers (Mihajlov et al. 1997a, 2011).

In the region $n \le 4$ as in Mihajlov et al. (2011) we used the data from Janev, Langer & Evans (1987) to obtain the semi-empirical rate coefficients $K_{\rm cr,ci}^{\rm (a)}(n = 3, T)$ and $K_{\rm cr,ci}^{\rm (a)}(n = 4, T)$. For chemi-ionization/recombination processes with $n = 2$ the rate coefficients used by us are 10–30 per cent larger from the coefficients obtained with the help of data from Janev et al. (1987).

Relative contribution of associative and non-associative channels i.e. partial chemi-ionization and recombination processes for given n and T can be characterized by corresponding branch coefficients $X_{\rm ci}^{\rm (a,b)}(n, T)$, namely

$$X_{\rm ci}^{\rm (a,b)}(n, T) = \frac{K_{\rm ci}^{\rm (a,b)}(n, T)}{K_{\rm ci}(n, T)}, \quad X_{\rm cr}^{(a,b)}(n, T) = \frac{K_{\rm cr}^{\rm (a,b)}(n, T)}{K_{\rm cr}(n, T)}. \qquad (12)$$

Since $X_{\rm ci,cr}^{\rm (b)}(n, T) = 1 - X_{\rm ci,cr}^{\rm (a)}(n, T)$ and $X_{\rm ci}^{\rm (a,b)}(n, T) = X_{\rm cr}^{\rm (a,b)}(n, T) \equiv X^{\rm (a,b)}(n, T)$, it is enough to present only the values of one of the coefficients $X^{\rm (a,b)}(n, T)$.

4 RESULTS AND DISCUSSION

The values of the partial cross-sections $\sigma_{\rm ci}^{\rm (a,b)}(n; E)$ of the chemi-ionization processes (3) and (4) are determined for the principal quantum number $2 \le n \le 20$ and energies E up to 20 eV. This is illustrated by Figs 1(a) and 1(b) by surface plot. These data are very useful since according to Janev, Reiter & Samm (2003) cross-section data are not available at present for the non-associative ionization channel (4).

In Fig. 2, the comparison of collisional ionization rate coefficients for selected excited states is presented. The black lines are the data from the existing literature analysed in Barklem (2007) but only for non-associative channel (4), in the narrow parameter region ($T \le 10\,000$ K and $n \le 10$). The red lines are total rate coefficients obtained in this work for associative and non-associative channels (3) and (4). It is noticeable the present uncertainties on the rate coefficients due to hydrogen collisions in almost all cases as concluded in Barklem (2007). One can see the observable importance of associative channel in the region of lower temperatures (the red line is much higher than the full black line in the oval marked region). This provides important information about presence and abundance of molecular ion H_2^+. It is visible that the importance of associative channel decreases with the increase of temperature and, after some value, the second channel prevails (right-hand side of figure).

In Mihajlov et al. (2011), the values of the total chemi-ionization and recombination rate coefficients $K_{\rm ci}(n,T)$ and $K_{\rm cr}(n,T)$ and of the branching coefficient $X^{\rm (a)}(n,T)$ have been calculated for principal quantum number $2 \le n \le 8$ and $4000\,{\rm K} \le T \le 10\,000$ K. As can be seen from Table 1, in this work we extended the region of n and T ($T \ge 10\,000$ K for $n > 8$ and low-temperature region $T < 4000$ K for all analysed n, i.e. $2 \le n \le 20$) for both collisional ionization processes.

The values of the total chemi-ionization and recombination rate coefficients, $K_{\rm ci}(n,T)$ and $K_{\rm cr}(n,T)$, are shown in the corresponding tables (Tables 3–8) in the online version of this article. Here, in Table 1, only a sample of the results is provided in order to demonstrate the content of additional data and their form. These tables cover the regions $2 \le n \le 20$ and $3000\,{\rm K} \le T \le 20\,000$ K that are relevant for moderately ionized layers of very dense parts of clouds in the BLR region as well as for such layers in solar photosphere and photospheres of solar-like stars. Rate coefficients data for quantum numbers $n \le 8$ are presented here in the extended range of temperatures $T \ge 10\,000$ K and, for the first time, for quantum numbers $n > 8$ for $3000\,\mathrm{K} \le T \le 20\,000$ K. This enables the inclusion of these processes in the modelling not only of particular moderately ionized layers of the photospheres of the Sun and solar-like stars, but also of very dense parts of the clouds in AGN BLR region that could be used to confirm or exclude their existence.

Here, the values of the coefficient $X^{(a)}(n,T)$, which directly describe relative contributions of the associative ionization and dissociative recombination processes, are presented in Tables and in the online version of this article. One can see that associative channel is dominant for lower n and T. This provides important information about presence of molecular ion H_2^+. The importance of associative channel decreases with temperature increase when non-associative channel takes dominant place. It is also interesting to examine in detail the influence of charge exchange reactions of the type $A + H^+ = A^+ + H$ between metals (A) and proton since they can have large rate coefficients (Netzer 1990, section 4.3.5), in particular if metal is oxygen or nitrogen (Netzer 1990; Osterbrock & Ferland 2006). This can modify the influence of the non-associative channel since a part of created protons in the process (4) will become again H atoms due to charge exchange with metals.

In order to enable the better and more adequate use of data, we give for the rate coefficients a simple and accurate fitting formula based on a least-squares method, which is logarithmic and represented by a second-degree polynomial (Sahal-Bréchot et al. 2014):

$$\log(K_{\mathrm{ci}}(T)) = k_1 + k_2 \log(T) + k_3(\log(T))^2. \quad (13)$$

The fits are valid over the temperature range of $2000\,\mathrm{K} \le T \le 20\,000$ K. Also, it is possible that the fit is applicable outside this area but with caution. In the Table 2, the selected fits are presented (for $4 \le n \le 20$).

$I_{\mathrm{ci}}(n, T)$, $I_{\mathrm{cr}}(n, T)$ are the total chemi-ionization and chemi-recombination fluxes due to processes (3, 4) and (5, 6), i.e.

$$I_{\mathrm{ci}}(n, T) = K_{\mathrm{ci}}(n, T) \cdot N_n N_1,$$
$$I_{\mathrm{cr}}(n, T) = K_{\mathrm{cr}}(n, T) \cdot N_1 N_i N_e, \quad (14)$$

and $I_{\mathrm{i;ea}}(n,T)$, $I_{\mathrm{r;eei}}(n,T)$, and $I_{\mathrm{r;ph}}(n,T)$ are the fluxes for ionization and recombination processes (7), (8), and (9), i.e.

$$I_{\mathrm{i;ea}}(n, T) = K_{\mathrm{ea}}(n, T) \cdot N_n N_e,$$
$$I_{\mathrm{r;eei}}(n, T) = K_{\mathrm{eei}}(n, T) \cdot N_i N_e N_e,$$
$$I_{\mathrm{r;ph}}(n, T) = K_{\mathrm{ph}}(n, T) \cdot N_i N_e. \quad (15)$$

Here, N_1, N_n, N_i, and N_e are the densities of the ground and excited states of a hydrogen atom, of ion, and of free electron, for given T.

With the help of these relations, we calculated $F_{\mathrm{i,ea}}(n,T)$ that is given by the expression

$$F_{\mathrm{i,ea}}(n, T) = \frac{I_{\mathrm{ci}}(n, T)}{I_{\mathrm{i;ea}}(n, T)} = \frac{K_{\mathrm{ci}}(n, T)}{K_{\mathrm{ea}}(n, T)} \cdot N_1 N_e. \quad (16)$$

This quantity characterizes the relative efficiency of partial chemi-ionization processes (3) and (4) together and the impact of electron–atom ionization (7). The impact ionization rate coefficients $K_{\mathrm{ea}}(n,T)$ are taken as in Mihajlov et al. (2011). In Fig. 3, the behaviour of the quantities $F_{\mathrm{i,ea}}(n,T)$ (for $2 \le n \le 8$, the neutral hydrogen atom in the ground-state densities $N_1 = 10^{12}$ and 10^{13} cm^{-3} and the electron density of 0.01 N_1), as functions of temperature, is shown. One can see that the efficiency of the considered chemi-ionization processes compared to the electron–atom impact ionization increases with increasing temperature and N_1 density from 10^{12} to 10^{13} cm^{-3} when it become dominant for $2 \le n \le 5$ and comparable for $n = 6$, 7, and 8.

We can see as well that even around the value of $N_1 = 10^{12}$ cm^{-3} the inclusion of the considered chemi-ionization/recombination processes could improve the modelling and analysis of such regions not only in photospheres of the Sun and solar-like stars but also in clouds in AGN BLR. Additionally, Fig. 3 demonstrates as well the high sensitivity of the influence of these processes to the relatively small changes of N_1 that can be of interest for the determination of limiting N_1 densities in clouds in AGN BLR. The same conclusion goes for influence of the chemi-recombination processes (5) and (6) together on the same block of excited hydrogen atom states. Namely, the influence of analysed processes increases linearly with N, and, for example for $N = 10^{13}$ cm^{-3} some optical characteristics may be different than for $N = 10^{12}$ cm^{-3}, for example due to changes in energy level populations, electron density, influence on the formation of hydrogen molecule, opacity, line profiles etc. It will be very useful to perform an analysis for example with the code CLOUDY in order to see which changes in optical characteristics may be used in order to establish the presence of such dense layers.

The results show that the considered chemi-ionization/recombination processes could be used for determination of limiting high densities in clouds in AGN BLR region and for the improvement of modelling of dense moderately ionized layers in them. Of course, the presented values of the rate coefficients and branch coefficient are also very useful for the modelling and analysis of similar layers in the photospheres of the Sun and solar-like stars (Przybilla & Butler 2004a,b; Barklem 2007; Mashonkina 2009).

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Additional Supporting Information (Tables 3–8) may be found in the online version of this article. The tables are available in its entirety for $2 \le n \le 20$, and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$ in machine-readable form in the online journal as additional data.

Table 3. Calculated Values of Coefficient $K_{ci}[\mathrm{cm}^3\ \mathrm{s}^{-1}]$ as a function of n and T ($2 \le n \le 10$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

Table 4. Calculated Values of Coefficient $K_{ci}[\mathrm{cm}^3\ \mathrm{s}^{-1}]$ as a function of n and T ($11 \le n \le 20$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

Table 5. Calculated Values of Coefficient $K_{cr}[\mathrm{cm}^3\ \mathrm{s}^{-1}]$ as a function of n and T ($2 \le n \le 10$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

Table 6. Calculated Values of Coefficient $K_{cr}[\mathrm{cm}^3\ \mathrm{s}^{-1}]$ as a function of n and T ($11 \le n \le 20$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

Table 7. Calculated Values of Branch Coefficient $X^{(a)}$ equation (12) as a Function of n and T ($2 \le n \le 10$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

Table 8. Calculated Values of Branch Coefficient $X^{(a)}$ equation (12) as a function of n and T ($11 \le n \le 20$ and $3000\,\mathrm{K} \le T \le 20\,000\,\mathrm{K}$).

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Free–free absorption coefficients and Gaunt factors for dense hydrogen-like stellar plasma

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ABSTRACT

In this work, we present a study dedicated to determination of the inverse bremsstrahlung absorption coefficients and the corresponding Gaunt factor of dense hydrogen-like stellar-atmosphere plasmas where electron density and temperature change in a wide range. A method suitable for this wide range is suggested and applied to the inner layers of the solar atmosphere, as well as the plasmas of partially ionized layers of some other stellar atmospheres (for example, some DA and DB white dwarfs) where the electron densities vary from 10^{14} cm^{-3} to 10^{20} cm^{-3} and temperatures from 6000 K to 300 000 K in the wavelength region of 10 nm $\leq \lambda \leq$ 3000 nm. The results of the calculations are illustrated by the corresponding figures and tables.

Key words: atomic processes – Sun: atmosphere – stars: atmospheres – white dwarfs.

1 INTRODUCTION

Although, of all the plasma internal absorption processes, we have so far considered only ion–atom radiative ones, we are aware of the need to consider other possible absorption processes too. Namely, some of them must be treated as concurrent to the ones that we have studied, and others warrant our attention for more diverse reasons. One such kind of process is that of electron–ion bremsstrahlung, which, by its very nature, suggests its importance, as its efficiency increases proportionally to the square of the free-electron density. Anyone interested in these processes must be fascinated by the amount of works about them. Indeed, so much has been done in this field that any new work should contain a very important result. However, we believe that for some time now we have had results of significant importance; we mean the possibility of determining the spectral characteristics of inverse bremsstrahlung (absorption coefficients and Gaunt factors) in the same way in a wide range of electron densities and temperatures. We note that some preliminary results have been presented at the X Serbian Conference on Spectral Line Shapes in Astrophysics (Mihajlov, Srećković & Sakan 2015), in order to inform other researchers of the potential possibilities existing in the field of inverse bremsstrahlung processes.

The aims of this work require determination of the corresponding spectral absorption coefficients for the inverse bremsstrahlung process and the corresponding Gaunt factors for a broad class of weakly non-ideal plasmas, as well as for plasmas of higher non-ideality. It is shown that this process can be successfully described in the frame of the cut-off Coulomb potential model within the range of the physical parameters that cover the area important for modelling astrophysical plasma (white dwarfs, solar atmospheres, etc). The physical sense and the properties of a group screening parameter for two-component systems that are used in this paper are discussed in detail in our previous papers (Mihajlov, Vitel & Ignjatović 2009a,b). This method for describing the electrostatic screening in two-component systems is applicable to systems of higher non-ideality degree. On the basis of data from the above-mentioned papers are determined new characteristic lengths that complete a new system of screening lengths in plasma. This topic itself, the discussion and search for more consistent models of screening and more realistic potentials in plasmas is still continuing and is very current (see Mihajlov et al. 2009b; Demura 2010, and references therein).

For the sake of further considerations, we will introduce some designations that are used below: E and E': respectively, the energies of the initial and final states of the electron–ion system (absorber); $\varepsilon_{\rm ph}$: the energy of the absorbed photon and $\hbar k$: its impulse; $\hbar q$: the impulse of the electron in its initial state; and m, e: respectively, the mass of the electron and the modulus of its charge.

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2 NECESSARY THEORETICAL REMARKS

2.1 The potential and electrostatic screening model

In Mihajlov et al. (2015) the significance of the model potential used in this paper was emphasized. One of the model Coulomb screening potentials, known as the cut-off potential, had already been introduced in Suchy (1964), and had been investigated in connection with the transport plasma properties in Mihajlov et al. (1986). This potential is given by

$$U(r) = \begin{cases} -\dfrac{e^2}{r} + \dfrac{e^2}{r_{\rm cut}} & 0 < r \le r_{\rm cut} \\ 0 & r_{\rm cut} < r, \end{cases} \quad (1)$$

where r is the distance from the coordinate origin and $r_{\rm cut}$ is a parameter defined and determined further on in the text.

This is the model, illustrated by Fig. 1, used in this work. Let us note that in Mihajlov et al. (2011) the universality of the screening model did not arise at all. However, in the case of the electron–ion inverse bremsstrahlung process, which is possible in plasmas with enormous differences in electron densities and temperature, the situation is the other way round. Namely, in this case we have to start from the inner plasma electrostatic screening model of any considered system and to solve the problem of its applicability. For that purpose we will first consider the models used in the papers that exist in the literature (Hazak et al. 2002; Armstrong et al. 2014; van Hoof et al. 2014).

One can see that the electron–ion scattering is treated in those models as scattering of the electron upon the adequate Debye potential. This fact is a serious handicap of the mentioned models, as was discussed in our previous papers.

This is caused by the fact that the Debye potential is defined as a potential of the observed ion and the entirety of its surrounding as a function of the distance from the ion, and can be used only for determination of its average potential energy in the observed plasma. Because of this, in Mihajlov et al. (2011) the model of the inner plasma screening was applied for the first time. Fig. 1 implies that in this screening model the potential energy of the free electron $U_{\rm scr.}(r)$ is of a strictly Coulomb nature: $U_{\rm scr.}(r) = -e^2/r$ in the region $r < r_{\rm cut}$, where $r_{\rm cut}$ is the corresponding cut-off radius, and $U_{\rm scr.}(r) = {\rm const} = U_{\rm cut}$ in the region $r > r_{\rm cut}$, where $U_{\rm cut}$ is equal to the average energy of the free electron in the considered system. In further consideration of this, we take $U_{\rm cut} = -e^2/r_{\rm cut}$ as the zero of the energy and describe such plasma just by means of the model cut-off potential given by equation (1), which is especially suitable for describing electron–ion scattering within plasma. Certainly, we assume that the above-described electrostatic screening model could be applicable in such a wide range of electron densities and temperatures that this allows one to consider it as an almost universal model. For that very reason the cut-off potential equation (1) could also be considered as almost universal.

2.2 Transformation of the dipole moments

It is only after an explanation of the universality of the potential equation 1 that the procedures gain importance for the determination of inverse bremsstrahlung processes as characteristic spectral absorption coefficients, Gaunt factors, and the possibility of improvement of these procedures.

As the first improvement, for the inverse bremsstrahlung cross-section $\sigma^{\rm (ex)}_{\rm i.b.}$, the standard expressions from Sobelman (1979) will be used here, since the potential equation (1) has a finite radius.

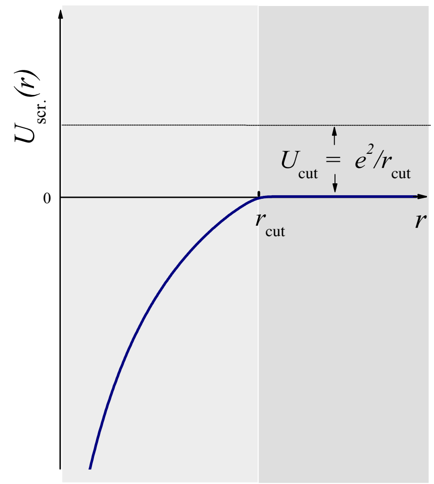

Figure 1. Behaviour of the potential $U_{\rm scr.}(r)$, where $r_{\rm cut}$ is the cut-off parameter presented in equations (6) and (7).

Consequently,

$$\sigma^{\rm (ex)}_{\rm i.b.}(E;E') = \frac{8\pi^4}{3}\frac{\hbar e^2 k}{q^2}\sum_{l'=l\pm1} l_{\max}|\hat{D}_{E,l;E'l'}|^2,$$

$$\hat{D}_{E,l;E'l'} = \int_0^\infty P_{E';l'}(r)\cdot r\cdot P_{E;l}(r){\rm d}r, \quad (2)$$

where $l_{\max}$ is defined in section 2.4, the radial functions $P_{E;\,l}(r)$ and $P_{E';l'}(r)$ are the solutions of the radial Schrödinger equation

$$\frac{{\rm d}^2 P_{E;l}(r)}{{\rm d}r^2} + \left[\frac{2m}{\hbar^2}(E - U(r)) - \frac{l(l+1)}{r^2}\right]P_{E;l}(r) = 0, \quad (3)$$

and $U(r)$ is the cut-off Coulomb potential given by equation (1). The radial functions $P_{E;\,l}(r)$ of all states that are possible in the potential $U(r)$ are described and discussed by Mihajlov et al. (1986). As the next step, using the transformation characteristics of the matrix element of the solutions $P_{E;\,l}(r)$ we will replace the dipole matrix element $\hat{D}_{E,l;E'l'}$ in equation 2 by the matrix element of the gradient of the potential energy $U(r)$. This procedure is described by the expressions

$$|\hat{D}(r)_{E,l;E'l'}|^2 = \frac{\hbar^4}{m^2\left(E - E'\right)^4}|\nabla U_{E,l;E'l'}|^2, \quad (4)$$

$$\nabla_r U_{E,l;E'l'} = \int_0^{r_{\rm cut}} P_{E,l}(r)\cdot\nabla_r U(r)\cdot P_{E'l'}(r){\rm d}r, \quad (5)$$

where $U(r)$ is given by equation (1).

It is known that the transition from the dipole matrix element $\hat{D}_{E,l;E'l'}$ to the dipole matrix element $\nabla_r U_{E,l;E'l'}$ in principle does not mean much. However, in the case of $U(r)$, which is given by equation (1), it means a transition from determination of the quantity $\hat{D}_{E,l;E'l'}$, which cannot be factually calculated, to determination of a quantity that can be calculated routinely. Namely, in the case of this potential the integral of two functions of the Coulomb continuum from 0 to ∞ gets replaced by the integral of the same two functions, but from 0 to $r_{\rm cut}$.

2.3 Determination of the cut-off radius

In order to complete the described model we have to determine the cut-off parameter $r_{\rm cut}$ and the energy parameter $U_{\rm cut}$ as functions of the electron density N_e and the temperature T. Here we will

Table 1. Values of the Gaunt factor for $N_e = 1 \times 10^{17}$ [cm^{-3}] as a function of wavelength λ and temperature T. The tables are available in their entirety for 10^{14} cm^{-3} to 10^{20} cm^{-3} and temperatures from 6000 K to 300 000 K in the wavelength region of 10 nm ≤ λ ≤ 3000 nm in machine-readable form in the online journal as additional data. A portion is shown here for guidance regarding their form and content.

λ [*nm*]/T [K]	10 000	20 000	40 000	50 000	100 000	150 000	200 000	250 000	300 000
10	1.084E+00	1.101E+00	1.121E+00	1.133E+00	1.207E+00	1.244E+00	1.291E+00	1.341E+00	1.415E+00
100	1.088E+00	1.104E+00	1.166E+00	1.217E+00	1.588E+00	1.813E+00	2.053E+00	2.303E+00	2.562E+00
200	1.093E+00	1.151E+00	1.402E+00	1.565E+00	2.522E+00	3.053E+00	3.609E+00	4.185E+00	4.778E+00
500	1.167E+00	1.512E+00	2.425E+00	2.932E+00	5.769E+00	7.322E+00	8.940E+00	1.061E+01	1.233E+01
1000	1.469E+00	2.340E+00	4.401E+00	5.533E+00	1.182E+01	1.524E+01	1.877E+01	2.240E+01	2.611E+01
1500	1.845E+00	3.251E+00	6.532E+00	8.330E+00	1.825E+01	2.359E+01	2.908E+01	3.469E+01	4.039E+01
2000	2.251E+00	4.207E+00	8.762E+00	1.125E+01	2.486E+01	3.213E+01	3.957E+01	4.715E+01	5.484E+01
2500	2.675E+00	5.197E+00	1.106E+01	1.424E+01	3.157E+01	4.075E+01	5.014E+01	5.968E+01	6.934E+01
3000	3.110E+00	6.216E+00	1.339E+01	1.729E+01	3.833E+01	4.942E+01	6.074E+01	7.223E+01	8.385E+01

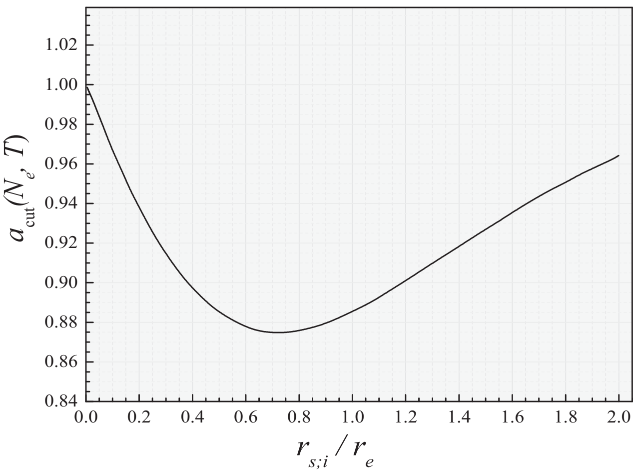

Figure 2. Behaviour of the parameters $a_{\rm cut} = r_{\rm cut}/r_e$ as a function of the ratio $r_{s;\,i}/r_e$, where r_e is given by equation (6) and $r_{s;\,i}$ is the ion Wigner–Seitz radius for the considered electron–ion plasma. The presented curve is obtained on the basis of data presented in Mihajlov et al. (2009a).

use the fact that these parameters can be determined by means of Fig. 2, which is obtained using the data from Mihajlov et al. (2009a). Namely, the curve presented in Fig. 2 shows the behaviour of the parameter $a_{\rm cut} = r_{\rm cut}/r_e$ as a function of the ratio $r_{s;\,i}/r_e$, where r_e and the ion Wigner–Seitz radius $r_{s;\,i}$ are given by the relations

$$r_{s;i} = \left[\frac{3}{4\pi N_i}\right]^{1/3}, \quad r_e = \left[\frac{kT}{4\pi N_e e^2}\right]^{1/2}, \tag{6}$$

where N_i is the ion density. After that the cut-off radius $r_{\rm cut}$ is determined here as a function of N_e, T by means of the relation

$$r_{\rm cut} = a_{\rm cut} \cdot r_e, \tag{7}$$

where the parameter $a_{\rm cut}$ can be directly determined from Fig. 2. The procedure for the determination of $a_{\rm cut}$ is to calculate the ratio $r_{s;\,i}/r_e$ (by equation 6) for the required values of plasma parameters (electron density and temperature) and to directly obtain (download) the y values on the curve in Fig. 2 for the known x value.

2.4 The numerical procedure

The numerical procedure consists of two important elements. The *first element* refers to the way of determining $P_{E;\,l}(r)$ in the area $r > r_{\rm cut}$. As known, the necessary solution of equation 3 is given by superposition of the spherical Bessel functions, i.e. $C_1 j_n(z) + C_2 y_n(z)$, where $j_n(z)$ and $y_n(z)$ are spherical Bessel functions of the first and second kinds and they are of the nth order. However, here is used the fact that these functions are expressed over the Coulomb functions $F_l(0, \frac{\sqrt{2mE}}{\hbar} r)$ and $G_l(0, \frac{\sqrt{2mE}}{\hbar} r)$ by means of the relations (see e.g. Gough 2009) $j_L(\rho) = \rho^{-1} F_L(0, \rho)$ and $y_L(\rho) = -\rho^{-1} G_L(0, \rho)$, where $G_L(0, \rho)$ is the Coulomb function that is irregular at the coordinate origin. In accordance with that, the necessary radial function $P_{E;\,l}(r)$ in the case $r > r_{\rm cut}$ is used here in the form

$$P_{E;l}(r) = C_N^c \left\{ C_F F_l\left(0, \frac{\sqrt{2mE}}{\hbar} r\right) + C_G G_l \left(0, \frac{\sqrt{2mE}}{\hbar} r\right)\right\}, \tag{8}$$

where C_N^c is the normalization constant and C_F and C_G are the constants that provide the behaviour of the solution according to the convergent value for infinite radii. In such a way, we have fully standardized the expressions for the necessary (continual) radial solutions of equation (3).

The *second element* of the numerical procedure refers to the method of summing in equation 2 for the inverse bremsstrahlung cross-section $\sigma^{\rm (ex)}_{\rm i.b.}(E; E')$. After a detailed investigation, the following method of summation is chosen: the sum goes over l' from 0 to $l_{\rm max}$ with no need for initial checking of the convergence, and for $l' > l_{\rm max}$ the sum is checked for convergence, e.g. when l' is greater than $l_{\rm max}$ the Cauchy criteria for the convergence test is applied since it is expected that the sum monotonically converges towards the limit value. The behaviour of the sum after reaching the limiting value $l_{\rm max}$ was examined and convergence is proved in the limiting series of $r_{\rm cut}$, when the cut-off radius converges towards infinity $r_{\rm cut} \to \infty$. To determine the start of the checking boundary we use $l_{\rm max} = \lfloor l^* \rfloor + 1$ where l^* is determined from the relation $\frac{\hbar^2 \cdot l(l+1)}{2mr^2_{\rm cut}} = E$ From here, keeping in mind that $l(l+1) = (l+1/2)^2 - 1/4$, we get the boundary value l^* in the form $l^* = 0.5 \cdot (\sqrt{1 + 8 \cdot \frac{2mE}{\hbar^2} r^2_{\rm cut}} - 1)$. It has been shown that summing over l in the region $l > l_{\rm max}$ ends very quickly, so that the total number of summands is not much greater than $l_{\rm max}$. Such behaviour of the sum is proof of a well defined $l_{\rm max}$ boundary. After these improvements we could use the possibilities provided by the universality of the electrostatic screening model that we used and finally perform extensive calculations of the inverse bremsstrahlung characteristics that could be the basis for creation of the corresponding data base.

3 THE CALCULATED QUANTITIES

We consider here plasmas with electron densities from 10^{14} cm^{-3} to $1 \cdot 10^{20}$ cm^{-3} and temperatures from 6000 K to 300 000 K. In

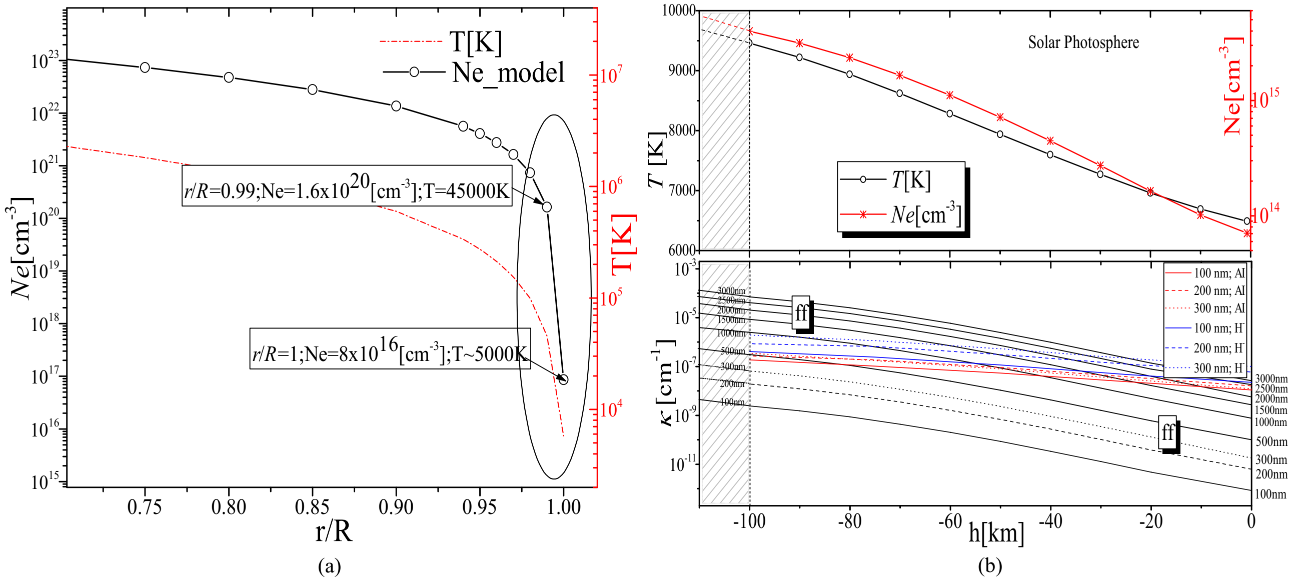

Figure 3. (a) Electron density and temperature in the interior of the Sun as a function of radius for the Standard Solar Models (Bahcall, Serenelli & Basu 2006). (b) Upper panel: behaviour of the temperature T and N_e as a function of height h within the considered part of the solar atmosphere model of Fontenla, Balasubramaniam & Harder (2007). Lower panel: plots of the absorption coefficients (equation (9)) of the absorption processes considered for the case of a solar atmosphere model from Fontenla et al. (2007). Black lines denote free–free (ff) absorption processes, i.e. inverse bremsstrahlung absorption coefficients, blue electron–atom and red ion–atom absorption coefficients (Ignjatović et al. 2014; Srećković et al. 2014). The extrapolated values are in the left shaded region in front of the dashed line.

accordance with Mihajlov et al. (1993) and Adamyan et al. (1994), for such conditions we find that, for the electron component, treated as an appropriate electron gas on a positively charged background, the value of the chemical potential is practically equal to the classical one, so that the distribution function for electrons is Maxwellian $f_T(v) = 4\pi(m/2\pi kT)^{3/2}v^2 \mathrm{e}^{-mv^2/2kT}$, for a given temperature T. Consequently,

$$\kappa_{\mathrm{i.b.}}^{(\mathrm{ex})}(\varepsilon_\lambda; N_e, T) = N_e^2 \cdot \int_0^\infty \sigma_{\mathrm{i.b.}}^{(\mathrm{ex})}(E; E')v \cdot f_T(v)dv \cdot \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \quad (9)$$

where the expression in parentheses takes into account the effect of stimulated emission. Additionally, we take the quasi-classical Kramer's $k_{\mathrm{i.b.}}^{\mathrm{q.c.}}(\lambda, T; Ne)$ (see e.g. Sobelman 1979) as

$$k_{\mathrm{i.b.}}^{\mathrm{q.c.}}(\lambda, T; Ne) = N_e^2 \cdot \frac{16\pi^{5/2}\sqrt{2}e^6}{3\sqrt{3}cm^{3/2}\varepsilon_{\mathrm{ph}}^3} \frac{\hbar^2}{(kT)^{1/2}} \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \quad (10)$$

where $\varepsilon_{\mathrm{ph}} = 2\pi\hbar c/\lambda$, and the averaged Gaunt factor $G_{\mathrm{i.b.}}(\lambda, T)$ is

$$k_{\mathrm{i.b.}}^{(\mathrm{ex})}(\lambda, T; N_e) = k_{\mathrm{i.b.}}^{\mathrm{q.c.}}(\lambda, T; N_e) \cdot G_{\mathrm{i.b.}}(\lambda, T), \quad (11)$$

where $k_{\mathrm{i.b.}}^{(\mathrm{ex})}(\lambda, T; Ne)$ and $k_{\mathrm{i.b.}}^{\mathrm{q.c.}}(\lambda, T; Ne)$ are given by equations (9) and (10).

4 RESULTS AND DISCUSSION

The contribution of inverse bremsstrahlung to the total absorption in stellar atmospheres is not so important, but its contribution increases with density, and for very dense plasmas it becomes dominant. For example, Grinenko & Gericke (2009) stated that inverse bremsstrahlung is the dominant absorption mechanism for lasers with parameters typical for inertial confinement fusion. Plasma in inertial confinement fusion experiments has properties that are similar to the conditions in stellar interiors. Consequently, it is of interest to investigate the role of inverse bremsstrahlung in subphotospheric and deeper layers, and to examine its influence on radiative transfer through such layers.

In addition to other factors that determine the importance of inverse bremsstrahlung, we should bear in mind the existence of a physical area where inverse bremsstrahlung is dominant compared to other processes. The examples that demonstrate this can be found in the literature (Rozsnyai 2001; Grinenko & Gericke 2009). Moreover, we expect a major contribution to the inverse bremsstrahlung process in a dense highly ionized plasma (see e.g. Fig. 3(a), the marked region of r) in the process of transfer of radiation. Here we mean the high electron density and temperature that occur in the interior of the Sun, which are in Fig. 3(a) presented as a function of radius (Standard Solar Models, Bahcall et al. 2006).

In the lower panel in Fig. 3(b), the plot of each absorption coefficient of the considered absorption processes for the case of a solar atmosphere model from Fontenla et al. (2007) is shown as a function of height for various values of wavelengths. Here h is the height of the considered layer with respect to the chosen reference one. The corresponding plasma parameters are presented in the upper panel of Fig. 3(b). The electron–atom processes that are sometimes treated as the H^- continuum. With AI, i.e. κ_{ai}, atom–ion symmetric and non-symmetric processes (Ignjatović et al. 2014; Srećković et al. 2014) are represented. From this figure one can see that the inverse bremsstrahlung absorption coefficients are comparable with the concurrent ones, especially in the region of higher electron density and temperature $h \leq -70$ km (left-hand part of Fig. 3(b)). Consequently, we can conclude that the influence of the inverse bremsstrahlung process increases with temperature and density.

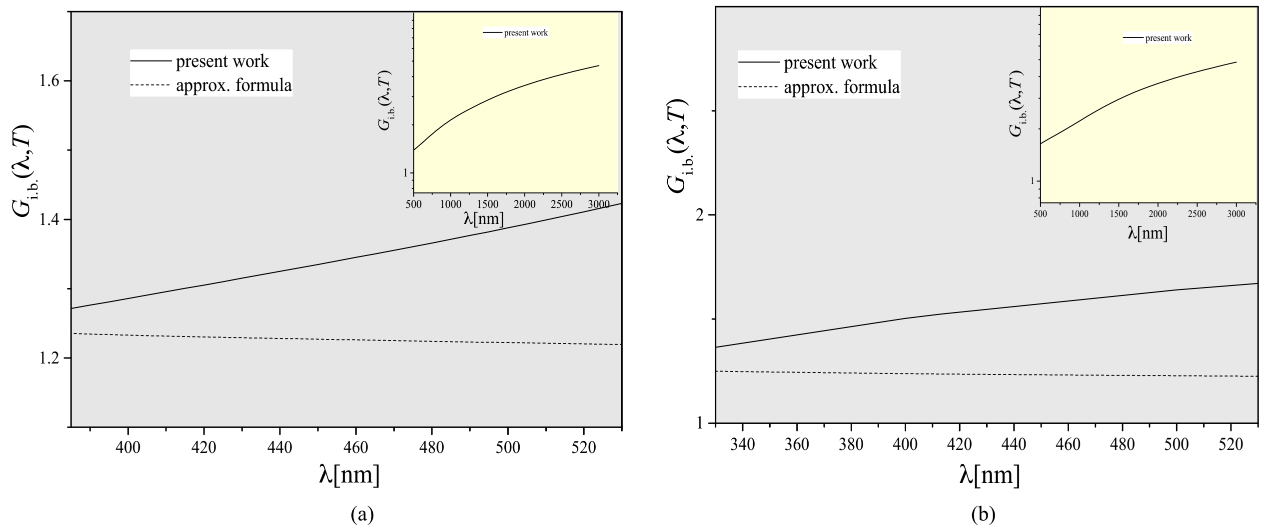

Figure 4. (a) Dynamics of the Gaunt factor data from this work (equation (11)) and data obtained by the approximation formula (D'yachkov 1990) for the electron density $N_e = 6.5 \cdot 10^{18}\,\mathrm{cm}^{-3}$ and temperature $T = 18\,000$ K (from Vitel et al. 2004; Mihajlov et al. 2011). (b) Behaviour of the mean Gaunt factor data from this work and data obtained by the approximation formula (D'yachkov 1990) for the electron density $N_e = 1.5 \cdot 10^{19}\,\mathrm{cm}^{-3}$ and $T = 23\,000$ K (from Vitel et al. 2004; Mihajlov et al. 2011).

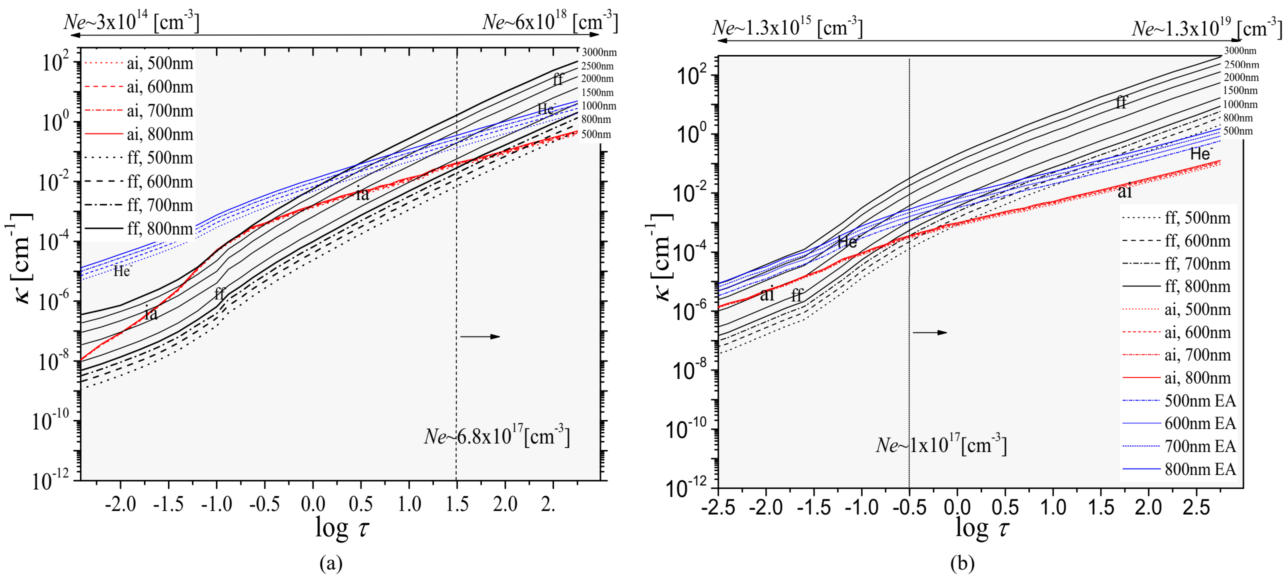

Figure 5. (a) Plots of the absorption coefficients (equation (9)) of the considered absorption processes for the case of a DB white dwarf with $T_{\mathrm{eff}} = 12\,000$ K and $\log g = 8$ as functions of $\log \tau$, where τ is the Rosseland optical depth. (b) Plots of the absorption coefficients (equation (9)) of the considered absorption processes for the case of a DB white dwarf with $T_{\mathrm{eff}} = 16\,000$ K and $\log g = 8$ as functions of $\log \tau$, where τ is the Rosseland optical depth. Black lines denote ff absorption processes, i.e. inverse bremsstrahlung absorption coefficients, blue concurrent electron–atom (EA) processes (He^- continuum) and red concurrent ion–atom absorption coefficients (ai).

The behaviour of the Gaunt factor in the area of higher parameters of non-ideality is shown in Figs 4(a) and (b). In these figures are presented the dynamics of the Gaunt factor for the electron density $N_e = 6.5 \cdot 10^{18}\,\mathrm{cm}^{-3}$ and temperature $T = 18\,000$ K as well as for $N_e = 1.5 \cdot 10^{19}\,\mathrm{cm}^{-3}$ and $T = 23\,000$ K (parameters obtained in the experiment by Vitel et al. 2004; Mihajlov et al. 2011). The data from this work are marked by solid lines and data obtained by the use of the approximation formula (D'yachkov 1990) by the dashed line. The insets show the data from this work but in a wider wavelength region. One can notice that there is an evident difference between the data presented here and data obtained by the use of the approximation formula (D'yachkov 1990). These differences are affected by the principal differences in the way of describing the electron–ion scattering in the rest of the plasma (see Mihajlov et al. 2009a). It is understood that some of these results may be useful for further laboratory plasma investigations.

Good conditions for studying the impact of the increase of electron density and temperature on the inverse bremsstrahlung contribution is provided by plasmas of white dwarf atmospheres. This is illustrated in Figs 5(a) and (b), where the plots of the considered absorption processes, including the inverse bremsstrahlung processes, are shown for the case of a DB white dwarf with $\log g = 8$, $T_{\mathrm{eff}} = 12\,000$ K and $T_{\mathrm{eff}} = 16\,000$ K from the atmosphere model of Koester (2015, private communication). The electron–atom processes (He^- continuum), are represented in these figures by blue lines marked by EA (κ_{EA}). ai, i.e. κ_{ai}, represents atom–ion symmetric and non-symmetric processes. From these figures one can see that the inverse bremsstrahlung absorption coefficients are comparable with concurrent ones, especially in the region of higher electron density (the parts of Figs 5(a) and (b) marked with arrows). Finally, within the considered DB white dwarf atmospheres, the investigated radiative processes strongly influence the atmosphere's opacity, especially for the cases of white dwarf atmospheres with larger effective temperature, i.e. higher electron densities and temperatures.

Concerning the accuracy, a number of factors may affect it. First, we discuss the screening parameters. It is likely that such a change in the screening length will affect the accuracy. Since the method that is used here is applicable to systems of higher non-ideality degree, its use is limited to certain areas of plasma temperatures and densities. For plasmas with low non-ideality (i.e. low density and high temperature) or plasmas with extreme non-ideality with the coupling parameter Γ much greater than 1 (high density and very low temperature), this approach is not capable of providing high accuracy (here $\Gamma = e^2/(akT)$ and $a = (3/4\pi N_e)^{1/3}$). Finally, we are also able to notice that the data are highly sensitive to changes in temperature.

To summarize, the presented exact quantum-mechanical method is used to obtain the spectral coefficients for the inverse bremsstrahlung process and the corresponding Gaunt factors for a broad class of moderately non-ideal plasmas, as well as for plasmas of higher non-ideality. The range of the physical parameters covers the area important for plasma modelling from an astrophysical standpoint (white dwarfs, central stars of planetary nebulae, etc). For this purpose, calculation of the Gaunt factors in a wide region of wavelengths for series of electron densities and plasma temperatures was done. The results of the calculations are illustrated by the corresponding tables in the online version of this article (table for every N_e and T taken).

Further directions in the development of the method would be determination of absorption coefficients and Gaunt factors for two-component systems (ions with an arbitrary charge Z and electron component) as well as for three-component systems.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Additional Supporting Information (tables) may be found in the online version of this article. The tables are available in their entirety for 10^{14} cm^{-3} to 10^{20} cm^{-3} and temperatures from 6000 K to 300 000 K in the wavelength region of 10 nm $\leq \lambda \leq$ 3000 nm in machine-readable form in the online journal as additional data.

Table 1. This table gives values of the Gaunt factor for $N_e = 1 \times 10^{17}$ [cm^{-3}] for temperatures 10 000 K $\leq T \leq$ 300 000 K in the wavelength region 10 nm $\leq \lambda \leq$ 3000 nm.

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Atom–Rydberg-atom chemi-ionization processes in solar and DB white-dwarf atmospheres in the presence of ($n - n'$)-mixing channels

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ABSTRACT

In this paper, the rate coefficients of the chemi-ionization processes in H(1s) + H*(n, l) and He(1s^2) + He*(n, l) collisions (where the principal quantum number $n \gg 1$) are determined for the first time, taking into account the influence of the corresponding ($n - n'$)-mixing processes. It is demonstrated that the inclusion of ($n - n'$) mixing in the calculation influences the values of chemi-ionization rate coefficients significantly, particularly in the lower part of the block of Rydberg states. The interpretation of this influence is based on two existing methods of describing inelastic processes in symmetrical atom–Rydberg-atom collisions. The calculations of the chemi-ionization rate coefficients are performed for the temperature region that is characteristic of solar and DB white-dwarf atmospheres.

Key words: atomic processes – molecular processes – Sun: atmosphere – Sun: photosphere – stars: atmospheres – white dwarfs.

1 INTRODUCTION

Our main aim in this paper is to consider of two types of atomic collision processes, which occur simultaneously in stellar atmospheres and have an influence on one another. This is about the chemi-ionization processes

$$A^*(n,l) + A \Longrightarrow \mathrm{e} + A + A^+, \tag{1a}$$

$$A^*(n,l) + A \Longrightarrow \mathrm{e} + A_2^+, \tag{1b}$$

and the ($n - n'$)-mixing excitation–de-excitation processes

$$A^*(n,l) + A \Longrightarrow A + A^*(n',l), \tag{2}$$

where A and A^+ are atoms and their positive ions in their ground states, $A^*(n,l)$ is the atom in a highly excited (Rydberg) state with the principal quantum number $n \gg 1$ and orbital quantum number l, A_2^+ is the corresponding molecular ion in the ground electronic state, and e is a free electron. In this paper, we consider the most significant astrophysical cases A = H and A = He.

Because the history of the investigations of the processes (1) and (2) and the current state of this body of literature have recently been presented in Mihajlov et al. (2012), only the articles directly connected to the material of this work will be cited here. Until now, these processes have always been considered separately, although both processes are caused by the same mechanism. Here we consider the dipole resonant mechanism, which has been described in the literature several times and has been discussed in detail in the review paper Mihajlov et al. (2012). For the first time, in this paper, we consider the chemi-ionization processes (1) in the presence of ($n - n'$)-mixing processes.

Fig. 1 illustrates the above-mentioned dipole resonant mechanism as a resonant energy exchange within the electronic component of the collision system $A^*(n,l) + A$: the transition of the subsystem $A + A^+$, from the excited electronic state with the energy $U_2(R)$ to the ground electronic state with the energy $U_1(R)$ (long arrow pointing downward), is followed by the simultaneous transition of the Rydberg electron from the initial bound state with energy $\epsilon_n < 0$ to the free state with the energy $\varepsilon(k)$, under the resonance condition, $U_2(R) - U_1(R) = \varepsilon(k) - \varepsilon(n, l)$ (long arrow pointing upward). Similarly, in the case of ($n - n'$)-mixing, the same mechanism causes transitions of the subsystem $A + A^+$, between the excited and ground electronic states (in the domain of larger R), together with transitions of the Rydberg electron from the state with energy $\varepsilon(n, l)$ to the states $\varepsilon(n', l')$, where $n' \neq n$. These transitions are illustrated in Fig. 1 with the corresponding short arrows.

As we can see from Fig. 1, the atomic collision that we consider proceeds in accordance with the excited molecular term $U_2(R)$.

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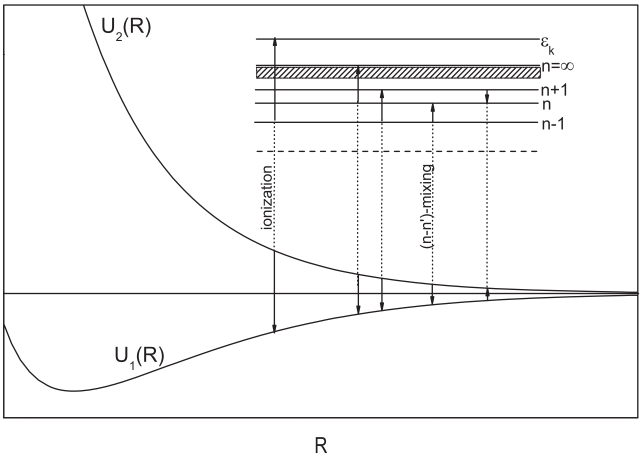

Figure 1. Schematic illustration of the resonant transitions that cause the processes (1) and (2).

Before it enters the zone where the chemi-ionization processes (1) are possible, the system $A^*(n, l) + A$ passes through the zone where the processes (2) take place. Because of this, a way to include processes (2) in the calculation of the rate coefficients of the chemi-ionization processes (1) is developed in this paper.

The processes (1) are characterized by the partial rate coefficients, which are a function of quantum numbers n and l as well as a function of plasma temperature T. In this work, these rate coefficients are calculated in the cases of both hydrogen and helium, for $3 \le n \le 15$. Bearing in mind the application of the results obtained here to the photosphere of the Sun and to some DB white dwarfs, the averaged rate coefficients are determined in the corresponding temperature ranges: for $4000 \le T \le 10\,000$ K in the case of hydrogen, and for $7000 \le T \le 24\,000$ K in the case of helium.

The values of chemi-ionization rate coefficients obtained here are compared with the corresponding values of the rate coefficients determined earlier, for the same atmospheres, in Mihajlov et al. (2003a, 2011a), where $(n - n')$-mixing processes were not taken into account. In the paper, all expressions are given in atomic units. As a final note, the presented material consists of five tables in the supporting material.

2 THEORY

2.1 Description and general formulae

Let $K_A^{\mathrm{a}}(n, l; T)$ and $K_A^{\mathrm{b}}(n, l; T)$ be the partial rate coefficients of processes (1a) and (1b) determined separately for given n, l and T, and let $K_A^{\mathrm{ab}}(n, l; T)$ be the total rate coefficient of processes (1) defined by

$$K_A^{\mathrm{ab}}(n, l; T) = K_A^{\mathrm{a}}(n, l; T) + K_A^{\mathrm{b}}(n, l; T). \tag{3}$$

The rate coefficients $K_A^{\mathrm{ab}}(n, l; T)$ and $K_A^{\mathrm{b}}(n, l; T)$ are determined on the basis of standard expressions

$$K_A^{\mathrm{ab}}(n, l; T) = \int_{E_{n;i}}^{\infty} \sigma_A^{\mathrm{ab}}(n, l; E)\sqrt{\frac{2E}{m_{\mathrm{red}}}}\, f_T(E)\,\mathrm{d}E, \tag{4}$$

$$K_A^{\mathrm{b}}(n, l; T) = \int_{E_{n;i}}^{\infty} \sigma_A^{\mathrm{b}}(n, l; E)\sqrt{\frac{2E}{m_{\mathrm{red}}}}\, f_T(E)\,\mathrm{d}E, \tag{5}$$

where E is impact energy, $\sigma_A^{\mathrm{ab}}(n, l; E)$ and $\sigma_A^{\mathrm{b}}(n, l; E)$ are the corresponding cross-sections, m_{red} is the reduced mass of the subsystem $A + A^+$ and $f_T(E)$ is the Maxwell distribution function, $f_T(E) = \exp(-E/kT)\sqrt{E}$. The parameter $E_{n;i}$ is given here by the relation $E_{n;i} = U_2(R_{n;i})$ where $R_{n;i}$ is the upper limit of the chemi-ionization zone, defined as the root of the equation

$$U_{12}(R) \equiv U_2(R) - U_1(R) = \frac{1}{2n^2}. \tag{6}$$

The above-mentioned cross-sections are determined here within the semi-classical approximation, by means of the standard expressions

$$\sigma_A^{\mathrm{ab}}(n, l; E) = 2\pi \int_0^{\rho_{\max;A}^{\mathrm{ab}}} P_A^{\mathrm{ab}}(n, l; \rho; E)\rho\,\mathrm{d}\rho,$$

$$\sigma_A^{\mathrm{b}}(n, l; E) = 2\pi \int_0^{\rho_{\max;A}^{\mathrm{b}}} P_A^{\mathrm{b}}(n, l; \rho; E)\rho\,\mathrm{d}\rho \tag{7}$$

where ρ is the impact parameter, $\rho_{\max;A}^{\mathrm{ab}}$ and $\rho_{\max;A}^{\mathrm{b}}$ are its corresponding maximal values of this parameter, and $P_A^{\mathrm{ab}}(n, l; \rho; E)$ and $P_A^{\mathrm{b}}(n, l; \rho; E)$ are the total probability of chemi-ionization and the probability of associative ionization, respectively, determined for the given values of n, l, ρ and E. These probabilities are taken here in the forms

$$P_A^{\mathrm{ab}}(n, l; \rho; E) = \frac{1}{2} p_0(n, l; \rho; E) p_{i;A}^{\mathrm{ab}}(n, l; \rho; E) \tag{8}$$

and

$$P_A^{\mathrm{b}}(n, l; \rho; E) = \frac{1}{2} p_0(n, l; \rho; E) p_{i;A}^{\mathrm{b}}(n, l; \rho; E), \tag{9}$$

where $1/2$ is the probability that the subsystem $A + A^+$ develops according to the term $U_2(R)$. The quantity $p_0(n,\ l;\ \rho;\ E)$ is the probability that in the domain of values of R where the processes (2) with $n' > n$ are possible, the mentioned subsystem remains in the same electronic state with the energy $U_2(R)$. Finally, $p_{i;A}^{\mathrm{ab}}(n, l; \rho; E)$ and $p_{i;A}^{\mathrm{b}}(n, l; \rho; E)$ are the corresponding ionization probabilities determined under the condition that the subsystem $\mathrm{H}(1\mathrm{s}) + \mathrm{H}^+$ or $\mathrm{He}(1\mathrm{s}^2) + \mathrm{He}^+(1\mathrm{s})$ enters in the ionization zone in the mentioned state with a probability equal to one.

Now, we determine the average total rate coefficient

$$K_A(n, T) = \frac{1}{n^2}\sum_{l=0}^{n-1}(2l + 1)K_A^{\mathrm{ab}}(n, l; T), \tag{10}$$

as well as the average rate coefficient of the associative ionization $K_A^{\mathrm{b}}(n, T)$ given by

$$K_A^{\mathrm{b}}(n, T) = \frac{1}{n^2}\sum_{l=0}^{n-1}(2l + 1)K_A^{\mathrm{b}}(n, l; T), \tag{11}$$

(e.g. Ryabtsev et al. 2005; Golubkov & Devdariani 2011; O'Keeffe et al. 2012). The efficiency of associative ionization is characterized by the corresponding branch coefficients

$$X_A^{\mathrm{b}}(n; T) = \frac{K_A^{\mathrm{b}}(n; T)}{K_A(n, T)}. \tag{12}$$

2.2 Ionization decay: the probability

The probabilities $p_{i;1}^{\mathrm{ab}}(n, l; \rho; E)$ and $p_{i;1}^{\mathrm{b}}(n, l; \rho; E)$ are determined here within the quasi-static approximation. These probabilities are taken in the form (Mihajlov et al. 2007, 2011a,b)

$$p_{i;A}^{\mathrm{ab}}(n, l; \rho; E) = 1 - \mathrm{e}^{-2q_{i;A}^{\mathrm{I}}},$$

$$p_{i;A}^{\mathrm{b}}(n, l; \rho; E) = \mathrm{e}^{-q_{i;A}^{\mathrm{II}}}[1 - \mathrm{e}^{-2q_{ias;A}}]. \tag{13}$$

The variables $q^{\rm I}_{i;A}$, $q^{\rm II}_{i;A}$ and $q_{ias;A}$ are given by expressions

$$q_{ias;A} = q^{\rm I}_{i;A} - q^{\rm II}_{i;A},$$
$$q^{\rm I}_{i;A} = \int_{R_0}^{R_{n;i}} \frac{W_i(n,l;R)}{\upsilon_{\rm rad}(E,\rho;R)}\,{\rm d}R,$$
$$q^{\rm II}_{i;A} = \int_{R^{\rm b}_{A;\max}}^{R_{n;i}} \frac{W_i(n,l;R)}{\upsilon_{\rm rad}(E,\rho;R)}\,{\rm d}R, \qquad (14)$$

where the rate coefficients of ionization decay $W_i(n, l; R)$ and radial ion–atom velocity $\upsilon_{\rm rad}(E, \rho; R)$ are given by expressions

$$W_i(n,l;R) = \frac{1}{2\pi}\, c\, U^3_{12}(R) D^2_{12}(R) \sigma_{\rm ph.i}(n,l,\varepsilon_{\rm ph}),$$
$$\upsilon_{\rm rad}(E,\rho;R) = \sqrt{\frac{2}{m_{\rm red}}\left[E - U_2(R) - \frac{E\rho^2}{R^2}\right]}. \qquad (15)$$

In these expressions, c is the speed of light, $D_{12} = |<1|\widehat{d}_{m.i}|2>|$ is the molecular-ion dipole matrix element, $\sigma_{\rm ph.i}(n,\ l,\ \varepsilon_{\rm ph})$ is the cross-section for photoionization of excited hydrogen atom $H^*(n, l)$ or helium atom $He^*(n, l)$ by a photon with energy $\varepsilon_{\rm ph} = U_{12}(R)$. In the expression for the dipole matrix element, $\hat{d}$ denotes the operator of the corresponding ion dipole momentum where $|1>$, $|2>$ denote the ground and first excited state of this ion.

In equation (14), R_0 is the lower limit of the domain R that is reached during the collision with a given ρ and E, and $R^{\rm b}_{1,2;{\rm man}}$ denotes the upper limit of the domain R where only the process of associative ionization (1b) is possible. Thus, the parameters R_0 here represent the roots of the equation $U_2(R) = E(1 - \rho^2/R^2)$, and $R^{\rm b}_{A;\max}$ represents the root of the equation $U_{12}(R) = E$. Let us note that in expressions (13) and (14) it is assumed that $R^{\rm b}_{A;\max} < R_{n;i}$. In the case of $R^{\rm b}_{A;\max} > R_{n;i}$ we have the quantity $q^{\rm II}_{i;A} = 0$ and $q_{ias} = q^{\rm I}_{i;A}$.

Here, we draw attention to the fact that at this point there is already a difference from the previous works of Mihajlov et al. (2007, 2011a,b) concerning the chemi-ionization processes in stellar atmospheres. There, the chemi-ionization rate coefficients were determined with the average ionization decay rate, obtained by averaging the partial rates over the whole shell with given n. This makes it possible to use the Kramers photoionization cross-section averaged over the shell adjusted by means of the approximate Gaunt factor. In contrast, here the rate coefficients $K^{\rm ab}_A(n, l; T)$ and $K^{\rm b}_A(n, l; T)$ were determined on the basis of equations (4) and (5) using the partial cross-sections for photoionization, determined here on the basis of the exact expressions from Sobelman (1979).

2.3 Pre-ionization decay: the probability

We can see from equations (8) and (9) that the basic difference from the previous papers is that we directly take into account the effect of the decay of the initial electronic state of the considered atom–Rydberg-atom system, because of the possibility of the occurrence of excitation processes (2) with $n' > n$. This is done by introducing the probability of maintenance of this state $p_0(n, l; \rho; E)$. This probability is determined through a modified version of the approximate method described in Mihajlov et al. (2004) dedicated to the $(n - n')$-mixing processes. Note that the essence of this method is that, at given n, each block of Rydberg states from $n' = n + p_1$ to $n' = n + p_2$ is spreading in a part of the quasi-continuum limited by the values $n + p_1 - \delta_n$ and $n + p_2 + 1 - \delta_n$, where the parameters δ_n are determined from the condition of maintenance of the total number of states and total oscillator strengths for transitions from the initial state of Rydberg electron to all states of the separated block (see Fig. 2).

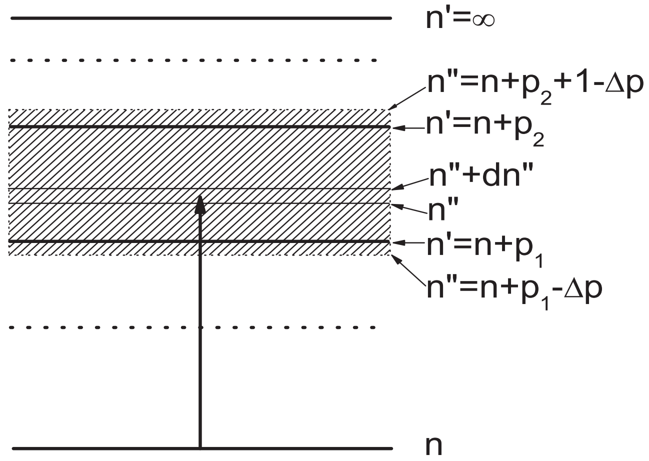

Figure 2. A diagram showing the partial spreading of the discrete Coulomb spectre into the continuum.

This modification is conditioned by the fact that in Mihajlov et al. (2004) an approximate average rate was used for the transition of the Rydberg electron of the considered system from a whole shell with the given n to a whole shell with $n' = n + p$, where $p \geq 1$. In contrast, here we must consider transitions of the Rydberg electron from an individual state $|n, l>$ to individual states $|n + p, l - 1>$ and $|n + p, l + 1>$. Note that this difference does not affect the size of the pre-ionization zone. Therefore, similarly to Mihajlov et al. (2004), we accept that the pre-ionization zone generally forms the domain of internuclear distances such that

$$R_{n;i} < R < R_{n;n+1-\delta_n}, \qquad (16)$$

where $\delta_n = 0.5 \times [1 - (1/3) \times O(1/n)]$. Note that, here and later in the paper, $R_{n;n'}$, where $n' > n$ means the root of the equation

$$U_{12}(R) = 0.5 \times [1/n^2 - 1/n'^2]. \qquad (17)$$

Finally, in Mihajlov et al. (2004), it was taken that the domains of R corresponding to the partial transitions with $p > 1$ make up the intervals $(R_{n;n+p-\delta_n}, R_{n;n+p-1-\delta_n})$. However, with the method used here, it is taken that the domain of R corresponding to a partial transition with $p > 1$ in the general case only belongs to the mentioned intervals, and does not coincide with them.

In this paper, we take into account the transitions with $1 \leq p \leq 5$. Therefore, the probability $p_0(n, l; \rho; E)$ could be represented as

$$p_0(n,l;\rho;E) = \prod_{p=1}^{5} p_{p;0}(n,l;\rho;E), \qquad (18)$$

where $p_{p;0}(n,\ l;\ \rho;\ E)$ is the probability of the maintenance of the initial state of the system remaining within the interval $(R_{n;n+p+1-\delta_n}, R_{n;n+p-\delta_n})$.

Because the mechanism of the pre-ionization decay is the same as the one for the ionization, we assume that probabilities $p_{p;0}(n, l; \rho; E)$ are given by the relations

$$p_{p;0}(n,l;\rho;E) = {\rm e}^{-x_p},$$
$$x_p = \int_{R_{n;n+p+1-\delta_n}}^{R_p} \frac{w_{n;n+p}(n,l:R)}{\upsilon_{\rm rad}(E,\rho,R)}. \qquad (19)$$

Here, the decay rate $w_{n;n+p}(n,\ l;\ R)$ is conditioned by the dipole mechanism within the interval $(R_{n;n+p+1-\delta_n}, R_{n;n+p-\delta_n})$. The upper limit is $R_p = R_{n;n+p-\delta_n}$ if $R_{n;n+p-\delta_n} \le R_{up;\mathrm{mix}}(E, \rho)$ and $R_p = R_{up;\mathrm{mix}}(E, \rho)$ if $R_{n;n+p-\delta_n} > R_{up;\mathrm{mix}}(E, \rho) \ge R_{n;n+p}$, where the resonant distance is $R_{n;n+p}$ for the process (2) at given n and $n' = n + p$. This distance is determined as the root of the equation, $U_{12}(R) = 0.5 \times [1/n^2 - 1/(n+p)^2]$. The meaning of parameter $R_{up;\mathrm{mix}}(E, \rho)$ is discussed separately later in Section 2.3.1. Let us point out that here, when $R_{up;\mathrm{mix}}(E, \rho) < R_{n;n+p}$ is considered, $p_{p;0}(n, l; \rho; E) = 0$. Thus, the decay rate $w_{n;n+p}(n, l; R)$ is given here by the relations

$$w_{n;n+p}(n, l; R) = \frac{2\pi}{3} U_{12}^4(R_{n;n+p}) \widetilde{n}^3 D_{12}^2 r_{n,l;n+p}^2,$$

$$\widetilde{n} = n[1 - 2n^2 U_{12}(R)]^{-1/2}, \tag{20}$$

where $r_{n,l;n+p}^2 = | < n, l|\hat{d}_{at}|n, l-1 > |^2 + | < n, l|\hat{d}_{at}|n, l+1 > |^2$, $\hat{d}_{at}$ is the operator of the dipole moment of the hydrogen atom, and $|n, l >$, $|n, l-1 >$ and $|n, l+1 >$ denote the corresponding states of the Rydberg electron.

2.3.1 *The parameter* $R_{up;\mathrm{mix}}$

The characteristic length $R_{up;\mathrm{mix}}$ is defined here as the upper limit of the domain R where at given E and ρ we can consider that the inner electron is in the subsystems $H^+ + H(1s)$ and $He^+(1s) + He(1s^2)$ and that it is sufficiently delocalized, so that these subsystems can be treated as quasi-molecular complexes. As a qualitative characteristic of the mentioned delocalization, we take here the probability of resonant charge exchange $P_{\mathrm{c.exc}}(R; E; \rho)$ in the mentioned subsystems as a function of R at given ρ and E. The basis for this is found in the theory of the resonant charge exchange of the processes in the symmetric ion–atom collisions, developed in Firsov (1951) and Bates & Boyd (1962).

From this theory, it follows that

$$P_{\mathrm{c.exc}}(R; E; \rho) = \sin^2[\varphi(R; E; \rho)], \tag{21}$$

where the phase $\varphi(R; E; \rho)$ is given by the relation

$$\varphi(R; E; \rho) = \frac{1}{2} \int_R^\infty \frac{U_{12}(R')}{\upsilon_{\mathrm{rad}}(R', \rho, E)} \mathrm{d}R'. \tag{22}$$

This can be used in the case considered because $P_{\mathrm{c.exc}}(R; E; \rho)$ becomes noticeably different from zero only deeply inside the orbit of the Rydberg electron at given n. Taking into account data from Firsov (1951) and Bates & Boyd (1962), we can consider that when $P_{\mathrm{c.exc}}(R; E; \rho)$ reaches the value of $1/2\pi$, the corresponding R can be treated as the upper limit of the charge exchange zone at given ρ and E, and thus as the upper limit of the domain with a sufficient degree of delocalization of the electron in the subsystems $H^+ + H(1s)$ and $He^+(1s) + He(1s^2)$. Consequently, the parameter $R_{up;\mathrm{mix}}$ is determined here as the root of the equation

$$\sin^2[\varphi(R; E; \rho)] = \frac{1}{2\pi}, \tag{23}$$

where $\varphi(R; E; \rho)$ is given by equation (22) under the condition that this root is in the domain of monotonic increase of the left-hand side of equation (23).

The behaviour of the phase $\varphi(R; E; \rho)$ in the hydrogen and helium cases is illustrated in Table 1 in the supporting material, where its values for $E = E_{n;i}$, $\rho = 0$ and $R = R_{n;n+1}$ within the range $3 \le n \le 15$ are shown. Note that the values for the helium case in Table 1 are connected with the excited states of the $He^*(n, l)$ atom with $l > 0$. Of course, these data should be treated as the qualitative data as equations (21) and (22) make strict sense when $E \gg U_{12}(R)$, while in the hydrogen case this condition is fulfilled only for $n > 7$ and for helium.

3 RESULTS AND DISCUSSION

From the above presented material, it follows that the total average rate coefficients of the processes (1) as well as the rate coefficients for the associative ionization (1b), $K_A(n; T)$ and $K_A^{\mathrm{b}}(n; T)$, are determined by means of equations (3)–(20). Note that the chemi-ionization processes (1) can be described on the basis of the dipole resonant mechanism only in the case of a state with $n \ge 5$, for which the potential curves of the system $H^*(n, l) + H(1s)$ lie above the potential curve of the system $H^+ + H^-(1s^2)$, where $H^-(1s^2)$ is the stable negative hydrogen ion. However, it can be shown that the points of the intersection of the potential curves of the system $H^*(n, l)$+ H(1s) with $n = 3$ and 4 with the potential curve of the system $H^+ + H^-(1s^2)$ are located at internuclear distances, which are several times larger than the average atomic radius $H^*(n, l)$. Therefore, the existence of these intersections cannot significantly affect the values of the corresponding rate coefficients of the processes (1a). From this aspect, the application of the dipole resonant mechanism can be completely justified in the case of states with $n = 3$ and 4.

In Tables 2 and 4 in the supporting material, the values are presented of the total average rate coefficients of chemi-ionization processes in the hydrogen and helium cases $K_{\mathrm{H}}(n; T)$ and $K_{\mathrm{He}}(n; T)$ within the range $3 \le n \le 15$. Bearing in mind that the main applications of the results obtained here are to the photosphere and lower chromosphere of the Sun (hydrogen case) and to the corresponding parts of the atmospheres of DB white dwarfs (helium case), the calculations of these rate coefficients were performed here for temperatures $4000 \le T \le 10\,000$ K in Table 2 and $7000 \le T \le 24\,000$ K in Table 4. The values of the corresponding branch coefficients $X_A^{\mathrm{b}}(n; T)$ for the same n and T are presented in the supporting material in Tables 3 and 5. In accordance with the above, the rate coefficients have been calculated by summing the probability of the decay of the initial state of the collisional system in the pre-ionization zone with the Rydberg electron's transitions from a state $|n >$ to a state $|n + p >$, where $1 \le p \le 5$.

To allow an estimation of significance of the changes introduced by this work to the method of determining the rate coefficients of the considered chemi-ionization processes and to allow a comparison with the method from Mihajlov et al. (2003a, 2011a), not only are the values of the total rate coefficient $K_A(n; T)$ determined here, but also the values of the rate coefficient $K_A^*(n; T)$. This is obtained if we take $p_0(n, l; \rho; E) = 0$, where $p_0(n, l; \rho; E)$ is the total probability of the pre-ionization decay, given by equations (18)–(20). All these quantities are presented in Fig. 3 for the hydrogen case and $T = 5000$ K and in Fig. 4 for the helium case and $T = 10\,000$ K. We can see from these figures that there are considerable differences between the values of the rate coefficients determined in Mihajlov et al. (2003a, 2011a) and the values $K_A^*(n; T)$, while the differences with respect to the rate coefficients $K_A(n; T)$ are very large for $n \le 6$ and decrease quickly with the increase of n in the area $n > 6$. This is a consequence of the way of $K_A^*(n; T)$ is detemined without the simplifications in the previous papers.

In the above-mentioned works Mihajlov et al. (2003b) and Mihajlov et al. (2007), related to the photosphere of an M red dwarf with a temperature close to 4000 K, it has been shown that only the chemi-ionization processes (1a) and (1b) with $4 \le n \le 8$ influence strongly the populations of hydrogenic Rydberg states in this photosphere, as well as its other characteristics. It is clear that, even for this reason alone, it is crucial and necessary to take into account the changes of the rate coefficients of these processes, which, according to our results, are particularly large for $n \le 6$.

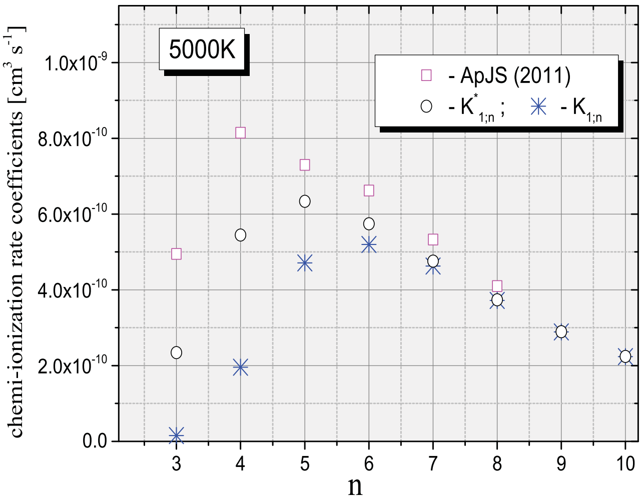

Figure 3. Comparison of the calculated values of rate coefficients of the chemi-ionization processes (1a) and (1b) with the data from Mihajlov et al. (2011a).

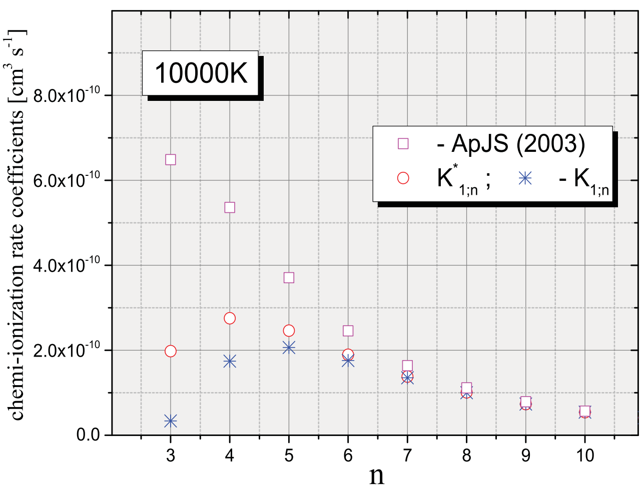

Figure 4. Comparison of the calculated values of rate coefficients of the chemi-ionization processes (1a) and (1b) with the data from Mihajlov et al. (2003a).

From the presented material, we can see that it is also very important to further investigate the properties of decay of the initial state of the collision system $H^*(n, l) + H(1s)$ or $He^*(n, l) + He(1s^2)$ in the pre-ionization zone. Additionally, the results obtained here suggest that the rate coefficients of the chemi-ionization processes (1) could be affected also through other channels of influence by the processes (2), by which we mean the processes of $(n - n')$ mixing, taking place in two or more steps.

In order to show the importance of the investigated chemi-ionization processes, we compared their efficiencies with the efficiencies of the relevant concurrent processes, that is, electron–Rydberg-atom impact ionization

$$H^*(n) + e \rightarrow H^+ + e + e, \tag{24}$$

in the hydrogen case and

$$He^*(n) + e \rightarrow He^+ + e + e, \tag{25}$$

in the helium case, which are treated in the same range of principal quantum numbers.

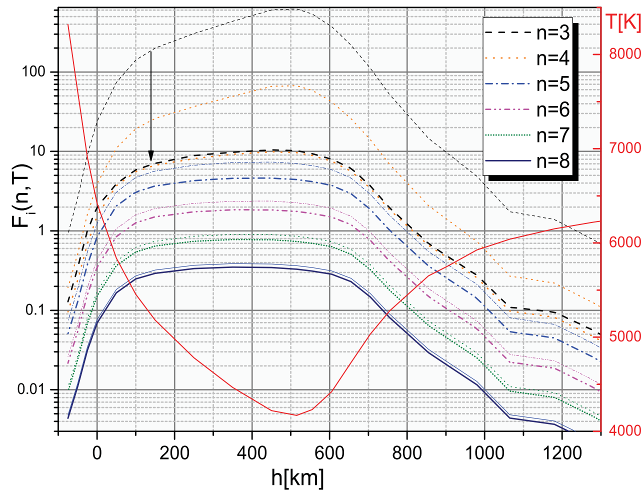

Figure 5. Parameter $F_i[n, T; H^*(n)]$ as a function of the height h, for principal quantum numbers $n = 3$–8, for a model of the solar photosphere (Vernazza, Avrett & Loeser 1981); the wider bold lines denote present calculations, and the fainter lines denote calculations from Mihajlov et al. (2003a).

Fluxes generated in atom–Rydberg-atom and electron–excited-atom impact ionization are denoted by $I_A^{aa}(T; A^*)$ and $I_A^{ea}(T; A^*)$ and given by the expressions

$$I_A^{aa}(T; A^*) = K_A(n, T; A^*) N(A^*) N(A), \tag{26}$$

$$I_A^{ea}(T; A^*) = \alpha_A^{ea}(n, T; A^*) N(A^*) N(e), \tag{27}$$

where $A^* = H^*(n)$ or $He^*(n)$, the rate coefficient $K_A(n, T; A^*)$ is given by equation (10) and the ionization rate coefficient $\alpha_A^{ea}(n, T; A^*)$ is determined by means of semi-empirical expressions from Vriens & Smeets (1980).

The relative importance of the chemi-ionization processes in comparison with electron–excited-atom impact ionization can be characterized by parameters $F_A(n, T)$ defined as $F_A(n, T) = I_A^{aa}(T; A^*)/I_A^{ea}(T; A^*)$. According to equations (26) and (27) we have

$$F_A(n, T; A^*) = \frac{K_A(n, T; A^*)}{\alpha_A^{ea}(n, T; A^*)} \frac{N(A)}{N(e)}. \tag{28}$$

Illustrative calculations were carried out for the photosphere of the Sun, for the hydrogen case, and for some DB white dwarfs with $\log g = 8$ and the temperatures $T_{\rm eff} = 12\,000$ K for the case of helium.

Figs 6 and 5 show the results of these calculations (wider bold lines) as well as the results of our previous work presented in Mihajlov et al. (2003a, 2011a) (fainter lines). As we can see, the influence of processes (2) decreases with the increase of n, and for $n > 10$ it practically does not exist. With the increase of temperature, the influence of chemi-ionization processes decreases, which is manifested in Figs 6 and 5. These parameters are shown as functions of height h for the case of the solar photosphere, and of $\log(\tau)$ for DB white dwarfs, where τ is the Rosseland optical depth. Temperatures and atom and electron densities necessary to determine $F_A[n, T; A^*(n)]$ have been taken from DB white-dwarf models (Koester, private communication) and in the case of the solar photosphere from Vernazza et al. (1981).

Our results show that for lower temperatures the chemi-ionization processes are still dominant over electron–excited-atom ionization processes, for $n = 3$, 4 and 6 almost in the whole observed

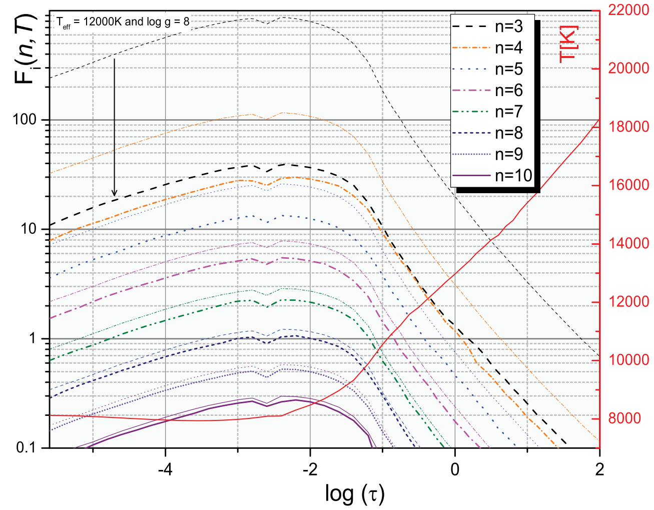

Figure 6. Parameter $F_i[n, T; \mathrm{He}^*(n)]$ as a function of the logarithm of Rosseland optical depth $\log(\tau)$, for principal quantum numbers n = 3–10, with $T_{\rm eff}$ = 12 000 K and $\log g$ = 8; the wider bold lines denote present calculations, and the fainter lines denote calculation from Mihajlov et al. (2011a).

atmosphere, as illustrated by Figs 6 and 5. For n = 6, 7 and 8 and in the whole observed atmosphere, chemi-ionization processes are comparable with electron–excited-atom ionization processes. This is illustrated in Fig. 6, where $T_{\rm eff}$ = 12 000 K in the helium case, and in Fig. 5 for hydrogen. The behaviour of the curves in these figures indicates the effective temperature range where it is particularly important to take into account the studied processes.

4 CONCLUSIONS

From the presented material, it is shown that the processes of $(n - n')$-mixing (2) have considerable influence on the rates of chemi-ionization processes (1). Direct calculations have been performed, which show this influence on the quantitative level. The results obtained here are presented in tabular form as supporting material, where the values of total constants for rates of the processes (1), and also just the rates for the process of associative ionization (1b) for the hydrogen and helium cases are presented. Tables 2 and 4 (provided as supporting information) cover the range of values of principal quantum numbers of the Rydberg states of hydrogen and helium atoms from n = 3 to n = 15 and the temperature range from T = 4000 K to T = 10 000 K and T = 7000 K to T = 24 000 K respectively, so that they can be directly applied in connection with the modelling of the photosphere and the lower chromosphere of the Sun and the atmosphere of DB white dwarfs. The obtained results show that the efficiency of the chemi-ionization processes, in spite of the influence of $(n - n')$-mixing processes (2) with $n' > n$ in most parts of the photosphere of the Sun and most parts of white-dwarf atmospheres, remains dominant or at least comparable to the efficiency of the concurrent processes (24) and (25). Note that the presented results point to further directions of the investigation of the influence of $(n - n')$-mixing processes on the chemi-ionization processes. Principally, this means taking into consideration the processes (2) with $n' < n$ (i.e. processes that take place in several steps).

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THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Diagnostics of plasma in the ionospheric D-region: detection and study of different ionospheric disturbance types*

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Abstract. Here we discuss our recent investigations of the ionospheric plasma by using very low and low frequency (VLF/LF) radio waves. We give a review of how to detect different low ionospheric reactions (sudden ionospheric disturbances) to various terrestrial and extra-terrestrial events, show their classification according to intensity and time duration, and present some methods for their detections in time and frequency domains. Investigations of detection in time domain are carried out for intensive long-lasting perturbations induced by solar X-ray flares and for short-lasting perturbations caused by gamma ray bursts. We also analyze time variations of signals used in the low ionospheric monitoring after earthquake events. In addition, we describe a procedure for the detection of acoustic and gravity waves from the VLF/LF signal analysis in frequency domain. The research of the low ionospheric plasma is based on data collected by the VLF/LF receivers located in Belgrade, Serbia.

1 Introduction

The ionosphere is the part of the atmosphere located between about 50 km and 1000 km where the charged particles significantly influence its physical and chemical properties [1,2]. For this reason the study of plasma properties and all processes with a focus on charged particle production plays a crucial role in its understanding. In addition to scientific importance [3–5], studies of the ionospheric plasma and the dynamics of perturbations induced therein can, for example, be of great practical significance in fields related to telecommunications [6] and may also contribute to a better insight into features related to elementary disasters like earthquakes [7].

The ionosphere being a part of the terrestrial outer layer is constantly exposed to many influences coming from the outer space in addition to those occurring in the Earth's layers which all affect its dynamics [8–10]. Consequently, the physical properties of the atmosphere (density, temperature, etc.) are time and space dependent [11,12] which justifies the use of monitoring variations of atmospheric parameters for indirect detection of different phenomena both of cosmic and terrestrial origin [13–15].

Generally, the phenomena that affect the local environment cause different reactions of its constituents. These responses vary in intensity, duration and location of the perturbation, which requires application of various observational setups and techniques for their detection. Some of the most important measurement characteristics are the distance between the experimental setup and observed area, observed altitude range, time resolution and sensitivity. Based on this, one can divide the observation methods in various ways:

- Based on distance between the experimental setup and observed area. There are two types of atmospheric monitoring: in situ (by rockets and satellites/space probes) and remote sensing (by satellites, radars, ionosondes, very low and low frequency (VLF/LF) emitters and receivers). In the first case, the instruments are placed at the location that is being observed while the remote sensing observations are based on detection of signals emitted by transmitters located at some distance away from the receivers and the area which is being monitored. Data obtained by remote sensing techniques are less precise than those by in situ measurements but they cover a significantly broader observational area.
- Based on the observed altitude range. Thus, LIDAR (Light Detection and Ranging) [16] is used for observations of the atmosphere at altitudes of a few kilometers, balloons are enforceable for measurements at about 30 km [17] while radar, rocket, and measurements by radio signals [18–21] can be used for observations of the ionosphere.

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– Based on time resolution, taking advantage from the fact that the duration times of phenomena can be very different. For example, some disturbances, such as those caused by lightnings, gamma ray bursts (GRBs) [22] and meteor passings through the atmosphere [23] can last up to several ms while phenomena like solar X-ray flares, coronal mass ejections, and hurricane events can perturb part of the atmosphere for periods lasting tens of minutes, hours, or days. For this reason the time resolution of the received data must be adapted to the duration time of the observed phenomenon.
– Based on sensitivity, which is particularly important in the case of weak perturbations. In addition to instrument characteristics it depends on the area where signals propagate (length of the signal propagation path and plasma medium properties).

In this paper we focus our research on the lower ionosphere located between 50 km and 90 km where the dominant source of ionization under unperturbed conditions comes from the solar Lyα radiation (above about 70 km at daytime) which induces formation of the D-region, and cosmic rays (at nighttime and below about 70 km at daytime). Variations in intensity of these radiations as well as the increase of incoming X and gamma radiation fluxes in the atmosphere, induction of different types of waves, and changes in the atmospheric electric conductivity cause sudden changes in the ionospheric plasma properties. The sources of these sudden ionospheric disturbances (SIDs) have extraterrestrial and terrestrial origins. The most important SIDs result from solar X-ray flares and lightnings while influence of other noticed phenomena like GRBs rarely induce very significant SIDs. These perturbations have various properties reflected in their duration and intensity which can further be used for their classification.

The aim of the paper is to present methods of SID detection and their differences depending on causing events (terrestrial and extra-terrestrial) based on time and frequency domain analysis. We point out the importance of certain characteristics of the low ionosphere monitoring in study of its non-periodic, local, short-term, and weak reactions. Keeping in mind that SIDs can be classified according to their duration time as short-term (like in the case of lightning occurrence) and long-term (like in the case of some solar influences), and based on intensity to strong (e.g. induced by solar X-ray flares) and weak (e.g. due to GRBs), we classify the relevant procedures for extraction of SIDs. This kind of investigation is important for further analyses of characteristics of plasma parameters such as electron density, electron gain and loss rates, recombination coefficients and temperature under perturbed conditions [12,24–26]. In these researches it is necessary to implement a numerical program package like the Long-Wave Propagation Capability (LWPC) [27] and use analytical procedures like those given in [11,26].

Here we analyze the indirect detection of non-periodic phenomena and solar terminator (ST) by monitoring VLF/LF radio waves whose propagation depends on the low ionosphere properties and, consequently, varies with induced disturbances in this atmospheric part. The presented examples of given procedures are obtained in analyses of data collected by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) [28] and AbsPAL (Absolute Phase and Amplitude Logger) VLF/LF receivers in Belgrade, Serbia for signals emitted by the DHO, ICV, and NAA transmitters located in Germany, Italy and the USA, respectively.

Here we limit our study to ionospheric variations after and during occurrences of considered events. We point out that there are some studies which analyze prediction of particular events using ionospheric perturbation detections, but this task requires a more detailed analysis which is out of the scope of this paper but will be in focus of our upcoming investigations.

The paper is organized as follows: in Section 2 we describe our observations and experimental setup, in Section 3 we present time domain analysis, and in Section 4 we give a model for detection of SIDs using the frequency analysis. Results of our research concerning detections of SIDs using VLF signal analyses in time and frequency domain are presented in Section 5, and, finally, a short summary of this study is given in Section 6.

2 Observations and experimental setup

As said in Sestion 1, this study is focused on ground based measurements of the VLF/LF radio waves (3–30 kHz and 30–300 kHz frequency domains) which are reflected in the Earth-ionosphere waveguide. This met- hod is based on the fact that the considered signals propagate through the low ionosphere which affects characteristics of their propagation and, consequently, the shapes of registered VLF/LF wave variations in real time, indicating the presence of non-stationary physical and chemical conditions in the perturbed medium along the VLF/LF wave trajectories (for details see, for example [24,29]). Namely, perturbations make the local electron density and, consequently, the height of the wave reflection, time dependent [25] which further alters the VLF/LF wave trajectory and causes the registered wave amplitude and phase to be time dependent.

The global experimental setup for the VLF/LF monitoring technique consists of numerous transmitters and receivers distributed worldwide that enable observations of a large part of the low ionosphere and detections of local plasma perturbation patterns in the D-region. A number of receivers are incorporated in some international networks like AWESOME [28], SAVNET [30] and AARDDVARK [9]. A very important characteristic of this technique for ionospheric monitoring is a continuous emission and reception of radio signals with a very good time resolution (it can be 10 μs) allowing detections of sudden, and, consequently, non precisely predicted, events, as well as detection of short-term ionospheric reactions.

In this work we present data recorded by the VLF/LF AWESOME and AbsPAL receivers located in the Institute of Physics in Belgrade, Serbia. These receivers operate

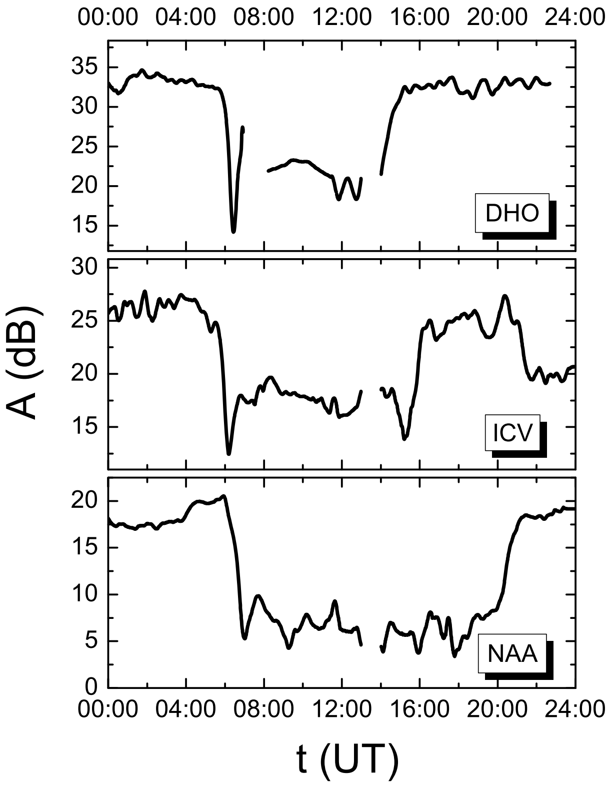

Fig. 1. Time-evolutions of the amplitude of signals emitted by the DHO (upper panel), ICV (middle panel) and NAA (bottom panel) transmitters and recorded by the Belgrade AWESOME VLF/LF receiver on December 21, 2010.

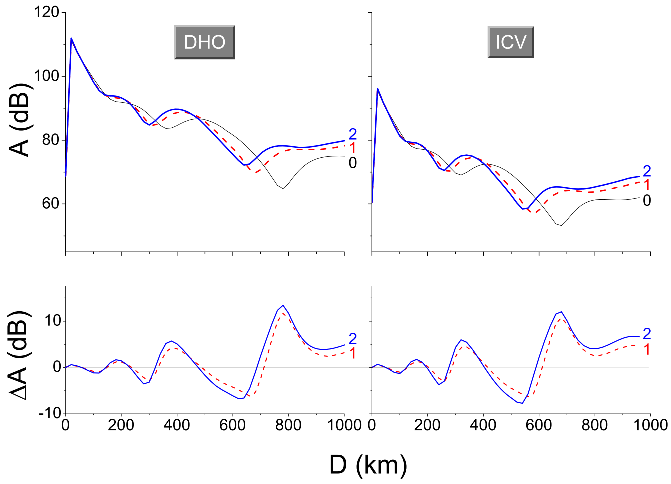

Fig. 2. Simulated amplitudes (upper panels) and their changes (bottom panels) relative to the initial quiet ionospheric state of the VLF signals versus distance from the DHO (left panels) and ICV (right panels) transmitters that emit them during the quiet condition "0" and in two perturbed stages "1" and "2" induced by the solar X-ray flare occurred on May 5, 2010.

since 2004 and 2010, respectively. Here we study connections of SIDs with three specific events for time-domain: GRBs (2009–2012), solar X-flare in 2010 and earthquake in Serbia in 2010, as well as connections with ST in 2010 for the frequency domain analysis.

We consider the 23.4 kHz, 20.27 kHz and 24 kHz signals emitted by the DHO (Germany), ICV (Italy) and NAA (USA) transmitters, respectively, with time resolutions of 0.02 s (for the analysis of short-term SIDs, such as those induced by GRBs), 1 s (for the analysis of perturbations induced by solar X-ray flares) and 1 min (for the analysis of long-term SIDs, possibly induced by earthquakes). The emission power of these signals is 800 kW, 20 kW and 1000 kW, respectively, and they are transmitted as can be seen in Figure 1 showing the amplitudes recorded by the Belgrade AWESOME receiver on December 21, 2010. The detection breaks occurring in time intervals 7–8 UT and 13–14 UT are of a pure technical nature related to the DHO transmitter being off-air, and the procedure of how the collected data are preprocessed and archived [28], respectively.

3 Time domain analysis

Characteristics of a detected signal by a particular device for the VLF/LF radio wave acquisition are time dependent and connections of their signatures with ionospheric perturbers are very hard to track. There are two main reasons for that:

- First, as it was anticipated in Section 1, the plasma located in the low ionosphere is simultaneously exposed to influences of numerous natural and artificial events. Consequently, the recorded signal characteristics which indirectly reflect ionospheric plasma properties are subject to noise and different tendencies which become of prime importance in detection of particularly weak perturbations.
- Second, in addition to periodical and sudden variations of ionospheric plasma conditions, characteristics of signals like mutual locations of the transmitter and receiver, power of transmitted signal, and the geographical area through which the signal propagates affect the recorded signal properties. Namely, the intensity of the received signal amplitude depends on the emission power and on the distance between the transmitter and receiver. In the case of emitter power, a more intense emission induces a larger amplitude of the received signal than emitted signal with lower power. On the other hand, the influence of the transmitter-receiver distance on the considered relationship is not so simple. This can be visualized using simulations of signal propagation within the Earth-ionosphere waveguide by the LWPC numerical model developed by the Naval Ocean Systems Center (NOSC), San Diego, USA [27]. In Figure 2, upper panels, we show simulated amplitude of signals emitted by the DHO transmitter (Germany) with the emission power of 800 kW and by the ICV transmitter (Italy) with the emission power of 20 kW at the ground in directions toward the Belgrade VLF/LF receiver. We analyze three moments in period before and during the solar X-ray flare occurred on May 5, 2010. We take the quiet period before the flare,

denoted as period “0” in the panels, as the reference dependency, while the periods “1” and “2” correspond to perturbed stages where we estimated the ionospheric conditions, before the perturbation maximum and at the peak of the perturbation, respectively. In this figure we can see that the amplitude intensity is weaker for the ICV signal than for the stronger DHO signal at all distances from the transmitters. Also, the dependencies between the ionospheric changes of electron density induced by the X-ray radiation increase and the VLF/LF signal amplitudes are not monotonous, e.g. a growth of the electron density ($N_e(0) < N_e(1) < N_e(2)$) does not necessarily imply an increase of the recorded signal amplitudes. This is visible in the bottom panels showing that the amplitude changes can be both positive and negative when the electron density is larger (cases “1” and “2”) than in the case of quiet conditions “0”. One can see that these changes in amplitude depend on the distance from the transmitter.

As an experimentally recorded example of different reaction on electron density increase/decrease we present amplitude variations of signals emitted by the NAA, ICV and DHO transmitters located in the USA, Italy and Germany, respectively, which were induced by the electron density increase due to the solar X-ray flare occurred on March 25, 2011 (see Fig. 3). It is noticeable that more intensive ionization processes result in the increase of the NAA signal amplitude (upper panel), decrease of the ICV signal amplitude (middle panel) and the combined tendency of the DHO signal amplitude (bottom panel).

Despite of numerous impacts on the ionospheric plasma, individual events can cause dominant influence on local plasma properties. In that case the relationship between a particular event and the corresponding SIDs (here classified as strong SIDs) can be analyzed. However, in some cases we can not extract the low ionospheric reaction induced by some considered events. There are three main reasons for that:

– The intensity of the SID is weak and it cannot be extracted from the noise in one particular case;
– The shape of signal variation caused by the considered event is the same or very similar to those induced by some other phenomena occurring in the same time period;
– The reaction does not induce clearly visible changes in recorded signal properties

Here, we take these reactions as weak SIDs. The study of the relationship between the considered events and relevant local plasma reactions is primarily based on statistical analyses. For these procedures it is very important that no other processes, inducing reactions similar to those expected in the considered case, are present. For example, the statistical analysis of the short-term SIDs induced by GRBs is not relevant in the case when numerous amplitude peaks exist before the satellite detection of the GRB (Fig. 4, bottom panel).

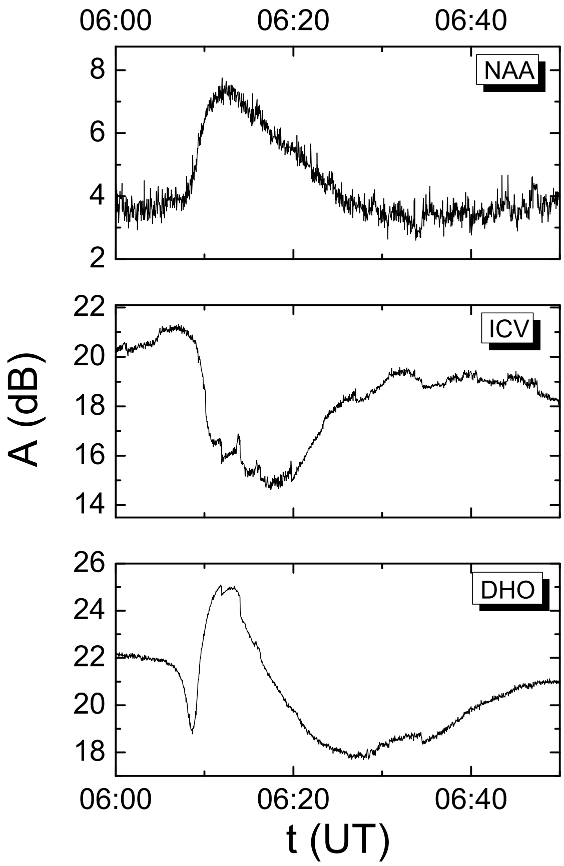

Fig. 3. Differences in the amplitude time evolutions of the signal emitted in the USA (upper panel), Italy (middle panel), and Germany (bottom panel) and received by the AWESOME VLF/LF receiver in Serbia during the influence of the solar X-ray flare occurred on March 25, 2011.

There are different procedures for detection of weak SIDs. Here we explain the following methods:

– Extraction of amplitude peaks. This technique is used and described in [22] where the short duration low ionospheric reaction on a GRB is confirmed. This is based on determination of times when the peaks of the signal amplitude $A(t)$ deviate from the base curve $A_{base}(t)$ by more than r times the amplitude of noise $A_{noise}(t)$:
$$\frac{A(t) - A_{base}(t)}{A_{noise}} \geq r, \quad (1)$$
and their occurrence in time bins before or after the registration of the considered events.
– Comparison with relevant quiet period. Information about the existence of SIDs can be obtained using a comparison of signal characteristics from time periods with practically the same conditions, but in absence of SIDs. This procedure is very useful in the case when there are no sudden strong variations in the signal characteristics time evolutions.
– Superposed epoch technique. This technique is applicable when we have a weak perturbation which is not clearly visible in one particular case because of the low

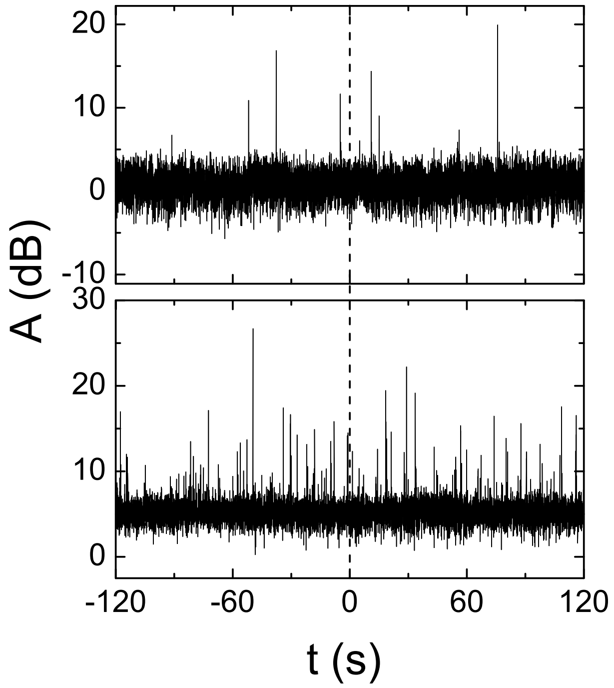

Fig. 4. Examples of the signal amplitude time evolutions during quiet (upper panel) and perturbed (bottom panel) conditions.

signal intensity but which is repeated under the same influence. For example, this method is used to detect the transmitter-induced precipitation of the inner radiation belt electrons in the low ionosphere which is practically very small [31]. It is based on the averaged sum of time series of the signal amplitude. Here it is important to say that perturbations are of the same duration. Namely, in the case when the amplitude variations are short-term with respect to the considered time interval, and are not frequent, this method can not confirm them although their occurrences are in the same time period after the influence of perturber. This conclusion is obtained for a short-term response of the low ionosphere on GRBs [22] whose detection is confirmed using the procedure for extraction of amplitude peaks.

For both types of SIDs, strong and weak, analyses of the ionospheric plasma require independent data related to detection of processes which perturb it like data collected by satellite-borne detectors for radiation coming from the outer space or ground-based optical meteor detectors.

In addition to the SID detection using the analysis of signal characteristics in time domain, SID can be discovered as intensification of waves at some frequency in the considered medium. In diagnostic of the low ionospheric plasma by radio waves, this method can be applied to electron density variations in periods when we can assume a monotonous relationship between the recorded signal characteristic and electron density.

4 Frequency domain analysis

In addition to the SID detection based on the signals analysis in the time domain, the recorded data can be processed by appropriate techniques and further analyzed in the frequency domain in order to extract waves existing in the considered medium. These waves can be excited by natural [32,33] and artificial [34] events and, depending on their frequency and medium properties, they can be divided into several types like acoustic, gravity and planetary waves.

Here, our attention is focused on explanation of the theoretical procedure for determination of possible acoustic and gravity waves (AGWs) in the lower ionosphere and on presentation of processing for determination of the excited wave frequency from the VLF/LF signal amplitude analysis.

4.1 Theory

Keeping in mind that typical atmosphere models give $n_n \sim 10^{21}$ m^{-3} for the neutral particle density and only $n_p \sim 10^8$ m^{-3} for charged plasma particles at heights $H_r < 90$ km where VLF/LF radio waves are being deflected, we can assume that the electric and magnetic effects play a negligible role in local dynamics. Consequently, standard hydrodynamic rather than magnetohydrodynamic (MHD) equations can be applied in analysis of the low ionospheric waves. For this reason in our study we start therefore from the general set of hydrodynamic equations for adiabatic processes in ideal neutral gas:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \quad p = \rho R_a T, \tag{2}$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla p + \rho \boldsymbol{g}, \tag{3}$$

$$\frac{\partial p}{\partial t} + (\boldsymbol{v} \cdot \nabla) p = \gamma \frac{p}{\rho} \left[\frac{\partial \rho}{\partial t} + (\boldsymbol{v} \cdot \nabla)\rho \right]. \tag{4}$$

Here $\gamma = c_p/c_v = (i+2)/i$ is the ratio of specific heats for gas particle with i degrees of freedom ($i = 3, 5$ for a mono atomic and two atom molecules, respectively), $R_a = k/m_a = R/M_a$ is the individual gas constant for molecules with particle mass m_a or molar mass M_a, $k = 1.3807 \times 10^{-23}$ [J/K] is Boltzmann's constant, and $R = 8.3145$ [J/K/mol] is the universal gas constant. Other quantities in equation (2) have their usual meanings.

In what follows, we consider waves whose spatial dimensions are sufficiently small in comparison with both the radius of the Earth $R_E = 6371$ km and any temperature inhomogeneity length $\mathcal{L}_T$ that can be defined on the basis of existing temperature profiles. Consequently, the plane parallel geometry can be applied with gravitational acceleration $\boldsymbol{g} = -g\hat{e}_z$ (with $g = 9.81$ m/s^2) in a locally isothermal medium. Under these assumptions the atmosphere is taken to be vertically stratified, initially in hydrostatic equilibrium, and then perturbed by harmonic waves of small amplitude. This means that equations (2)–(4) can be linearized by taking each variable $\Psi(x,y,z,t)$ as a sum of its basic state unperturbed value $\Psi_0(z)$ and a small first order perturbation $\Psi_1(x,y,z,t)$ arising from waves, i.e.:

$$\Psi(x,y,z,t) = \Psi_0(z) + \Psi_1(x,y,z,t), \tag{5}$$

where:

$$|\Psi_1(x,y,z,t)| \ll |\Psi_0(x,y,z,t)| \tag{6}$$

and

$$\Psi_1(x,y,z,t) = \hat{\Psi}_1(z)e^{-i\omega t + i(k_x x + k_y y)}. \tag{7}$$

Expressed in terms of the wavelength $\boldsymbol{\lambda} \equiv 2\pi(1/k_x, 1/k_y, 1/k_z)$, our modal analysis is restricted to atmospheric waves obeying the conditions:

$$\lambda_x, \lambda_y \ll R_E, \quad \lambda_z \ll \mathcal{L}_T, \tag{8}$$

which is equivalent to studying plane waves in a horizontally stratified isothermal atmosphere.

Equations (2)–(4), linearized with perturbations given by equations (5)–(7) and equation (8), reduce to two equations: one for the basic unperturbed state and one for small perturbations.

The basic unperturbed state is thus described by:

$$\frac{dp_0}{dz} + \rho_0 g = 0, \tag{9}$$

$$p_0 = \rho_0 R_a T_0, \text{ with } T_0 = \text{const.}, \tag{10}$$

whose solution is:

$$\rho_0(z) = \rho_0(0)e^{-z/H} \text{ or: } p_0(z) = p_0(0)e^{-z/H}, \tag{11}$$

with H being the characteristic scale-height of the isothermal atmosphere given by:

$$H \equiv \frac{p_0(0)}{\rho_0(0)g} = \frac{v_s^2}{\gamma g}, \tag{12}$$

while the small perturbations are governed by:

$$v_s^2\omega^2\frac{d^2\hat{v}_{1z}}{dz^2} - \gamma g\omega^2\frac{d\hat{v}_{1z}}{dz} + \left(\omega^4 - k_0^2 v_s^2\omega^2 + k_0^2 v_s^2 N_{BV}^2\right)\hat{v}_{1z} = 0. \tag{13}$$

Here ω is angular frequency, $k_0^2 \equiv k_x^2 + k_y^2$ is the total horizontal wavenumber, v_s is the adiabatic speed of sound defined as:

$$v_s^2 \equiv \gamma\frac{p_0}{\rho_0} = \gamma R_a T_0 = \text{const.},$$

and N_{BV} is the Brunt-Väisäläa frequency given as:

$$N_{BV}^2 = (\gamma - 1)\frac{g^2}{v_s^2}. \tag{14}$$

Taking equation (11) into account, equation (13) has solutions of the following form:

$$\hat{v}_{1z} = C \times e^{(1/2H \pm ik_z z)}, \tag{15}$$

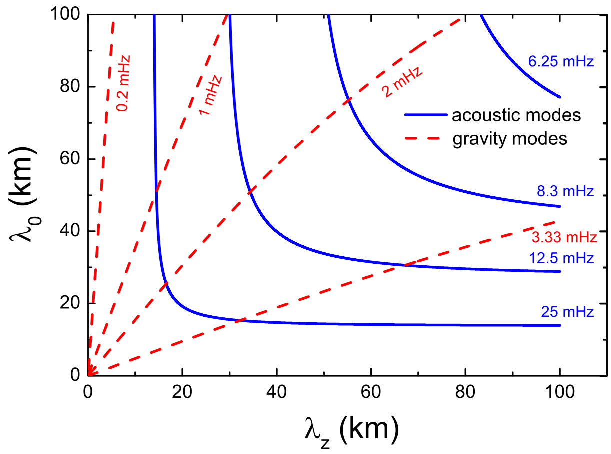

Fig. 5. Acoustic (solid lines) and gravity (dashed lines) modes for several wave frequencies.

which finally yields the dispersion relation:

$$\omega^4 - \left(k_0^2 + k_z^2 + \frac{1}{4H^2}\right)v_s^2\omega^2 + k_0^2 v_s^2 N_{BV}^2 = 0 \tag{16}$$

that has to be satisfied for solutions like equation (15) to exist with a non-zero integration constant C.

The dispersion relation equation (16) is quadratic in ω^2 which indicates the existence of two wave-modes in the considered medium: AGW modes, also known as p- and g-modes in stellar seismology.

Due to the boundary conditions of equation (8), it is convenient to express the dispersion relation equation (16) in terms of wavelengths and wave frequencies in the following way:

$$\lambda_0^2(f) = \mathcal{D}_0(f)\left[1 + \frac{\mathcal{D}_2(f)}{\lambda_z^2 - \mathcal{D}_2(f)}\right], \tag{17}$$

with:

$$\mathcal{D}_0(f) = \frac{v_s^2(f^2 - {f_{BV}}^2)}{f^2(f^2 - {f_0}^2)}, \quad \mathcal{D}_2(f) = \frac{v_s^2}{f^2 - {f_0}^2}, \tag{18}$$

and:

$$f_{0} = \frac{\gamma g}{4\pi v_s}, \quad f_{BV} = \frac{N_{BV}}{2\pi}, \quad \lambda_{0,z} = \frac{2\pi}{k_{0,z}}, \tag{19}$$

where f_0 and f_{BV} correspond to the acoustic cut-off and Brunt-Väisäläa frequencies, respectively.

A family of hyperbolae obtained from equation (17) in a (λ_0,λ_z)-plot with f being a parameter is shown in Figure 5. In calculations we take $T_0 = 200$ K as typical temperature of the considered medium. The dispersion relation equation (17) has two separate domains describing:

– acoustic modes if $\infty > f \geq f_0 = 0.00606$ Hz, and
– gravity modes for $f \leq f_{BV} = 0.00594$ Hz.

There are no propagating waves with $f_{BV} \leq f \leq f_0$.

4.2 Signal processing

One of the procedures for frequency determination of the excited waves is based on the Fast Fourier Transform (FFT) applied on collected data for VLF/LF amplitude using equation:

$$A_F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-i\omega t} A(t) dt, \quad (20)$$

where $A_F(\omega)$ represents the Fourier amplitude at frequency ω.

To find excitation of waves, model described in details in [33], requires applying the FFT on time periods of the same duration before and after the considered perturbation. The first step of this procedure is calculation of ratios of the Fourier amplitude in the time periods "2" $A_F(f;2)$ and "1" $A_F(f;1)$:

$$\alpha_{21}(f) \equiv \frac{A_F(f;2)}{A_F(f;1)}. \quad (21)$$

As in the case of analysis in time domain, the detected variations by this equation can be consequences of different events. For this reason, to extract waves induced by one considered phenomenon, two additional criteria are introduced:

– Attenuation of the excited waves in time. This property can be analyzed in the same way as in the procedure for determination of the excited wave frequencies but for the time periods immediately after perturbation (period "2") and a subsequent period lasting the same amount of time (period "3"). Relevant frequency dependent coefficient is:

$$\alpha_{23}(f) \equiv \frac{A_F(f;2)}{A_F(f;3)}. \quad (22)$$

– Statistic confirmation of wave excitation by considered phenomenon taking more examples into consideration.

5 Results and discussions

Here, we present detections of SIDs using VLF signal analyses in time and frequency domain. The resulting detections are further connected with our recent research of the solar X-ray flare and GRB events influences on the low ionosphere as well as with an investigation of the possible relationship between earthquakes and the ionospheric perturbations, for which detailed analyses will be the focus of our upcoming studies.

5.1 Signal evolution in time domain

As we said in Section 2 the method for SID detections depends on their characteristics, especially on their intensity, duration, and repetition. Here we give examples for detections of strong and weak SIDs.

5.1.1 Detection of strong SIDs

As noted above, when SID is strong enough, we can use a comparison with independent detections of different processes and link it to some event. One of the most important sudden perturbers of the ionospheric D-region plasma is the solar X-ray flare [26,35–37] and here we will explain the main characteristics of SID on the example of this phenomenon occurred on March 24, 2011. In Figure 6 there are presented time evolutions of the X-radiation flux I recorded by the GOES-15 satellite in wavelength range between 0.1 nm and 0.8 nm (upper panel) and amplitude ΔA (middle panel) and phase ΔP (bottom panel) changes of the DHO signal recorded by the AWESOME receiver in Serbia in considered period. For comparison of satellite and VLF receiver recorded variations considering characteristic time periods, we can divide SID period in three specific time domains (TDs):

- **TD 1.** In this period denoted as time interval (TI) I the intensity of the X-radiation is too small to induce an increase in the electron production which can noticeably change receiving radio signal characteristics. For this reason the electron density increase is not detected and we can say that the start of the SID detection has a time delay with respect to the solar X-ray flare detection by satellite.
- **TD 2.** As we presented at the beginning of this section related to the explanation of Figure 3, the signal variations are different during the period of increased radiation after the SID beginning. Because of that modeling of the D-region plasma is necessary for comparison of variations in the radiation and ionospheric plasma characteristics. In the considered case, there are three TIs in this TD: TI II where both the radiation intensity as well as the signal amplitude and phase increase, TI III where ΔA and ΔP still grow in spite of start of solar radiation attenuation, and TI IV where signal characteristics also decrease. The last one is the simplest example where the signal has a similar time evolution as the X-radiation flux with time delay in relevant maximum values. However, other events may have different signal variations (see Fig. 3): decrease, complex shape, saturation in the extreme values etc. For these parameters the division of TD 2 is different than in this case.
- **TD 3.** When intensity of the X-radiation decreases to the values which do not produce enough electrons that noticeably affect ionization processes we can assume that the influence of a solar X-ray flare ends. Here we take that this happens when the intensity of the flare falls back to the level where the VLF signal started to increase (borderline between TD 1 and TD 2). Although there are no perturber influences in this TI V, signal characteristics reach values similar to those before the disturbance only at the end of TI V. So we can conclude that there are some relaxation periods to balance the processes of production and loss of electrons.

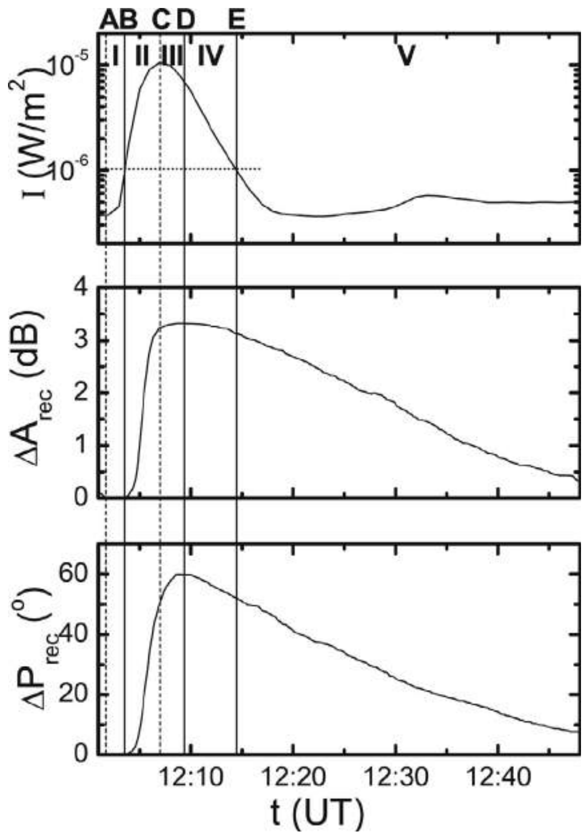

Fig. 6. Time evolutions of the X-radiation flux I in wavelength domain between 0.1 nm and 0.8 nm recorded by the GOES-15 satellite (upper panel), amplitude ΔA (middle panel) and phase ΔP (bottom panel) changes of the DHO signal recorded by the AWESOME receiver in Serbia. The vertical lines indicated as A, B, C, D and E indicate start of the time intervals TI I and boundaries between time intervals TI I - TI V described in text. The presented data are collected during influence of the solar X-ray flare occurred on March 24, 2011.

The explained properties related to Figure 6 are also noticed in several other events (solar X-ray flares occurred on May 5, 2010, February 18, 2011, April 22, 2011 (two flares)) which we studied in [11,12,19,24,25,29,38]. In these studies we analyzed different space and time dependent plasma parameters in the D-region (the electron density, effective recombination coefficient, electron temperature, electron plasma frequency, contribution of Lyα line in ionization processes, electron content in the D-region and its contribution in changes of the total electron content during solar X-ray flares) using:

– The equation for electron density dynamics:

$$\frac{dN(\boldsymbol{r},t)}{dt} = \mathcal{G}(\boldsymbol{r},t) - \mathcal{L}(\boldsymbol{r},t), \qquad (23)$$

where $\mathcal{G}(\boldsymbol{r},t)$ and $\mathcal{L}(\boldsymbol{r},t)$ are the electron gain and electron loss rate respectively that are related to the location $\boldsymbol{r}$ and time t.

– The electron density N_e calculations [39] from the Wait's parameters H' and β obtained using the LWPC numerical model:

$$N_e(h,t) = 1.43 \times 10^{13} e^{-\beta(t)H'(t)} e^{(\beta(t)-\beta_0)h}, \qquad (24)$$

where N_e is in m^{-3}, H'(t) and h are in km, β is in km^{-1} and $\beta_0 = 0.15$ km^{-1}.

– Procedure for numerical determination of the best combination of Wait's parameters which satisfied conditions [40]:

$$\Delta A_{\rm sim}(\beta, H') \approx \Delta A_{\rm rec}(t), \qquad (25)$$
$$\Delta P_{\rm sim}(\beta, H') \approx \Delta P_{\rm rec}(t), \qquad (26)$$

where $\Delta A_{\rm sim}$ and $\Delta P_{\rm sim}$ are simulated amplitude and phase changes, while $\Delta A_{\rm rec}$ and $\Delta P_{\rm rec}$ are registered ones. This procedure explained in [41] shows how we can use VLF/LF recorded data in diagnostic of the D-region plasma.

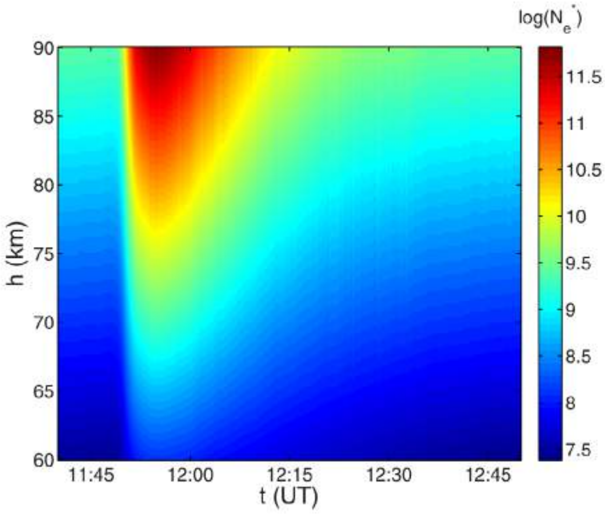

Fig. 7. Surface plot of $\log(N_e^*(t,h))$ as a function of time t and altitude h during the considered solar X-ray flare where $N_e^* = N_e/N_e^0$, and $N_e^0 = 1$ m^{-3} [19].

The calculated electron density values (see Fig. 7) show that these examples represent the group of events for which the electron density and signal characteristics have very similar time evolution shapes. For this reason the time intervals and time domains given in Figure 6 are relevant for the electron density, too. The analytical and numerical procedures given in these studies are based on recorded VLF/LF data and they are developed for calculations of:

– The electron density, electron plasma frequency and index of refractivity during perturbation time period [12,25].
– The photo-ionization rate in the upper part of the ionospheric D-region induced by the Lyα line radiation coming from the Sun in unperturbed conditions [11].
– The effective recombination coefficient during relaxation period [24].
– The Lyα line contribution in the ionization rate in the maximum of X-radiation flux [38].

– The electron temperature during relaxation period [12].
– The D-region electron content contribution in the total electron content [19].

The main results of presented studies are:

– The existence of a time delay between the onset and the maximum of the electron density perturbation with respect to the corresponding phases of the X-ray flux time evolution and the existence of a relaxation period for the D-region plasma [11].
– The dominant influence of the increased intensity of radiation lines in the X-ray spectrum on the enhancement of the electron density in the D-region during the solar flares [29,38].
– Increase of the electron density more than one order of magnitude at the top of the D-region [11].
– Increase of the effective recombination coefficient at the end of the relaxation and its decrease with altitude [24].
– Increase in contribution of the D-region electron content in the total electron content with X-radiation intensity maximum [19].
– Decrease of the electron temperature at the end of the relaxation and its increase with altitude [12].
– Increase of the electron temperature changes with altitude at the end of the relaxation [12].

5.1.2 Detection of weak SIDs

Detection of a weak SID depends on its characteristics: the intensity, duration and repetition. In these cases statistical analysis is needed to establish a potential link between some phenomenon and the considered type of SID. Here we present the methods for examination of the weak VLF/LF signal changes. We analyze periods around GRBs and earthquake:

Extraction of amplitude peaks. Figure 8 presents the increase in number of amplitude peaks $r = 2, 3, 4$ and 5 times larger than noise amplitude for a sample of 54 GRBs lasting less than 1 min which are observed by the SWIFT satellite in the period 2009–2012. In this sample we took in consideration the 24 kHz VLF signal emitted by NAA transmitter located in the USA and received in Serbia with time resolution of 20 ms within the periods from 2 min before to 2 min after satellite detection which is not significantly affected by other perturbers. These relatively quiet conditions are required for the shown procedure because of numerous peaks induced by other events which can significantly change statistics, as it is shown in Figure 4.

As one can see, the increase of number of relevant amplitude peaks is larger in periods of 2 min after GRB detections than in the same duration period before which confirms detectability of a short-term reaction of the low ionosphere to GRBs.

Here we point out that this method is based on the statistical analysis of one type event data set and it gives information about detectability of SIDs that can be connected with the considered phenomenon.

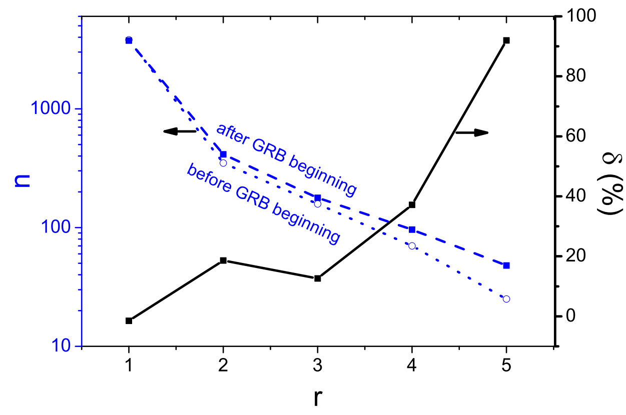

Fig. 8. The number of the relevant amplitude peaks that are $r = 1, 2, 3, 4$ and 5 times larger than the noise amplitude of the signal emitted by NAA (the USA) transmitter and received by AWESOME receiver in Serbia in periods of 2 min before (dotted line) and after (dashed line) detections of 54 GRB events by Swift satellite (left y axis) and their increase (solid line) after GRB events detection with respect to period before (right y axis).

Comparison with the relevant quiet period. As an example for this method we present the comparison of amplitude of the 20.27 kHz VLF signal emitted by the transmitter ICV in Isola di Tavolara, Italy, and received by the AbsPAL receiver located in the Institute of Physics in Belgrade, Serbia for three days in sunset period: the day of the earthquake that struck near Kraljevo, Serbia, on November 3, 2010 (00:57 UT) and one day before and after it. As we can see in Figure 9, in the day of the earthquake the inverse peaks after 15 h UT, A_{01} and A_{02} start earlier than in the other two days (A_{-1} for day before and A_1 for day after). It is important to point out that two minima are recorded although the two reference days indicate the existence of just one. Here we can not certainly claim that the signal changes are induced by the earthquake. However it is important to emphasize that similar correlation of the earthquake occurrence with such a signal perturbation is analyzed also in [42] and processing of the sample of the signal amplitudes in periods around particular earthquake events can be used for examination of the considered relationship.

5.2 Signal evolution in frequency domain

As illustrative example of method based on frequency analysis, we apply the procedure described in Section 4 on ST induced waves in the low ionosphere. We consider the 90 min time intervals at the beginning and end of the daytime and night sections when quasi-stationary conditions of the basic state (needed for analysis of the linear waves) are achieved. These intervals are noted as “a” (before sunrise), “b” (after sunrise), “c” (before sunset)

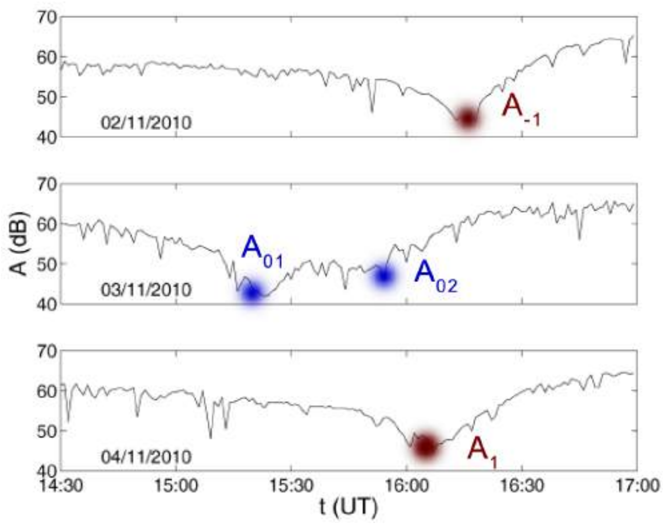

Fig. 9. Amplitudes of the VLF signal emitted in Italy by the ICV transmitter and received in Serbia during the day before (upper panel), the day of the earthquake occurred near Kraljevo, Serbia, on November 3, 2010 (00:57 UT) (middle panel) and the following day (bottom panel). The points indicate the inverse peak minima which are typical of the sunset periods.

and "d" (after sunset). The relevant coefficients related to sunrise r_{sr_exc} and r_{sr_att}, and sunset r_{ss_exc} and r_{ss_att} on May 9, 2010 are calculated by equations (21) and (22), and plotted in Figure 10. Here we can indicate three common peak domains in all plots. They correspond to perturbations that produce much larger Fourier amplitudes after perturbations and much smaller ones at the end than at the beginning of the related time section. These domains lie between 3×10^{-4} Hz and 10^{-3} Hz, 3×10^{-4} Hz and 4×10^{-3} Hz and 10^{-2} Hz and 2×10^{-2} Hz. According to the analysis given in Section 4.1 the first two oscillation frequency domains correspond to the gravity modes and the third one to the acoustic modes. The detailed analysis of five days given in [33] confirms that corresponding wave time periods are a result of the ST induced perturbation which is in agreement with those for higher altitudes of the E- and F-regions from literature [43,44]. Also, similar fluctuations in the form of magnetohydrodynamic waves were also found in high magnetospheric regions as externally driven modes with typical periods ranging from few seconds to more than 1000 s [45,46].

6 Summary

To conclude this research we point out the existence of different SIDs which required different methods for their detections by VLF/LF radio signals used for the low ionospheric monitoring. Here we give the classification of the SIDs and suggest several methods for their detections using time domain analyses:

- Strong SIDs. These plasma perturbations are sufficiently large to cause detectable changes in signal characteristics and in these cases we can analyze relationship between one particular event properties, and the ionosphere and, consequently, VLF/LF signals reactions. Here we point out time delays in the ionospheric response and its relaxation period after perturbation. Also, we point out and explain differences in the signal reactions to some phenomena.
- Weak SIDs. The uncertainty in detections of these particular events is induced by:
  - Weak intensity of SIDs;
  - The occurrence of other nearly simultaneous phenomena that induce very similar variations to the ones sought for;
  - No clearly visible changes in recorded signal properties.

  Here, statistical analysis is needed to establish a potential link between a phenomenon and the considered type of SID. The suggested methods which can be used for possible confirmation of the low ionospheric reactions to the considered phenomenon are:
  - Extraction of amplitude peaks.
  - Comparison with the relevant quiet period.
  - Superposed epoch technique.

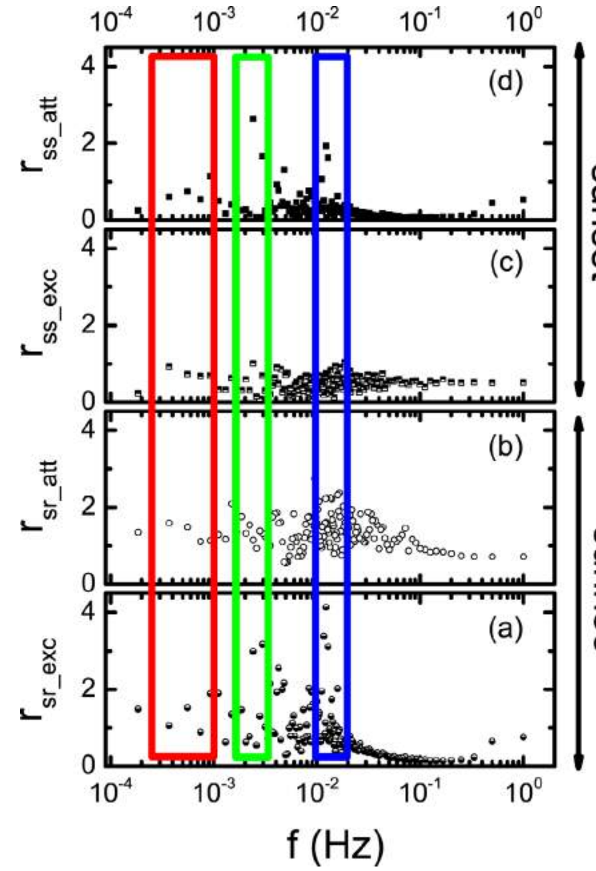

Fig. 10. Coefficients of excitations (panels (a) and (c)) and attenuations (panels (b) and (d)) of the waves for periods of sunrise (bottom panels) and sunset (upper panels) on May 9, 2010. Noticed areas represent frequency domains of the increase in their values e.g. indicate existing of ST induced waves.

In addition to the explained procedure for signal analyses in the time domain, we present a method for detection of AGWs. It is based on implementation of the FFT on recorded signal amplitude within periods before, immediately and some time after several events of the same type in order to determine the excited wave frequencies, their attenuation and repetition, which, consequently, confirm induction of AGWs by the considered phenomenon.

All these procedures have been described with some relevant examples for better clarity.

In addition to the application of various experimental settings to monitor different height domains, there are several types of measurements of the same area. Each of them has its own advantages and disadvantages. The presented study shows that our experimental equipment is completely suitable for the monitoring of different SIDs: periodical and unperiodical, long-lasting and short-lasting, global and local, strong and weak. This is possible since there is a continuous emission and reception of radio signals, very good time resolutions of collected data and numerous worldwide located transmitters and receivers. The main disadvantage of this technique is the absence of information on local plasma medium which can be obtained using in site measurements by the rockets. However, that kind of measurement is not continuous and usually it can not be used for detection of unpredicted SIDs like those induced by e.g. GRBs.

Finally, we want to point out the importance of large databases in different statistical analyses and their combination in statistical analyses of the relatively rare events, like earthquakes, and comparative analyses of the different signals or geographical areas reactions.

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Author contribution statement

All authors contributed in discussions, the text preparation and editing. A.N. have the full contribution to the paper. V.M.Č. initiated investigation of AGWs. L.Č.P. initiated study of short-term SIDs. V.A.S. participated in the experiment preparation.

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Key Points:
- Short-term ionospheric reactions to GRBs are studied for the first time
- Short-term ionospheric reactions are confirmed during and after GRB events
- Statistical analysis indicates possibility of direct and secondary ionization

Supporting Information:
- Supporting Information S1

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Detection of short-term response of the low ionosphere on gamma ray bursts

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Abstract In this paper, we study the possibility of detection of short-term terrestrial lower ionospheric response to gamma ray bursts (GRBs) using a statistical analysis of perturbations of six very low or low-frequency (VLF/LF) radio signals emitted by transmitters located worldwide and recorded by VLF/LF receiver located in Belgrade (Serbia). We consider a sample of 54 short-lasting GRBs (shorter than 1 min) detected by the Swift satellite during the period 2009–2012. We find that a statistically significant perturbation can be present in the low ionosphere, and reactions on GRBs may be observed immediately after the beginning of the GRB event or with a time delay of 60 s–90 s.

1. Introduction

Gamma ray bursts (GRBs) are known as the most energetic phenomena in the universe where a huge amount of energy is released and their investigation is of a great astrophysical importance (see, for review, *Gehrels et al.* [2009], and references therein). Consequently, there is a question: how much can a GRB event disturb the Earth atmosphere, especially the ionosphere? It is expected that photons with a minimum energy of a few keV can influence the electrical conductivity of the ionosphere; however, the very low ionization cross section for these photons in the ionosphere may provide an effective transit of GRBs without significant perturbation in the ionosphere.

On the other hand, the recording of a GRB event in the ionosphere is a very complex task since many physical phenomena perturb the ionosphere including lightning, electron precipitation, solar activity, and more. Also, GRBs and observed part of the ionosphere may have different characteristics during a GRB event. Therefore, it is very hard to prove that a particular perturbation, observed close to a GRB event, is related to it.

The ionospheric perturbation caused by a particular GRB can be confirmed if it is sufficiently intensive and long lasting as reported by *Inan et al.* [2007a] that the atmosphere exposed to the impact of radiation was disturbed more than 1 h at altitudes below about 70 km. The modeling of electron density perturbations for this case shows that the variation of this parameter increases toward the lower heights and reaches a rise of 4 orders of magnitude at an altitude of about 20 km. Although satellites have recorded an average of about one GRB per day, these intensive ionospheric reactions are very rare and only a few such events have been recorded. An indication of a long-term ionospheric perturbation was first reported by *Fishman and Inan* [1988] for the GRB30801 event. They proposed that a network of VLF signal monitors may provide some relevant information on GRBs and their influence on the ionosphere. However, after this report, there are only a few papers which reported the detection of long-term ionospheric perturbations due to GRB events: GRB030329 [*Maeda et al.*, 2005], GRB041227 [*Inan et al.*, 2007a; *Huang et al.*, 2008], GRB 060124 [*Hudec et al.*, 2010], GRB090122 [*Tanaka et al.*, 2010], GRB080320A [*Hudec et al.*, 2010], and GRB080319D [*Slosiar et al.*, 2011]. An effort for the indirect detection of GRBs by their ionospheric response observed by VLF/LF signals and discussion on its possible impact on the GRB science and investigations, in general, has been given in *Slosiar et al.* [2011].

However, there are no investigations of low intensive ionospheric perturbations. The aim of this paper is to present possible short-duration ionospheric perturbations caused by GRB events. We used VLF (3 kHz–30 kHz) and LF (30 kHz–300 kHz) radio signals to detect ionosphere disturbances in a short period around GRB events for 54 GRBs observed by Swift during 2009–2012.

2. Observations

In this study, we are trying to explore any perturbation in the ionosphere which may be connected with a GRB event and we are using a statistical analysis to find ionospheric perturbations in the period of a GRB event. Consequently, we search for any ionospheric perturbation around the GRB event. To determine time intervals around a GRB event recording by satellite we first analyzed several studies related to the low ionospheric reactions to GRBs.

2.1. The Observed Time Intervals and Duration of Ionospheric Perturbations

During X-ray flares, there is a time delay between the start of satellite recording and the moment when perturbation is observed in the ionosphere. One can expect the same to be true for GRBs. Moreover, this was confirmed during the GRB041227 event [see *Inan et al.*, 2007a], and GRB080319D and GRB080320A events [*Hudec et al.*, 2010].

The durations of ionospheric perturbations, presented in previous works, connected with GRB events are usually long term as can be seen, for example, in *Inan et al.* [2007a] (longer than 1 h) and *Chakrabarti et al.* [2010] (several seconds) and they depend on considered location [*Tanaka et al.*, 2010]. However, short-term perturbations are also presented during relevant long-term reaction [*Inan et al.*, 2007a]. Here we consider that short-duration ionospheric perturbations last less than 1 s and others we consider as long term. Therefore, for our investigation we use the VLF/LF data with a time resolution of 0.02 s.

One should consider that the ionospheric perturbations can appear during and after a GRB event; we consider an interval of 4 min around the GRB event, i.e., 2 min before and 2 min after the start of the GRB event recorded by the Swift satellite. It allows us to compare perturbations that occur immediately before and after the beginning of the GRB event. Figure 1 shows an example of short-term amplitude perturbations of signal (top) emitted by transmitters shown in the map (bottom) and recorded with Belgrade receiver less than 10 s after the GRB110223B event observed at 21:25:48 UT on 23 February 2010.

2.2. Experimental Setup

A low ionospheric electron density disturbance perturbs subionospheric VLF/LF signals which propagate in the Earth-ionosphere waveguide on Great Circle Paths (GCPs). The reflection of VLF/LF signal occurs below 85 km and depends on the local electron density. The electron density indicates ionospheric perturbation: this causes time variations of the VLF/LF wave trajectory and, consequently, recorded wave amplitude and phase [*Grubor et al.*, 2008].

The amplitude and phase of VLF/LF radio signals observed at any point can thus be used to measure the spatial and temporal characteristics of local disturbances in the lower ionosphere. The advantage of this method is that it provides continuous monitoring of a large portion of the lower ionosphere. This is achieved with VLF/LF receivers monitoring the signal, with <1 s time resolution, from VLF/LF transmitting beacons which are scattered around the world. These signal perturbations allow recording periodic and global influences as well as unforeseen and located events (for more details, see *Inan et al.* [1990], *Thomson and Clilverd* [2000], *Haldoupis et al.* [2006], *Nina and Čadež* [2013], and *Salut et al.* [2013]).

In this paper we used six radio signals in VLF and LF domains emitted from DHO (Germany), GQD (UK), ICV (Italy), NRK (Iceland), NAA (USA), and NWC (Australia) and recorded by the VLF/LF receiver located in Belgrade (Serbia) (see map in Figure 1). The characteristics of transmitters, signal propagation paths, and related amplitudes are given in Table 1.

We utilize the VLF/LF amplitudes of these transmitters recorded by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver system [*Cohen et al.*, 2010] located in Belgrade, Serbia (a part of Stanford/AWESOME Collaboration for Global VLF Research) with the sampling period of 0.02 s.

3. Methods

3.1. The GRB Sample

In this study, we selected a GRB sample observed by the Swift satellite when the received VLF/LF signal is not significantly affected by other perturbers. This satellite contains the gamma ray telescope which covers energy range from 15 to 150 keV, X-ray telescope monitoring from 0.2 to 10 keV, and ultraviolet/optical instrument for afterglow detection. In this study we consider the first phase of GRB events, the so-called gamma phase,

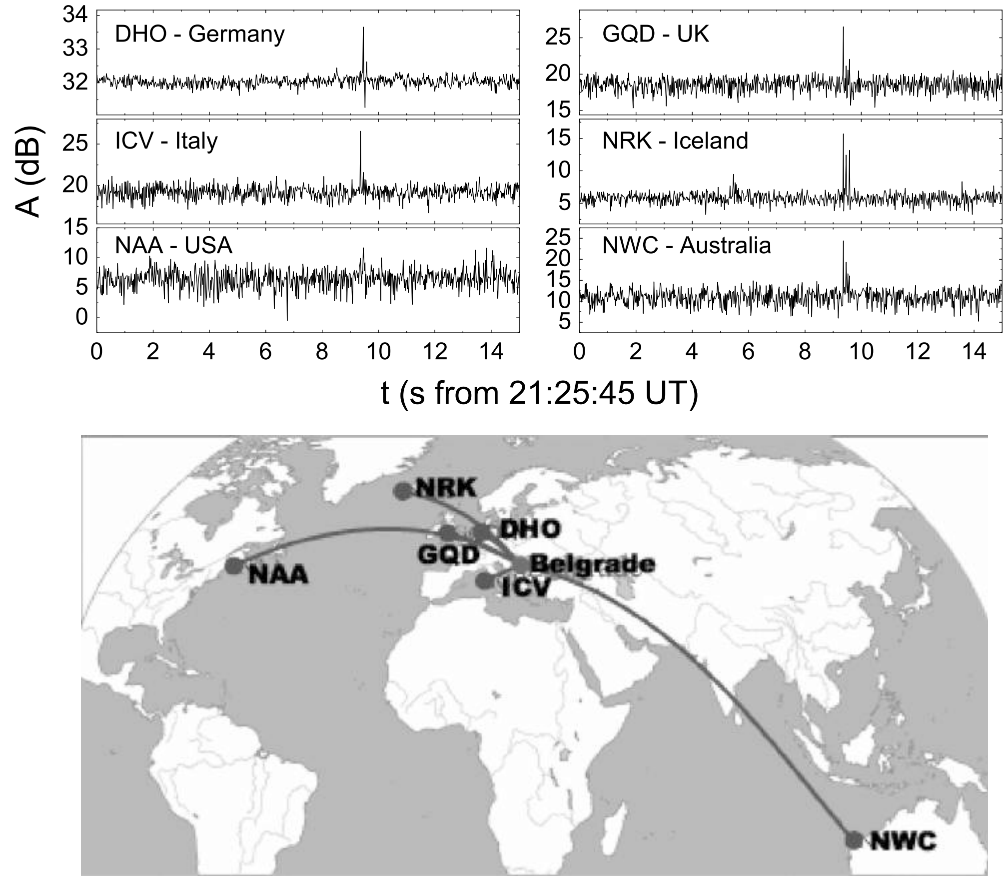

Figure 1. (top) A short-time amplitude amplification in the VLF/LF signals emitted from six transmitters (labeled at panels) and recorded by the Belgrade VLF/LF receiver possibly induced by the GRB110223B event occurred at 21:25:48 UT on 23 February 2010 less than 10 s after its beginning. (bottom) The transmitters and receiver locations and signal propagation paths indicated in the map. Transmitters and signal characteristics are given in Table 1.

with photon energies in GeV and MeV down to keV band and a time interval less then 100 s (for most of the bursts). We used data obtained by the gamma ray telescope related to the parts of hard X (12.4 keV – 124 keV) and γ radiation (above 124 keV). The time resolution of these data is 0.01 s. To analyze the whole duration of the GRBs and possible secondary reactions after the intrusion of intense high-energy radiation we selected only short-lasting GRBs, i.e., GRB events lasting less than 1 min. From the obtained data the maximum lasting of a GRB event in the sample is around 50 s.

To estimate the GRBs duration in the selected sample we used the so-called radiation intensity criteria; i.e., we start measurements at the moment when the radiation of pulses in a GRB light curve exceeds background noise by 10%. The duration is then measured in such a way to include all of the existing peaks

Table 1. Characteristics of Transmitters, Signal Propagation Paths, and Number of GRB Events Related to VLF/LF Signal Propagation During Daytime, Nighttime, and ST Conditions

Transmitter				Signal Path	Number of GRBs		
Sign	Location	Frequency (kHz)	Power (kW)	Length (km)	Daytime	Nighttime	ST
DHO	Rhauderfehn, Germany	23.4	800	1304	13	28	10
GQD	Anthorn, UK	22.1	200	1935	16	28	10
ICV	Isola di Tavolara, Italy	20.27	20	976	16	28	10
NRK	Grindavik, Island	37.5	800	3230	16	28	10
NAA	Cutler, Maine, USA	24.0	1000	6548	11	20	23
NWC	North West Cape, Australia	19.8	1000	11974	15	8	31

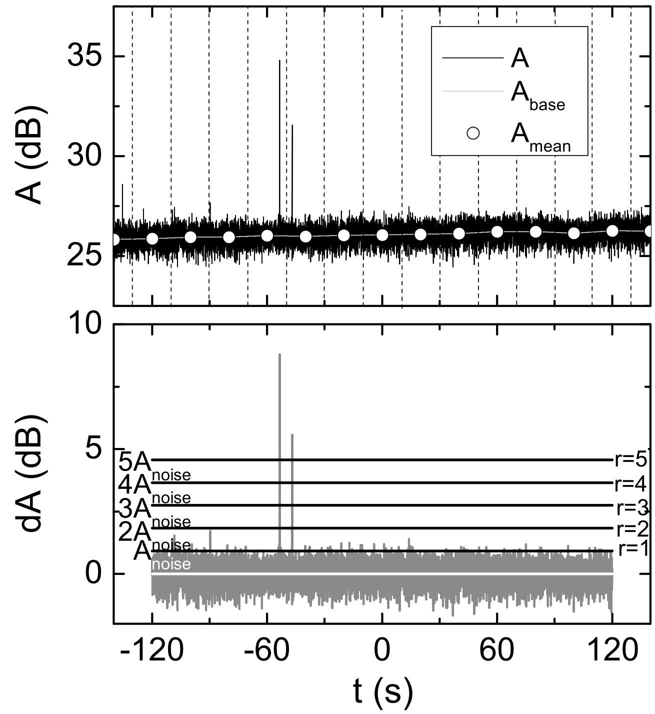

Figure 2. The method for peak determination in a VLF/LF signal. (top) Determination of baseline amplitude, A_{base}, (gray line) by interpolation of averaged amplitude, A_{mean}, (scatters) within 20 s intervals. (bottom) Determination of levels r that is 2 to 5 times larger than noise level. Amplitude noise A_{noise} is defined as the maximum absolute value of dA (deviation of recorded amplitude A of baseline amplitude A_{base}) after elimination $p = 2\%$ of its largest and lowest values.

in the observed light curve. This approach is good enough for our purpose, since we expect that sudden or sharp increase of the radiation could possibly produce some ionization events. Using the criteria mentioned above, we are able to select 54 GRBs in the period 2009–2012 (see Table S1 in the supporting information).

3.2. Signal Processing

In this study we developed a method for accounting peaks in the VLF/LF signal. We compare the signal 2 min before and 2 min after a GRB to find a number of peaks before and after the GRB event. The tendency of signal amplitude and its noise depends on signal characteristics and properties of the medium where it is propagating. Therefore, first, we found unperturbed signal amplitude, the so-called baseline, A_{base} as it is illustrated in Figure 2 (top). To find the noise level we calculated deviations of recorded amplitude $A(t)$ from A_{base} ($dA(t) = A(t) - A_{base(t)}$). Amplitude noise A_{noise} is defined as the maximum absolute value of dA after elimination $p = 2\%$ of maximum and minimum values of dA (see Figure 2, bottom). The detailed analysis shows that the noise level dependent on p affects only the value r (see equation (1)) at which the signal response detections start without essential effects on visualization of detections (see Figure S2 and its explanation in the supporting information). In the present analysis we fix p to 2% to provide better visibility without loss of significant information.

Peak classification is determined quantitatively by the ratio of deviations of the recorded amplitude $A(t)$ from the amplitude of the base curve $A_{base}(t)$ at the time t and the noise amplitude A_{noise} as follows:

$$\frac{A(t) - A_{base}(t)}{A_{noise}} \geq r \tag{1}$$

for $r = 2$, 3, 4, and 5 (see Figure 2, bottom). In the analysis we found that there is no big difference between the number of peaks for $r = 3$, 4, and 5; therefore, here we will present the results for $r = 2$ and 3.

To find statistical significance of appearing peaks in time interval (shown in Figures 3 and 4) we calculated

$$\sigma_i = \frac{x_i - \overline{X}}{\overline{X}} \cdot 100\%, \tag{2}$$

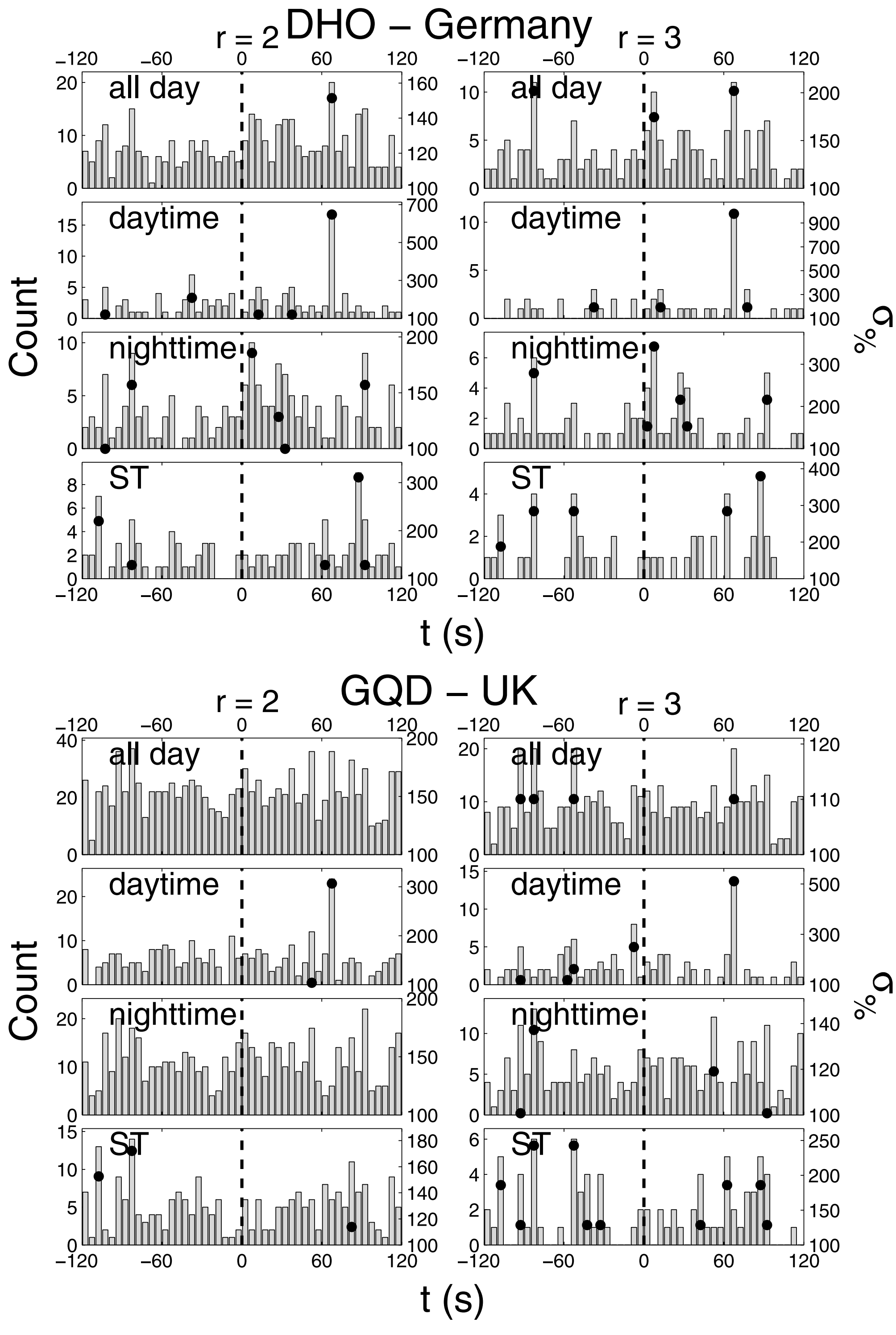

Figure 3. Histograms of number of peaks for signals emitted by different transmitters (noted on plots) accounted in time bins of 5 s for (left) $r = 2$ and (right) $r = 3$. The vertical lines denote the time of the satellite GRB recording and the black points indicate the statistically significant increase of peak numbers within bins indicated by values of σ given by equation (2) (right axes). For each transmitter the whole sample, daytime, nighttime, and ST conditions are given (from top to bottom).

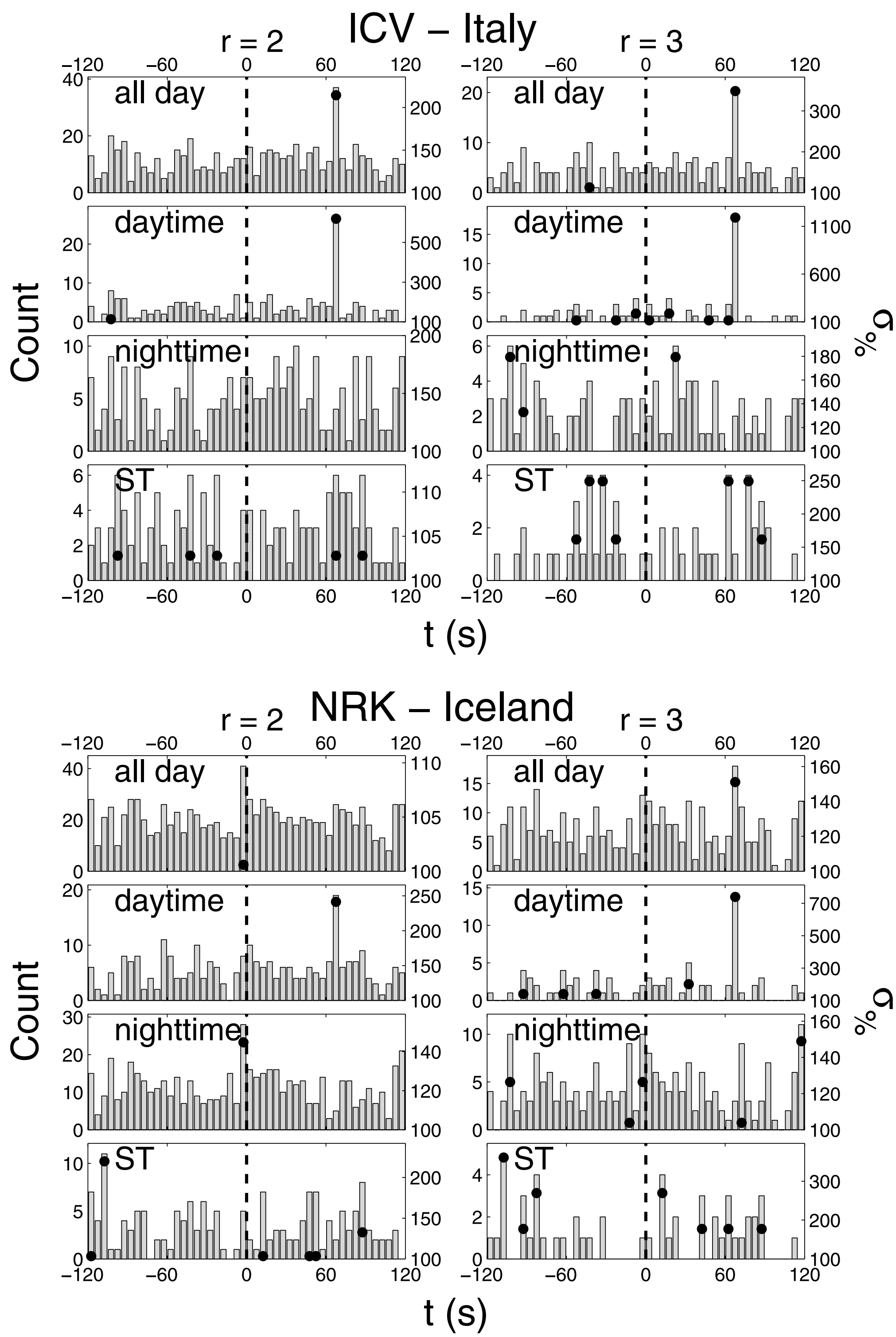

Figure 3. (continued)

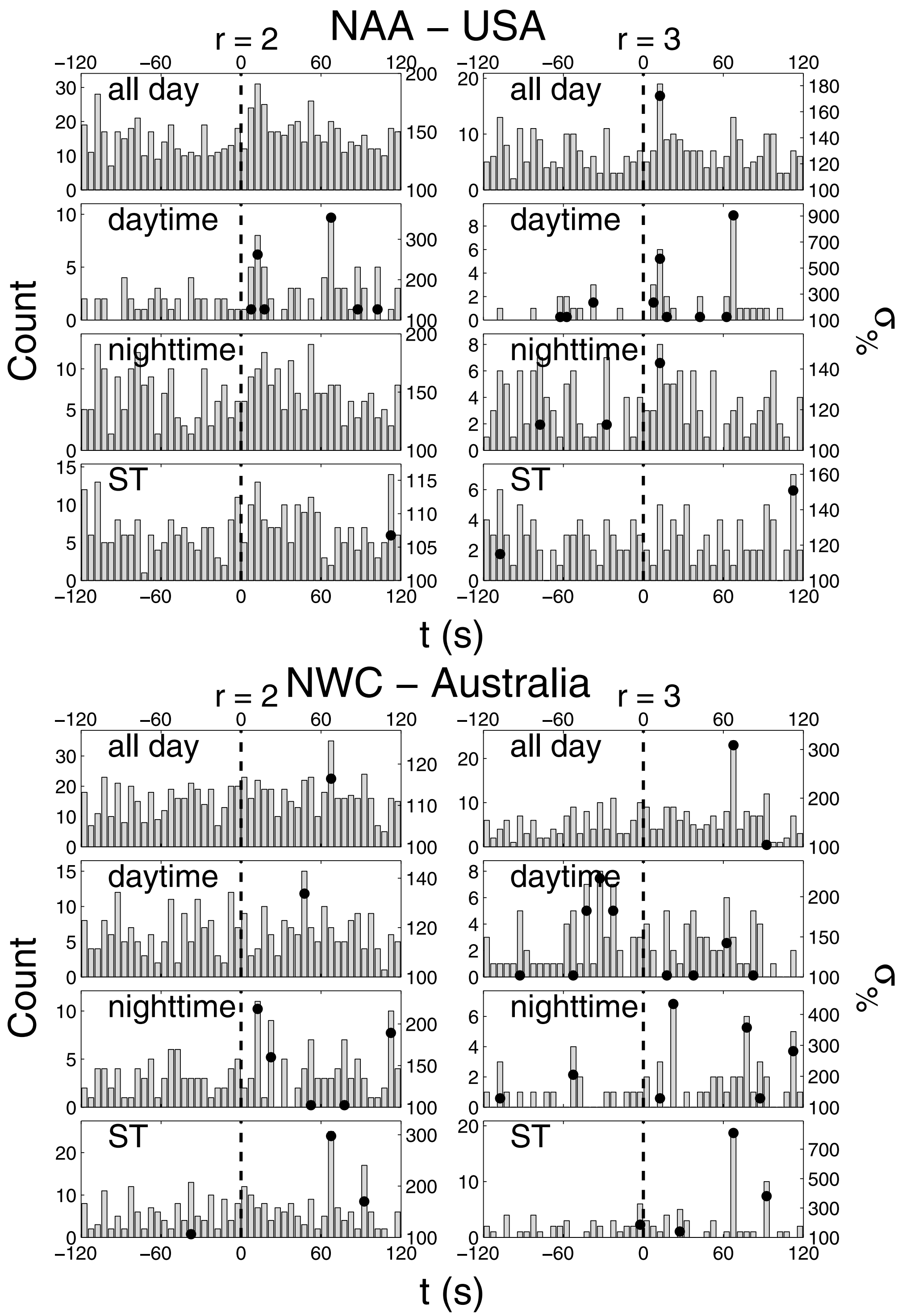

Figure 3. (continued)

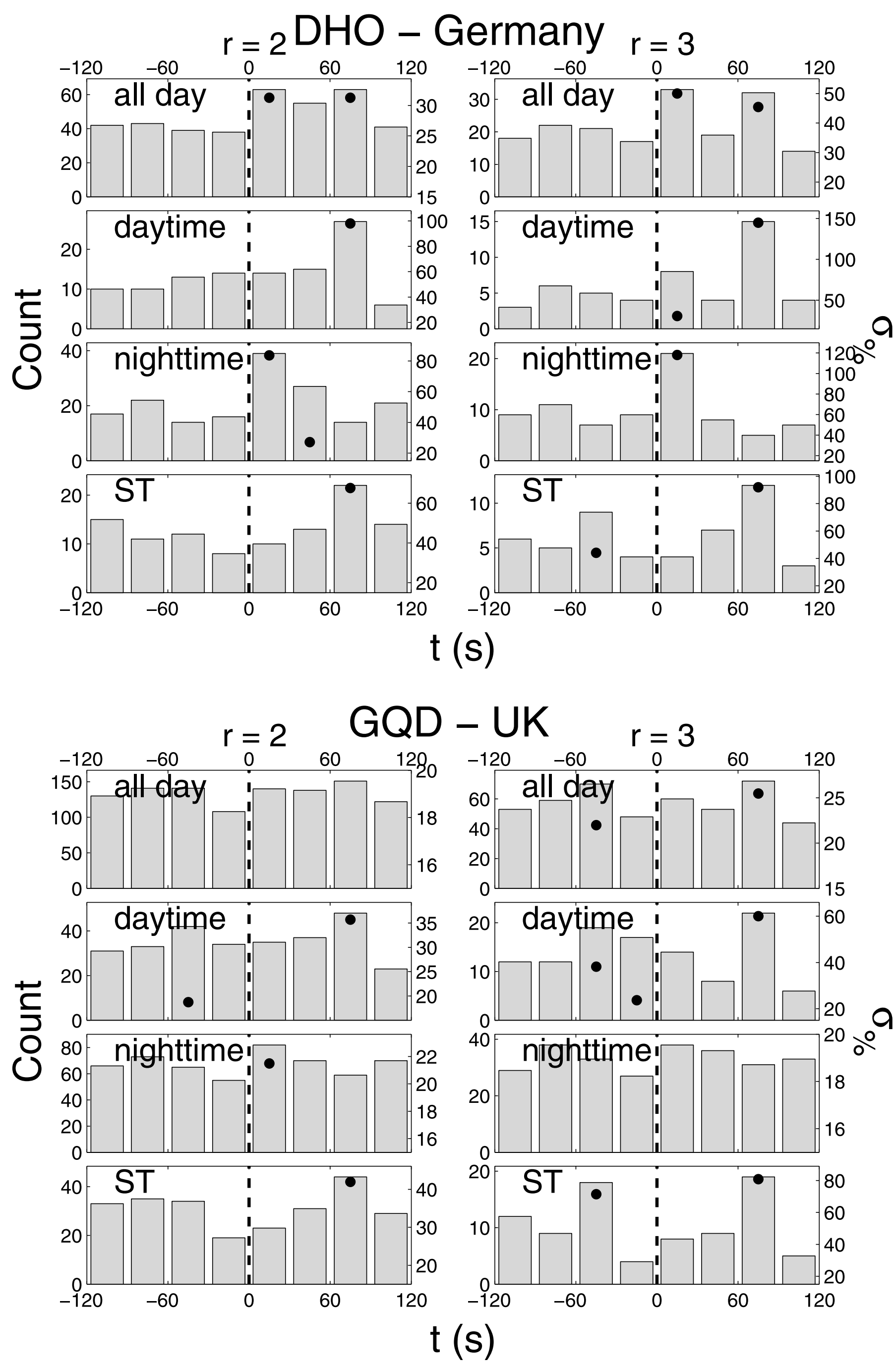

Figure 4. The same as in Figure 3 but for wider bins of 30 s.

where x_i is the corresponding number of peaks in the bin i and $\overline{X}$ is the averaged number of peaks in the whole interval, i.e.,

$$\overline{X} = \frac{1}{N}\sum_i x_i, \quad i = 1, ..., N. \tag{3}$$

In addition, only values of σ_i higher than 15% in the case of 30 s bins and 100% higher in the case of 5 s bins are marked with black circles in Figures 3 and 4.

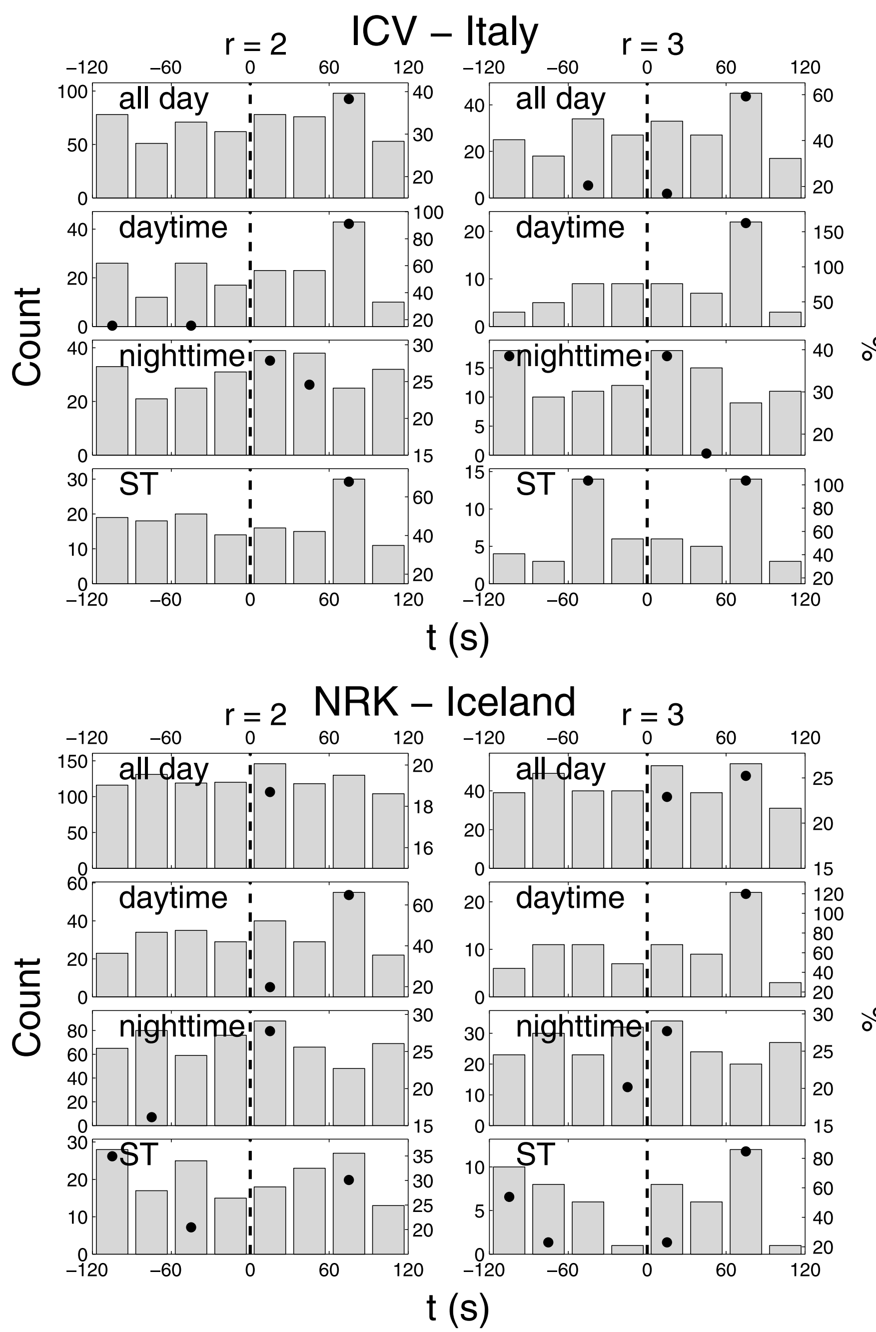

Figure 4. (continued)

It is well known that ionosphere is different during daytime and nighttime conditions. Therefore, our sample is additionally divided into three subsamples: signals obtained during daytime and nighttime, and periods when the solar terminator (ST) affects considered ionosphere part resulting into a nonstationary behavior of the recorded VLF/LF signal amplitude (see Figures 3 and 4).

Additionally, we apply the technique as given in *Inan et al.* [2007b]. However, contrary to the case of *Inan et al.* [2007b], the analysis of our sample shows that this method cannot account for short-term and temporary impacts from ionospheric natural fluctuations (see Figure S1 in the supporting information). Therefore, we will consider our method in further analysis.

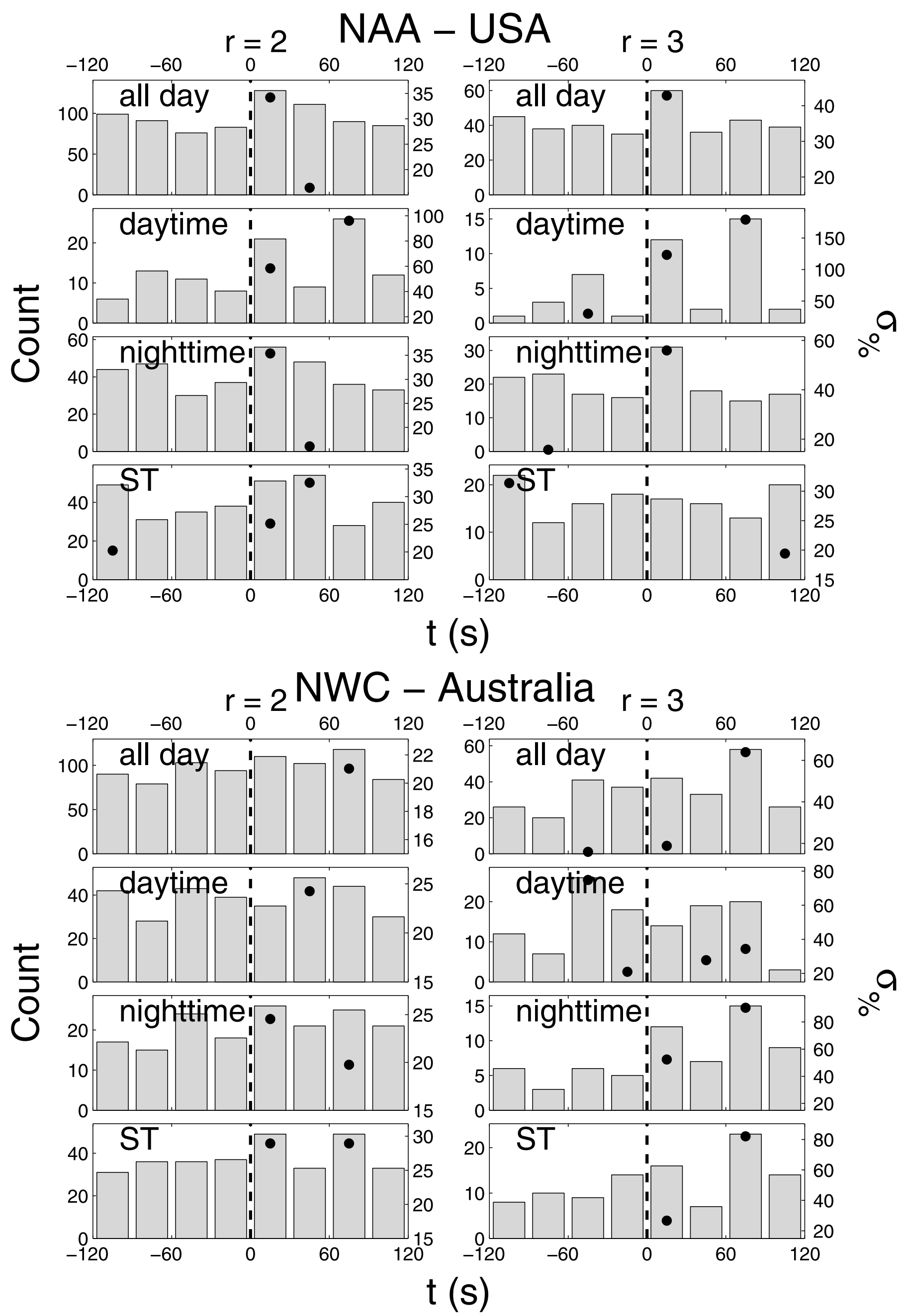

Figure 4. (continued)

4. Results and Conclusions

Here we explore the possibility of GRB influence on the low ionosphere by forming a sample of 54 GRBs and accounting the number of peaks in signal amplitudes before and after beginning of the GRB events recorded by Swift satellite. We analyze signals from six transmitters (see Table 1 and Figures 3 and 4).

As can be seen in Figures 3 and 4 we show histograms of the number of recorded amplitude peaks within the interval of 120 s before and after the GRB detections for bins time interval of 5 s and 30 s, respectively. Additionally, we separately considered daytime, nighttime, and ST subsamples (see Figures 3 and 4). The statistical analysis is given for the considered six signals recorded in Belgrade and 54 GRB events (except for the DHO signal from Germany that was used for 51 cases). Here we consider the number of peaks with $r = 2$ and 3 times larger amplitude than the noise amplitude A_{noise} (for a particular transmitter panel, left and right, respectively). For a particular transmitter panel, from top to bottom, we show the whole sample, daytime, and ST conditions, respectively.

As can be seen in Figure 3 in the case of narrow bins (NB), two time domains (TD) with jumps in the histograms can be noticed: (1) immediately after the beginning of the satellite recording of GRB (NB-TD1) and (2) some time after the beginning of the GRBs (NB-TD2).

1. *NB-TD1*. In the period after the satellite recordings of GRB, the peaks are noticeable for signals from Germany and Australia (nighttime conditions), and USA (both daytime and nighttime conditions).
2. *NB-TD2*. Increase of amplitude peak numbers after intrusion of the observed radiation, recorded within interval 65 s – 70 s, is noticeable in all signals.
   In any case, the analysis for NB-TD1 and NB-TD2 shows that the presence of considered reaction is statistically important in histograms with bin width of 5 s and that there exists a certain time interval from the recording of GRBs by satellite until the detected ionospheric perturbations.

The increase in number of amplitude peaks during and after GRB events is clearly seen in all six transmitter signals when the bin width is expanded from 5 s to 30 s (wide bins, WB). In this case one can notice (see Figure 4) the following:

1. *WB-TD1*. In the first 30 s, the most important jumps in the number of amplitude peaks are again recorded in all cases within the day period that depends on the signal. Also, the most important increases of intensive amplitude peaks are recorded during nighttime (for signals from Germany, Italy, and USA) in periods 30 s – 60 s after the GRB beginnings.
2. *WB-TD2*. Increase of amplitude peak number within the period of 60 s – 90 s from the beginning of the GRBs recording by satellite is significant for all transmitters in the daytime condition. Also, it is present during periods of ST influence on all signals except those from USA (for this signal, increase is present in the next bin) and Australia during nighttime.

This definitely confirms the presence of observed short-term perturbations and their appearance after the start of the GRB detection by satellite.

Comparison of results for different bin widths shows more clear confirmation of the GRB detectability by VLF/LF radio signals for the wider temporal bins which suggests that intensification of the ionospheric plasma ionization starts with different “delays” with respect to the satellite GRB recording. This conclusion and the occurrence of relevant peaks in the histograms after GRB duration indicate possible secondary processes that affect ionization in the low ionosphere.

Finally, we can point out the most important conclusion of this study: it confirms detectability of a short-term reaction of the low ionosphere to GRBs which does not cause intense long-term reactions in general. The important perturbations of the low ionospheric plasma occur at different times in relation to the beginning of GRB events which indicates a possibility of detection of ionization by the primary GRB radiation as well as by some of its secondary effects. The presented study indicates the possibility of intensive ionospheric perturbations during the whole day.

Obtained results in this paper show that a detailed analysis of GRB influence on the ionosphere is needed. This study will be in focus of our upcoming research. In addition, we want to point out that presented model for extraction of intensive peaks from the noise and further processing can be applied to different events.

Acknowledgments

The data for this paper collected by Swift satellite are available at NASA’s Goddard Space Flight Center. Data set name: Old Swift Trigger and Burst Information (for 2009–2012). http://gcn.gsfc.nasa.gov/swift2009_grbs.html, http://gcn.gsfc.nasa.gov/swift2010_grbs.html, http://gcn.gsfc.nasa.gov/swift2011_grbs.html, and http://gcn.gsfc.nasa.gov/swift2012_grbs.html. The used data are also given in the supporting information Table S1. Requests for the VLF/LF data used for analysis can be directed to the corresponding author. The authors are thankful to the Ministry of Education, Science and Technological Development of the Republic of Serbia for the support of this work within the projects 176001, 176002, and III44002. The authors are also grateful to Vladimir M. Čadež, Morris Cohen, and an anonymous referee for very useful suggestions and comments.

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Review

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Non-Elastic Processes in Atom Rydberg-Atom Collisions: Review of State of Art and Problems

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Abstract. Inour previous research, it has been demonstrated that inelastic processes in atom Rydberg-atom collisions, such as chemi-ionization and $(n-n')$ mixing, should be considered together. Here we will review the present state-of-the-art and the actual problems. In this context, we will consider the influence of the $(n-n')$-mixing during a symmetric atom Rydberg-atom collision processes on the intensity of chemi-ionization process. It will be taken into account H(1s) + H*(n) collisional systems, where the principal quantum number is $n >> 1$. It will be demonstrated that the inclusion of $(n-n')$ mixing in the calculation, influences significantly on the values of chemi-ionization rate coefficients, particularly in the lower part of the block of the Rydberg states. Different possible channels of the $(n-n')$-mixing influence on chemi-ionization rate coefficients will be demonstrated. The possibility of interpretation of the $(n-n')$-mixing influence will be considered on the basis of two existing methods for describing the inelastic processes in symmetrical atom Rydberg-atom collisions.

Key words. Atomic and molecular processes—plasmas—spectral line profiles.

1. Introduction

Exploring and improving the new calculation possibilities and simulation techniques, attracted extensive attention in the chemi-ionization and $(n-n')$-mixing processes in atom Rydberg-atom collisions, which resulted in numerous papers dedicated to this problem in various research fields like astrophysics, plasma physics, chemistry (see for example, Bohr *et al*. 2012; Barklem 2007; Mihajlov *et al*. 2007a; Ryabtsev *et al*. 2005).

Two groups of inelastic processes in slow atom Rydberg-atom collisions will be considered in this paper:

The chemi-ionization processes,

$$A^*(n,l) + A \rightarrow A + A^+ + \vec{e}, \quad (1a)$$

$$A^*(n,l) + A \rightarrow A_2^+ + \vec{e}. \quad (1b)$$

The processes of $(n-n')$*-mixing*,

$$A^*(n,l) + A \rightarrow A + A^*(n',l'). \quad (2)$$

Here A and $A^*(n,l)$ denote atom in the ground and in the highly excited (Rydberg) state with the given principal and orbital quantum numbers n and l, A^+ and $\vec{e}$ are atomic ion in the ground state and free electron, while A_2^+ denotes the molecular ion in the ground state.

The processes (1) and (2), illustrated in Figures 1(a) and 1(b), were examined and discussed in the literature for a long time (see Mihajlov & Janev 1981; Janev *et al*. 1987). These processes are conditioned by the dipole resonant mechanism which was described in detail in Mihajlov *et al.* (2012). Significant contribution of processes (1) and (2) in modeling of solar atmosphere is shown in Mihajlov *et al.* (2011a, 2011b) Barklem (2007), Mashonkina (2009, 2010), while the papers of Mihajlov *et al.* (2003) and Srećković *et al.* (2013) are devoted to the influence of these processes on the kinetic of helium-rich star atmospheres. Another important contribution is that the presented results suggest that these processes, due to their influence on free electron density and excited state populations in the atmospheres of M red dwarfs, should also influence the atomic spectral line shapes (see e.g. Mihajlov *et al*. 2007b).

In spite of the fact that processes (1) and (2) are caused by the same mechanism, they are considered separately up to now. The main aim of this work is to determine the influence of processes (2) on the processes of chemi-ionization (1a) and (1b). Namely, already from Fig. 1(b) one can notice the following: in the case when the considered atomic collision proceed in accordance with the excited molecular term $U_2(R)$, before it enters in the zone where the chemi-ionization processes (1a) and (1b) occur, the system $A^*(n,l) + A$ passes through the zone where the processes (2) with $n' > n$ take place.

First, the way the inclusion of process (2) in the procedure of calculation of rate coefficients of the chemi-ionization processes (1a) and (1b) will be described. For this purpose their values will be determined under the conditions characteristic for the solar photosphere in the case $A = \mathrm{H}(1s)$ and compared with the rate coefficients of the same chemi-ionization processes, determined in Mihajlov *et al.* (2011a), but without inclusion of $(n-n')$-mixing processes. We draw attention to the fact that, as a difference from this previous article, chemi-ionization rate coefficients are here without the simplification of the expression for Gaunt factor, connected with the photo-ionization cross sections for the transitions of Rydberg electron $\varepsilon(n,\ l) \rightarrow \varepsilon(k)$. Besides, here, as a difference from Mihajlov *et al.* (2011a), the average chemi-ionization rate coefficient for a given n is obtained as a result of

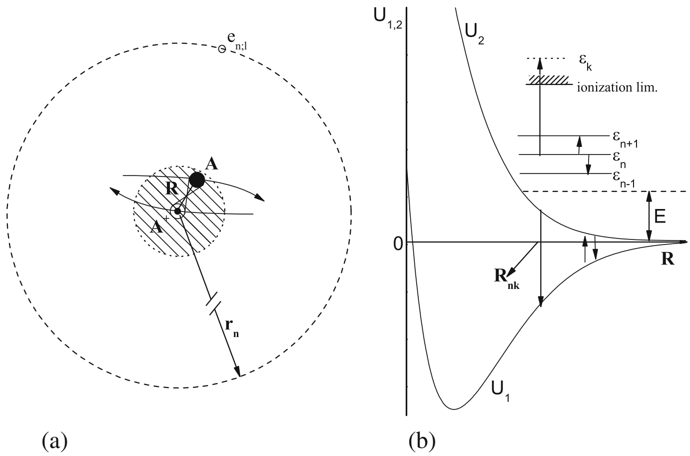

Figure 1. (**a**) Schematic illustration of $A^*(n, l) + A$ collision within the domain of internuclear distances $R \ll r_{n;l}$, where $r_{n;l} \sim n^2$ is the characteristic radius of Rydberg atom $A^*(n, l)$. (**b**) Schematic illustration of the simultaneous resonant transitions of the outer electron from the initial bound to the final state and the sub-system $A^+ + A$ from initial excited to the final ground electronic state. If the outer electron becomes free ($\varepsilon_k > 0$) the processes (1) occur, while if the outer electron remains in the bound state ($\varepsilon_{n'} < 0$) the processes (2) occur.

the corresponding averaging of partial chemi-ionization rate coefficients for every l where $0 \leq l \leq n - 1$.

Atomic units will be used throughout the paper.

2. Theory

2.1 *General formulas*

Let $K_{1a}(n, l; T)$ and $K_{1b}(n, l; T)$ are rate coefficients of processes (1a) and (1b), separately determined for a given n, l and T, where T is the temperature of the considered plasma, and $K_1(n, l; T)$ is the total rate coefficient of processes (1a) and (1b) together, namely $K_1(n, l; T) = K_{1a}(n, l; T) + K_{1b}(n, l; T)$.

Because of further applications, we will then determine the average total rate coefficient

$$K_{1;n}(T) = \frac{1}{n^2} \cdot \sum_{l=0}^{n-1} (2l + 1) \cdot K_1(n, l; T), \tag{3}$$

and average rate coefficient of associative ionization $K_{1b;n}(T)$,

$$K_{1b;n}(T) = \frac{1}{n^2} \cdot \sum_{l=0}^{n-1} (2l + 1) \cdot K_{1b}(n, l; T). \tag{4}$$

Partial rate coefficients $K_1(n, l; T)$ and $K_{1b}(n, l; T)$ are determined on the basis of standard expressions

$$K_1(n, l; T) = \int_{E_{n;i}}^{\infty} \sigma_1(n, l; E) \left(\frac{2E}{\mu_{\text{red}}}\right)^{1/2} f_T(E) \mathrm{d}E, \tag{5}$$

$$K_{1b}(n,l;T) = \int_{E_{n;i}}^{\infty} \sigma_{1b}(n,l;E) \left(\frac{2E}{\mu_{\text{red}}}\right)^{1/2} f_T(E)\mathrm{d}E, \tag{6}$$

where E is the impact energy, $\sigma_1(n,l;E)$ and $\sigma_{1b}(n,l;E)$ are the corresponding cross sections, μ_{red} is the reduced mass of the subsystem H(1s)+H^+, and $f_T(E)$ is the Maxwell distribution function: $f_T(E) = \exp(-E/kT)\sqrt{E}$. Parameter $E_{n;i}$ is given here with the relation $E_{n;i} = U_2(R_{n;i})$, where $R_{n;i}$ is the upper limit of the chemi-ionization zone which is the root of the equation $U_{12} = 1/2n^2$.

The mentioned cross sections are determined here within the semi-classical approximation, with the help of the standard expressions

$$\sigma_1(n,l;E) = 2\pi \int_0^{\rho_{1;\max}} P_1(n,l;\rho;E)\rho\mathrm{d}\rho,$$

$$\sigma_{1b}(n,l;E) = 2\pi \int_0^{\rho_{1b;\max}} P_{1b}(n,l;\rho;E)\rho\mathrm{d}\rho, \tag{7}$$

where ρ is the impact parameter, $\rho_{1;\max}$ and $\rho_{1b;\max}$ are the corresponding maximal values of this parameter, and $P_1(n,l;\rho;E)$ and $P_{1b}(n,l;\rho;E)$ are the total probability of chemi-ionization and the probability of associative ionization, respectively determined for the given values of n, l, ρ and E. We will determine these probabilities in the form

$$P_1(n,l;\rho;E) = \frac{1}{2} \cdot p_{\text{keep}}(n,l;\rho;E) \cdot p_{i;1}(n,l;\rho;E), \tag{8}$$

$$P_{1b}(n,l;\rho;E) = \frac{1}{2} \cdot p_{\text{keep}}(n,l;\rho;E) \cdot p_{i;1b}(n,l;\rho;E), \tag{9}$$

where $1/2$ is the probability that the subsystem H(1s)+H^+ develops in accordance with the term $U_2(R)$, $p_{\text{keep}}(n,l;\rho;E)$ the probability that in the domain of values of R where the processes (2) with $n' > n$ are possible, the state of this subsystem is held on, i.e. the excited electronic state with the energy $U_2(R)$, while $p_{i;1}(n,l;\rho;E)$ and $p_{i;1b}(n,l;\rho;E)$ are the corresponding ionization probabilities determined under the condition that subsystem H(1s) + H^+ enters into the ionization zone with probability equal to 1.

2.2 *Probability of ionization decay*

As in the previous papers, probabilities $p_{i;1}(n,l;\rho;E)$ and $p_{i;1b}(n,l;\rho;E)$ are determined here within the quasi-static decay approximation. Since these probabilities are determined in a similar way as in the previous works of Mihajlov *et al.* (2007a) and Mihajlov *et al.* (2011a), here they are taken in the form

$$p_{i;1}(n,l;\rho;E) \;=\; 1.0 - \exp(-2q_{i;1}),$$

$$p_{i;1b}(n,l;\rho;E) \;=\; \exp(-q_{i;2}) \cdot [1.0 - \exp(-2q_{i;as})], \tag{10}$$

where the quantities $q_{i;1}$, $q_{i;2}$ and $q_{i;as}$ are given as

$$q_{i;as} = q_{i;1} - q_{i;2}, \quad q_{i;1} = \int_{R_0}^{R_{n;i}} \frac{W_i(n,l;R)}{\upsilon_{\mathrm{rad}}(E,\rho;R)} \mathrm{d}R,$$

$$q_{i;2} = \int_{R_{1b;\max}}^{R_{n;i}} \frac{W_i(n,l;R)}{\upsilon_{\mathrm{rad}}(E,\rho;R)} \mathrm{d}R. \qquad (11)$$

The rate coefficient of ionization decay $W_i(n,l;R)$ and radial ion-atom velocity $\upsilon_{\mathrm{rad}}(E,\rho;R)$ are given by the expressions

$$W_i(n,l;R) = \frac{1}{2\pi} \cdot c \cdot U_{12}^3(R) \cdot D_{12}^2(R) \cdot \sigma_{ph.i}(n,l,\varepsilon_{ph}),$$

$$\upsilon_{\mathrm{rad}}(E,\rho;R) = \left(\frac{2}{\mu_{\mathrm{red}}} \left[E - U_2(R) - \frac{E\rho^2}{R^2} \right] \right)^{1/2}, \qquad (12)$$

where c is the speed of light, $D_{12} = |\langle 1|\hat{d}_{m.i}|2\rangle|$ is the molecular-ion dipole matrix element, $\sigma_{\mathrm{ph}.i}(n,\ l,\ \varepsilon_{\mathrm{ph}})$ is the cross section for photoionization of excited hydrogen atom $H^*(n,\ l)$ by a photon with energy $\varepsilon_{\mathrm{ph}} = U_{12}(R)$, and $U_{12}(R) = U_2(R) - U_1(R)$.

In the expression for dipole matrix element $\hat{d}$ denotes the operator of ion dipole momentum H_2^+ and $|1\rangle$ and $|2\rangle$ are the ground and first excited state of this ion.

In equation (11), R_0 is denoted by the lower limit of the domain R which is reached during the collision with a given ρ and E, and with $R_{1b;\min}$, the upper limit of the domain R where only the process of associative ionization (1b) is possible. Consequently, parameters R_0 represents the roots of the equation: $U_2(R) = E \cdot (1 - \rho^2/R^2)$ and $R_{1b;\max}$ is the root of the equation $U_{12}(R) = E$. Let us draw our attention to where it is assumed in expressions (10) and (11) that $R_{1b;\max} < R_{n;i}$ In the case of $R_{1b;\max} > R_{n;i}$ we have that the quantity $q_{i;2} = 0$ and $q_{i;as} = q_{i;1}$.

We draw our attention that already at this point there exist a difference compared to previous works concerning the chemi-ionization processes in stellar atmospheres (Mihajlov *et al.* 2007a, 2011a). Namely, in the mentioned works, the chemi-ionization rate coefficients were determined with the averaged ionization decay rate, obtained by averaging partial rates over the whole shell with a given n. This gives possibility to use the average over shell Kramers photo-ionization cross-section adjusted with the help of approximate Gaunt factor. As a difference, the rate coefficients $K_1(n,l;T)$ and $K_{1b}(n,l;T)$ were determined here on the basis of equations (5) and (6) with the help of partial cross sections for photo-ionization, determined here on the basis of exact expressions from Sobelman (1979).

2.3 *Probability of pre-ionization decay*

From equations (8) and (9) one can notice that the basic difference, in comparison with previous papers, represents taking into account of the effect of decay of the initial electronic state of the considered atom Rydberg-atom system, due to the possibility of execution of excitation processes (2) with $n' > n$. This one is taken into account by the introduction of probability of maintenance of this state $p_{\mathrm{keep}}(n,l;\rho;E)$. One determines this probability on the basis of the modified version of approximate method described in Mihajlov *et al.* (2004) dedicated to the $(n - n')$-mixing processes. Let us remind that the essence of this method is that, at a given n, each block of Rydberg states from $n' = n + p_1$ to $n' = n + p_2$ is 'spreading' in a part of 'quasicontinuum' limited by values $n + p_1 - \delta_n$ and $n + p_2 + 1 - \delta_n$, where the parameters δ_n are determined from the condition of maintainance of total number of states and total oscillator strengths for transitions from initial state of Rydberg electron to all states of the separated block. The mentioned modification has been conditioned with the fact that in the just mentioned work, an average rate of decay of the initial state of system connected with the transition of Rydberg electron from the state with the given n in states with $n' = n + p$, where $p \geq 1$, was determined while we must consider transitions of Rydberg electron from the state $|n, l\rangle$ to the states $|n + p, l - 1\rangle$ and $|n + p, l + 1\rangle$. In accordance, it is considered here that the preionization zone form the domain of internuclear distances such that $R_{n;i} < R < R_{n;n+1-\delta_n}$, where $\delta_n = 0.5{\cdot}[1 - (1/3){\cdot}O(1/n)]$, and domains R corresponding to the mentioned transitions with $p = 1, 2, 3...$ make intervals $(R_{n;n+2-\delta_n}, R_{n;n+1-\delta_n})$, $(R_{n;n+3-\delta_n}, R_{n;n+2-\delta_n})$ and $(R_{n;n+4-\delta_n}, R_{n;n+3-\delta_n})$. The limits of these domains $R_{n;n+p-\delta_n}$ are roots of the equations: $U_{12}(R) = 0.5{\cdot}[1/n^2 - 1/(n + p - \delta_n)^2]$.

In this work, the transitions with $1 \leq p \leq 5$ are taken into account. Consequently, the probability $p_{\text{keep}}(n, l; \rho; E)$ could be represented as

$$p_{\text{keep}}(n, l; \rho; E) = \prod_{p=1}^{5} p_{p;\text{keep}}(n, l; \rho; E), \tag{13}$$

where $p_{p;\text{keep}}(n, l; \rho; E)$ is the probability of the maintenance of the initial state of the system within the interval $(R_{n;n+p+1-\delta_n}, R_{n;n+p-\delta_n})$.

Since the mechanism of the pre-ionization decay is the same as in the case of the ionization one, we take immediately that probabilities $p_{p;\text{keep}}(n, l; \rho; E)$ are given by the relations

$$\begin{aligned} p_{p;\text{keep}}(n, l; \rho; E) &= \exp(-x_p), \\ x_p &= \int_{R_{n;n+p+1-\delta_n}}^{R_p} \frac{w_{n;n+p}(n, l : R)}{v_{\text{rad}}(E, \rho, R)}, \end{aligned} \tag{14}$$

where the decay rate $w_{n;n+p}(n, l; R)$ is conditioned by the dipole mechanism within the interval $(R_{n;n+p+1-\delta_n}, R_{n;n+p-\delta_n})$.

The upper limit R_p is given by

$$R_p = \begin{cases} R_{n;n+p-\delta_n}, & R_{n;n+p-\delta_n} \leq R_{up;\text{mix}}(E, \rho) \\ R_{up;\text{mix}}(E, \rho), & R_{n;n+p-\delta_n} > R_{up;\text{mix}}(E, \rho) \geq R_{n;n+p} \end{cases} \tag{15}$$

where $R_{n;n+p}$ is the resonant distance of the process (2) for a given $n - n' = n + p$, determined as the root of the equation

$$U_{12}(R) = \frac{1}{2} \cdot \left[\frac{1}{n^2} - \frac{1}{(n + p)^2} \right]. \tag{16}$$

The parameter $R_{up;\text{mix}}(E, \rho)$ is separately discussed in Appendix 4. Let us draw attention that in the case when $R_{up;\text{mix}}(E, \rho) < R_{n;n+p}$, it is considered that

$p_{p;\text{keep}}(n, l; \rho; E) = 0$. Thus the decay rate $w_{n;n+p}(n, l; R)$ is given by the relation

$$w_{n;n+p}(n, l; R) = \frac{2\pi}{3} \cdot U_{12}^4(R_{n;n+p}) \cdot \tilde{n}^3 \cdot D_{12}^2 \cdot r_{n,l;n+p}^2,$$
$$\tilde{n} = n \cdot [1 - 2n^2 \cdot U_{12}(R)]^{-1/2}, \tag{17}$$

where $r_{n,l;n+p}^2 = |\langle n, l|\hat{d}_{at}|n, l-1\rangle|^2 + |\langle n, l|\hat{d}_{at}|n, l+1\rangle|^2$, $\hat{d}_{at}$ is the operator of the dipole moment of hydrogen atom, and $|n, l\rangle$, $|n, l-1\rangle$ and $|n, l+1\rangle$ denote the corresponding states of Rydberg electrons.

3. Results and discussion

It follows from the above presented material that the total rate coefficients of the processes (1a) and (1b) together, and rate coefficients for the associative ionization (1b), i.e. $K_{1;n}(T)$ and $K_{1b;n}(T)$ are determined on the basis of equations (3)–(17). Let us draw attention that, strictly speaking, chemi-ionization processes (1a) and (1b) can be described on the basis of dipole resonant mechanism only in the case of the state with $n \geq 5$, for which the potential curves of the system $H^*(n, l) + H(1s)$ lie above the potential curve of the system $H^+ + H^-(1s^2)$, where $H^-(1s^2)$ is a stable negative hydrogen ion. However, it can be shown that the points of the intersection of potential curves of the system $H^*(n, l)+H(1s)$ with $n = 2$, 3 and 4 with the potential curve of the system $H^+ + H^-(1s^2)$ are located on the internuclear distances, which are several times larger than the average atomic radius $H^*(n, l)$ so that the existence of these intersections can not significantly affect the values of the corresponding rate coefficients of the processes (1a) and (1b). Consequently the applicability of the dipole resonance mechanism for the states with $n < 5$ depends to what degree it may be regarded as fulfilled condition $R_{n;n+1} \ll r_{n;l}$, where $r_{n;l}$ is the mean radius of the corresponding orbit of the outer electron. One notices that from this aspect, the dipole resonant mechanism can not be applied in the case of $n = 2$, while in the case of the states $n = 3$ and 4 the application of this mechanism can be completely justified.

Total values of the rate coefficients of chemi-ionization processes $K_{1;n}(T)$ within the range $3 \leq n \leq 15$ are presented in Table 1. Bearing in mind the main application (of the results obtained here), on the photosphere and lower chromosphere of the Sun, calculations of these rate coefficients were performed for temperatures 4000 K $\leq T \leq$ 10000 K. The processes (1b) are characterized in this paper via the corresponding branch coefficient $X_{1b;n}(T)$ given as

$$X_{1b;n}(T) = \frac{K_{1b;n}}{K_{1;n}}. \tag{18}$$

Values of coefficients $X_{1b;n}(T)$ for the same n and T are presented in Table 2. In accordance with the above, rate coefficients are determined by summing the probability of the decay of the initial state of the collisional system in preionization zone with Rydberg electron transitions from state $|n\rangle$ to state $|n + p\rangle$, where $1 \leq p \leq 5$.

In order to demonstrate significance of the presented calculation, we will compare the chemi-ionization rate coefficients $K_{i;n}(T)$ with the corresponding rate coefficients $K_{i;n}^*(T)$ from Mihajlov *et al.* (2011a). Let us note that the coefficients

Table 1. Calculated values of the coefficient $K_{1;n}(T)(\mathrm{cm}^3\ \mathrm{s}^{-1})$ as a function of n and T.

T	n = 3	4	5	6	7	8	9	10	11	12	13	14	15
4000	7.17E-12	1.54E-10	3.58E-10	4.28E-10	3.98E-10	3.30E-10	2.61E-10	2.06E-10	1.63E-10	1.28E-10	1.02E-10	8.14E-11	6.62E-11
4250	9.01E-12	1.63E-10	3.88E-10	4.52E-10	4.15E-10	3.42E-10	2.69E-10	2.11E-10	1.66E-10	1.31E-10	1.04E-10	8.28E-11	6.72E-11
4500	1.11E-11	1.72E-10	4.16E-10	4.76E-10	4.32E-10	3.53E-10	2.76E-10	2.16E-10	1.70E-10	1.33E-10	1.06E-10	8.40E-11	6.81E-11
4750	1.33E-11	1.83E-10	4.43E-10	4.98E-10	4.48E-10	3.63E-10	2.83E-10	2.20E-10	1.73E-10	1.35E-10	1.07E-10	8.51E-11	6.89E-11
5000	1.53E-11	1.96E-10	4.71E-10	5.20E-10	4.63E-10	3.72E-10	2.89E-10	2.24E-10	1.76E-10	1.38E-10	1.09E-10	8.62E-11	6.97E-11
5250	1.73E-11	2.12E-10	4.98E-10	5.42E-10	4.77E-10	3.81E-10	2.95E-10	2.28E-10	1.78E-10	1.40E-10	1.10E-10	8.73E-11	7.05E-11
5500	1.96E-11	2.31E-10	5.26E-10	5.63E-10	4.90E-10	3.89E-10	3.01E-10	2.31E-10	1.80E-10	1.41E-10	1.11E-10	8.84E-11	7.12E-11
5750	2.30E-11	2.51E-10	5.53E-10	5.83E-10	5.03E-10	3.96E-10	3.06E-10	2.35E-10	1.82E-10	1.43E-10	1.13E-10	8.94E-11	7.19E-11
6000	2.81E-11	2.71E-10	5.79E-10	6.03E-10	5.15E-10	4.04E-10	3.11E-10	2.38E-10	1.84E-10	1.44E-10	1.14E-10	9.03E-11	7.25E-11
6250	3.53E-11	2.91E-10	6.03E-10	6.21E-10	5.26E-10	4.11E-10	3.16E-10	2.41E-10	1.86E-10	1.46E-10	1.15E-10	9.12E-11	7.30E-11
6500	4.37E-11	3.11E-10	6.26E-10	6.39E-10	5.37E-10	4.17E-10	3.20E-10	2.44E-10	1.88E-10	1.47E-10	1.16E-10	9.19E-11	7.36E-11
7000	6.01E-11	3.50E-10	6.70E-10	6.72E-10	5.59E-10	4.30E-10	3.28E-10	2.50E-10	1.92E-10	1.49E-10	1.18E-10	9.33E-11	7.46E-11
7500	7.08E-11	3.90E-10	7.13E-10	7.03E-10	5.80E-10	4.43E-10	3.36E-10	2.55E-10	1.95E-10	1.51E-10	1.20E-10	9.46E-11	7.57E-11
8000	7.91E-11	4.31E-10	7.54E-10	7.31E-10	5.99E-10	4.55E-10	3.44E-10	2.60E-10	1.98E-10	1.54E-10	1.21E-10	9.57E-11	7.68E-11
8500	8.91E-11	4.71E-10	7.93E-10	7.57E-10	6.14E-10	4.65E-10	3.51E-10	2.64E-10	2.01E-10	1.56E-10	1.22E-10	9.66E-11	7.75E-11
9000	9.91E-11	5.13E-10	8.27E-10	7.82E-10	6.27E-10	4.74E-10	3.56E-10	2.68E-10	2.04E-10	1.58E-10	1.23E-10	9.74E-11	7.81E-11
9500	1.06E-10	5.56E-10	8.57E-10	8.06E-10	6.40E-10	4.82E-10	3.61E-10	2.72E-10	2.06E-10	1.59E-10	1.25E-10	9.82E-11	7.86E-11
10000	1.07E-10	6.03E-10	8.82E-10	8.30E-10	6.55E-10	4.90E-10	3.66E-10	2.75E-10	2.08E-10	1.61E-10	1.26E-10	9.91E-11	7.93E-11

$K^*_{i;n}(T)$ are obtained in the same way as the coefficients $K_{i;n}(T)$ by taking $p_{\text{keep}}(n, l; \rho; E) = 0$, where $p_{\text{keep}}(n, l; \rho; E)$ is the total probability of the preionization decay given by equations (13)–(17). All the mentioned quantities are presented in Fig. 2 for the case of $T = 5000$ K. Note that in relation to the previous work of Mihajlov *et al.* (2011a), in this figure are presented not only the total rate coefficients, determined on the basis of dipole resonance mechanism for $3 \leq n \leq 8$ but also rate coefficients are determined on the basis of data from Janev *et al.* (1987) for $n = 3$ and 4, and from

Table 2. Calculated values of the branch coefficient $X_{1b;n}$ as a function of n and T.

	n												
T	3	4	5	6	7	8	9	10	11	12	13	14	15
4000	0.684	0.608	0.458	0.365	0.306	0.243	0.218	0.208	0.201	0.186	0.169	0.154	0.137
4250	0.607	0.563	0.437	0.346	0.284	0.232	0.211	0.202	0.195	0.178	0.160	0.143	0.129
4500	0.543	0.519	0.421	0.329	0.265	0.222	0.206	0.198	0.189	0.170	0.152	0.132	0.122
4750	0.497	0.475	0.407	0.314	0.248	0.213	0.201	0.194	0.184	0.162	0.144	0.122	0.114
5000	0.467	0.431	0.395	0.301	0.232	0.205	0.197	0.190	0.180	0.155	0.137	0.112	0.108
5250	0.473	0.427	0.370	0.284	0.223	0.201	0.193	0.185	0.172	0.146	0.130	0.109	0.104
5500	0.467	0.419	0.347	0.269	0.215	0.197	0.189	0.181	0.164	0.137	0.123	0.107	0.101
5750	0.442	0.411	0.328	0.254	0.208	0.193	0.186	0.177	0.157	0.128	0.116	0.104	0.098
6000	0.397	0.403	0.310	0.242	0.201	0.190	0.183	0.173	0.150	0.119	0.110	0.101	0.095
6250	0.349	0.380	0.294	0.229	0.197	0.187	0.179	0.166	0.142	0.116	0.107	0.099	0.092
6500	0.308	0.360	0.279	0.218	0.194	0.184	0.175	0.159	0.134	0.113	0.104	0.096	0.089
7000	0.263	0.327	0.254	0.198	0.187	0.178	0.169	0.146	0.118	0.106	0.098	0.092	0.083
7500	0.223	0.292	0.234	0.190	0.180	0.172	0.157	0.133	0.112	0.101	0.093	0.086	0.078
8000	0.199	0.263	0.216	0.183	0.173	0.167	0.146	0.120	0.105	0.096	0.087	0.081	0.073
8500	0.198	0.243	0.194	0.178	0.169	0.161	0.134	0.112	0.100	0.092	0.083	0.075	0.070
9000	0.198	0.225	0.175	0.173	0.165	0.156	0.123	0.105	0.095	0.087	0.080	0.069	0.067
9500	0.201	0.210	0.164	0.167	0.161	0.142	0.116	0.099	0.091	0.084	0.075	0.067	0.065
10000	0.218	0.196	0.155	0.161	0.156	0.129	0.109	0.095	0.087	0.081	0.071	0.066	0.063

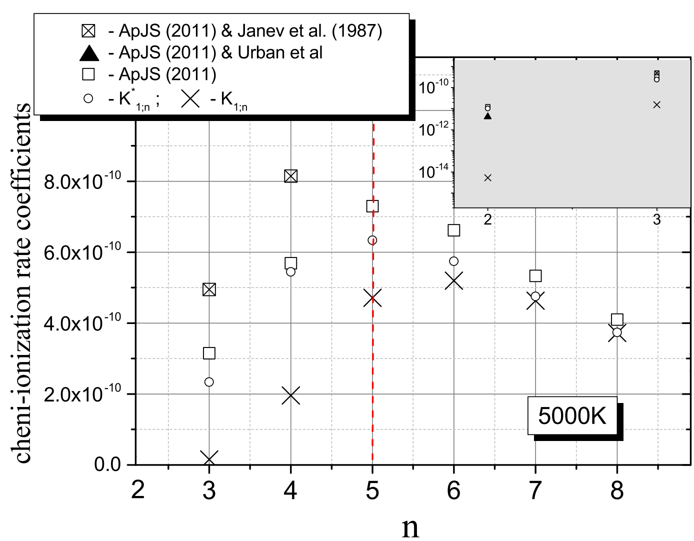

Figure 2. Comparison of the calculated values of rate coefficients of the chemi-ionization processes (1a) and (1b) with the data from Mihajlov *et al.* (2011a).

Urbain *et al.* (1991) for $n = 2$. One can notice from this figure that there are noticeable differences between the values of the rate coefficients determined in Mihajlov *et al.* (2011a) and values $K^{*}_{i;n}(T)$, while the differences in relation to the rate coefficients $K_{i;n}(T)$ are very large for $n \leq 6$ and decreases quickly with the increase of n in $n > 6$.

In previous works (Mihajlov *et al.* 2003, 2007b) related to the photosphere of a *M* red dwarf with temperature near to 4000 K, it has been shown that on populations of hydrogenic Rydberg states in this photosphere as well as on its other characteristics, the chemi-ionization processes (1a) and (1b) influence strongly with $4 \leq n \leq 8$. It is clear that because of this, it is indispensable to take into account the changes of rate coefficients of these processes, which, in accordance with our results, are particularly large for $n \leq 6$. From the material presented here, further investigation of the properties of decay of the initial state of the collisional system $H^{*}(n, l) + H(1s)$ in the pre-ionization zone is of great importance.

Additionally, results obtained here suggest that the rate coefficients of the chemi-ionization processes (1a) and (1b) could be affected by other channels of influence of the processes (2). Here we have in view the processes of $(n–n')$ mixing taking place in two or more steps.

4. Conclusions

In this work, it is shown that the processes of $(n–n')$-mixing (equation (2)) influence considerably the rates of chemi-ionization processes (1a) and (1b). Calculations, which characterize this influence on the quantitative level have been performed. As one can see from figure 2, inclusion of the $(n–n')$ mixing processes reduce the chemi-ionization rate coefficients. The obtained results are finalized in tabular form, where the values of total constants for rates of the processes (1a) and (1b) together, and rates for the process of associative ionization (1b) are presented. The tables cover the range of values, of the principal quantum number of Rydberg states of the hydrogen atom, from $n = 3$ to $n = 15$ and the temperature range from $T = 4000$ K to $T = 10000$ K, so that they can be directly applied in connection with the modeling of photosphere and lower chromosphere of the Sun. Moreover, investigation of the influence of $(n–n')$-mixing processes on the chemi-ionization processes taking into account $(n–n')$ mixing processes which occur in two or more steps have been discussed.

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Appendix

The characteristic length $R_{up;\mathrm{mix}}$ is defined here as the upper limit of the domain R where at a given E and ρ, we can consider that the inner electron is in the subsystem $H^{+} + H(1s)$ and that is sufficiently delocalized, so that this subsystem could be treated as a quasi-molecular complex. As a qualitative characteristics of the mentioned delocalization, one takes here the probability of resonant charge exchange $P_{c.\text{exc}}(R;\, E;\, \rho)$ in the subsystem $H^+ + H(1s)$ as a function of R at a given ρ and E. As a basis for this, is taken the theory of the process: $H^+ + H(1s) \to H(1s) + H^+$ developed in Firsov (1951) and Bates & Boyd (1962). From this theory it follows that

$$P_{c.\text{exc}}(R;\, E;\, \rho) = \sin^2(\varphi(R;\, E;\, \rho)), \tag{A1}$$

where the phase $\varphi(R;\, E;\, \rho)$ is given by the relation

$$\varphi(R;\, E;\, \rho) = \frac{1}{2}\int_R^\infty \frac{U_{12}(R')}{\upsilon_{\text{rad}}(R', \rho, E)} \mathrm{d}R', \tag{A2}$$

which can be used in the considered case since $P_{c.\text{exc}}(R;\, E;\, \rho)$ becomes noticeably different from zero only deeply inside the orbit of the Rydberg electron at a given n. On the basis of the data from Firsov (1951) and Bates & Boyd (1962), it can be considered that in the case when $P_{c.\text{exc}}(R;\, E;\, \rho)$ reaches the value of $1/2\pi$, the corresponding R may be considered as the upper limit of the charge exchange zone at a given ρ and E, and consequently, as the upper limit of domain with a sufficient degree of delocalization of electron in the subsystem $H^+ + H(1s)$. Thus, the parameter $R_{up;\text{mix}}$ is determined here as the root of the equation

$$\sin^2(\varphi(R;\, E;\, \rho)) = \frac{1}{2\pi}, \tag{A3}$$

where $\varphi(R;\, E;\, \rho)$ is given by equation (A2) under condition that this root is in the domain of monotonical increase of the left side of equation (A3).

The behavior of phase $\varphi(R;\, E;\, \rho)$ is illustrated in Table 3, where its values for $E = E_{n;i}$, $\rho = 0$ and $R = R_{n;n+1}$ within the range $3 \le n \le 15$ are shown. Of course, these data should be treated as qualitative ones since equations (A1) and (A2) have strict sense in the case $E \gg U_{12}(R)$ while in our case, this condition is fulfilled only for $n > 7$.

Table 3. Calculated values of the parameters which characterize pre-ionization zone. Phase $\varphi(R_{n,n+1}, E_{n;i};\, \rho = 0)$ is given by equation (A2).

n	R_{ni}	$E_{n;i} = U2(Rn;\, i)$	$R_{n,n+1}$	$\varphi(R_{n,n+1}, E_{n;i};\, \rho = 0)$	$P_{c.\text{exc}}(\varphi(R_{n,n+1}, E_{n;i};\, \rho = 0))$
3	4.79	0.02738	5.839	1.840	0.92929
4	5.52	0.01431	6.777	1.143	0.82824
5	6.08	0.00871	7.497	0.782	0.49618
6	6.52	0.00581	8.087	0.567	0.28891
7	6.89	0.00413	8.580	0.433	0.17619
8	7.21	0.00306	9.010	0.341	0.11201
9	7.49	0.00234	9.380	0.278	0.07544
10	7.73	0.00183	9.725	0.229	0.05167
11	7.95	0.00146	10.035	0.193	0.03667
12	8.16	0.00119	10.317	0.165	0.02691
13	8.34	0.00098	10.551	0.146	0.02108
14	8.51	0.00081	10.839	0.122	0.01489
15	8.66	0.00068	11.002	0.114	0.01297

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Review

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Inverse Bremsstrahlung in Astrophysical Plasmas: The Absorption Coefficients and Gaunt Factors

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Abstract. The electron–ion inverse Bremsstrahlung is considered here as a factor of the influence on the opacity of the different stellar atmospheres and other astrophysical plasmas. It is shown that this process can be successfully described in the frames of cut-off Coulomb potential model within the regions of the electron densities and temperatures. The relevant quantum mechanical method of the calculation of the corresponding spectral coefficient processes is described and discussed. The results obtained for the plasmas with the electron densities from 10^{14} cm^{-3} to $2 \cdot 10^{19}$ cm^{-3} and temperatures from $5 \cdot 10^3$ K to $3 \cdot 10^4$ K in the wavelength region 100 nm $< \lambda <$ 3000 nm are presented. Also, these results can be of interest for different laboratory plasmas.

Key words. Atomic and molecular processes—plasmas—spectral lines.

1. Introduction

Since the Bremsstrahlung process is inevitable in the case of plasma spectroscopy, until now the entire literature was devoted to the subject (see e.g. Berger 1956; Karzas & Latter 1961; D'yachkov 1990; Hazak *et al.* 2002; van Hoof *et al.* 2014; Armstrong *et al.* 2014).

It could be seen in the literature that most of the papers are devoted to the determination of the Gaunt factor for the inverse Bremsstrahlung process. The reason behind this approach lies in the exact relation for the direct Bremsstrahlung process differential cross section (Sommerfeld 1953). This automatically led to the possibility of the exact term for the $\sigma_{i.b.}^{(\mathrm{ex})}(E, \varepsilon_{\mathrm{ph}})$ cross section, where E is the free electron initial energy, $\varepsilon_{\mathrm{ph}}$ the absorbed photon energy, for the inverse Bremsstrahlung considered here. In relation with this, although mentioned exact term for $\sigma_{i.b.}^{(\mathrm{ex})}(E, \varepsilon_{\mathrm{ph}})$ relates, strictly speaking, to the case of scattering of the free electron onto the Coulomb potential, it is important to mention that it could be applied onto any diluted enough plasma (e.g. plasma with considerably small density). The fact that the practical applicability of this term was rather complex led to difficulties in its application. However, for the same process, a simple and widely used quasi classical, Kramer's cross section $\sigma_{i.b.}^{\text{q.c.}}(E, \varepsilon_{\text{ph}})$ was known and used in practice. The meaningful idea of presenting $\sigma_{i.b.}^{(\text{ex})}(E, \varepsilon_{\text{ph}})$ in the form

$$\sigma_{i.b.}^{(\text{ex})}(E, \varepsilon_{\text{ph}}) = \sigma_{i.b.}^{\text{q.c.}}(E, \varepsilon_{\text{ph}}) \cdot g_{i.b.}(E, \varepsilon_{\text{ph}}), \tag{1}$$

was derived. Here $g_{i.b.}(E, \varepsilon_{\text{ph}})$ is the adequate Gaunt factor. A further step was to yield simple approximations for this quantity.

We mention that, in the general case, both cross sections as well as Gaunt factors are functions not only of E, ε_{ph}, but also of the positively charged center on which the free electrons scatter, e.g. ze, where e is the modulus of the electron charge and $z > 0$. However, only the singly charged plasma should be considered in this manuscript, taking $z = 1$ in the entire space.

Since, in the case of plasma, adequate absorption coefficient is governed by the inverse Bremsstrahlung process, the natural transition towards the averaged values of the plasma parameters occurs. Such an averaged value is an implicit function of the plasma electron and ion concentration, and explicitly depends on plasma temperature T as well as absorbed photon wavelength λ. Here, the exact coefficients are denoted by $k_{i.b.}^{(\text{ex})}(\lambda, T; Ne, Ni)$ and $k_{i.b.}^{\text{q.c.}}(\lambda, T; Ne, Ni)$, where Ne is free electron density, and Ni is the positive ion density.

Accordingly, those coefficients are connected with the relation

$$k_{i.b.}^{(\text{ex})}(\lambda, T; Ne, Ni) = k_{i.b.}^{\text{q.c.}}(\lambda, T; Ne, Ni) \cdot G_{i.b.}(\lambda, T), \tag{2}$$

where $G_{i.b.}(\lambda, T)$ is the sought Gaunt factor. The determination of such averaged Gaunt factor as a function of λ and T was the object of investigation in majority of the previous papers devoted to the inverse Bremsstrahlung process. This is illustrated in Figure 1, where the behavior of the Gaunt factor $G_{i.b.}(\lambda, T)$ is shown on the base of the results obtained in several earlier papers (Berger 1956; Karzas & Latter 1961; D'yachkov 1990; van Hoof *et al.* 2014).

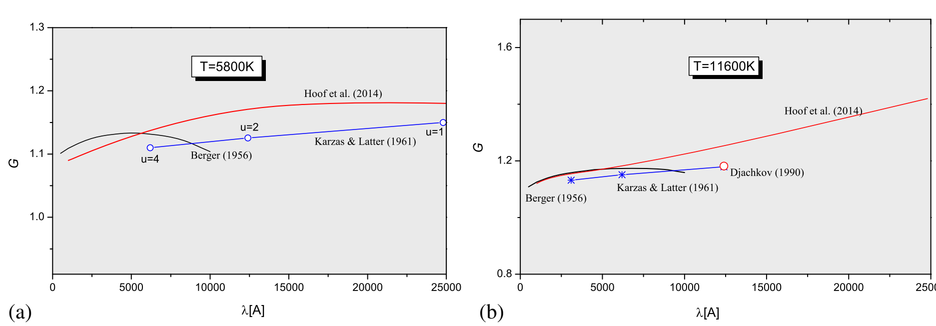

Figure 1. (**a**) Data for Gaunt factor from Berger (1956), Karzas & Latter (1961), D'yachkov (1990) and van Hoof *et al.* (2014) as a function of λ for $T = 5800$ K; (**b**) Same as in Figure 1(a) but for $T = 11600$ K.

It is clear that the application of the approximate relations, strictly applicable only on the case of diluted plasma, would lead to erroneous error in the case of plasma of higher densities, e.g. non-ideal plasma. The yielding of the applicable relations for the higher density plasma is related with the determination of the adequate coefficient $\sigma_{i.b.}^{(ex)}$. It represents a separate problem, and because of this, relatively small amount of published papers were devoted to the determination of the $\sigma_{i.b.}^{(ex)}$ applicable to the higher density plasma (see Hazak *et al.* 2002; Armstrong *et al.* 2014).

Since the objective of this work is exactly the determination of the absorption coefficient $k_{i.b.}^{(ex)}(\lambda, T; Ne, Ni)$ and Gaunt factor $G_{i.b.}(\lambda, T)$ applicable on the case of higher densities plasma, at this point it is necessary to make an observation on the method of their determination in the previous papers in the case of the mentioned dense plasma. Namely, the electron–ion scattering is treated there as a scattering of the electron onto the adequate Yukawa or Debye–Hückel potential. However, in Mihajlov *et al.* (1986), as well as in Mihajlov *et al.* (2011a, b) the fact that Debye-Hückel potential cannot be used for the description of the electron scattering in the case of dense plasma was taken into account. As a reminder, it should be mentioned that the Debye–Hückel potential is defined as a potential of the observed ion and its entire surrounding as a function of the distance from the ion, and as such could be used only for the determination of its average potential energy in the observed plasma. Because of this, in the papers of Mihajlov *et al.* (1986) and Mihajlov *et al.* (2011a, b), a model potential was applied, specially adopted for the description of the electron scattering onto the ion inside the plasma. Here the cut-off Coulomb potential, described by the relations

$$U_{\text{cut}}(r) = \begin{cases} -\dfrac{e^2}{r} + \dfrac{e^2}{r_c}, & 0 < r \le r_c, \\ 0, & r_c < r \end{cases} \tag{3}$$

is pointed out. Here r_c is the cut-off radius, and $-e^2/r_c$ is the average potential energy of the electron in the considered plasma. Let us note that such a potential, which was introduced in the considerations in Suchy (1964) in connection with the transport plasma processes was investigated in detail in Mihajlov *et al.* (1986). Here we will show that in the case of non-ideal plasmas this potential could be successfully applied also for determination of spectral coefficients for the electron–ion inverse Bremsstrahlung processes.

2. Theory

Since the potential equation (3) is one of the finite radius for determination of the cross section $\sigma_{i.b.}^{(ex)}$ for the inverse Bremsstrahlung process, we can use the standard expressions from Sobelman (1979), namely

$$\sigma_{i.b.}^{(ex)}(E; E') = \frac{8\pi^4}{3}\frac{\hbar e^2 k}{q^2} \sum_{l'=l\pm 1} l_{\max} |\hat{D}_{E,l;E'l'}|^2,$$
$$\hat{D}_{E,l;E'l'} = \int_0^\infty P_{E';l'}(r) \cdot r \cdot P_{E;l}(r) \mathrm{d}r, \tag{4}$$

where r is the distance from the beginning of the coordinate system, $P_{E;l}(r)$ is the solution of the radial Schroedinger equation

$$\frac{\mathrm{d}^2 P_{E;l}(r)}{\mathrm{d}r^2} + \left[\frac{2m}{\hbar^2}\left(E - U_{\mathrm{cut}}(r)\right) - \frac{l(l+1)}{r^2}\right] P_{E;l}(r) = 0, \tag{5}$$

and $U_{\mathrm{cut}}(r)$ is the cut-off Coulomb potential given by equation (3).

Let us note that because of the well known properties of the free electron wave functions, the direct calculation of the dipole matrix element $\hat{D}_{E,l;E'l'}$ is practically impossible until now.

However, cut-off Coulomb potential model gives the possibility of direct determination of the cross section for the inverse Bremsstrahlung process without any additional approximations. For that purpose it is enough to use in equation (4) the matrix element of the gradient of the potential energy instead of the dipole matrix element Sobelman (1979) given by

$$|\hat{D}(r)_{ab}|^2 = \frac{\hbar^4}{m^2\left(E_a - E_b\right)^4} |\nabla U_{ab}|^2, \tag{6}$$

$$\nabla_r U_{ab} = \int_0^{r_{\mathrm{cut}}} P_b(r) \cdot \nabla_r U(r) \cdot P_a(r) \mathrm{d}r. \tag{7}$$

Namely, in the case of the cut-off potential (3) in the last expression, integration over r is carried out only in the interval from 0 to r_{cut}.

The given method enabled the fast and reliable calculation of the discussed cross section and, consequentially, the corresponding spectral absorption coefficient.

Here, it is common to use a dimensionless coupling parameter, the plasma nonideality coefficient Γ, that characterizes the physical properties of the plasma. It is of special importance to describe dense, non-ideal plasmas, as the ones considered in this paper. The parameter $\Gamma = e^2/(akT)$ as such characterizes the potential energy of interaction at average distance between particles $a = (3/4\pi n_e)^{1/3}$ in comparison with the thermal energy. The well-known Brueckner parameter $r_s = a/a_B$ is the ratio of the Wigner–Seitz radii to the Bohr radius.

In connection with this, we considered here plasma with the electron densities from 10^{14} cm^{-3} to $2 \cdot 10^{19}$ cm^{-3} and temperatures from $5 \cdot 10^3$ K to $3 \cdot 10^4$ K, where the corresponding coupling parameter $\Gamma \leq 1.3$. For such plasmas, in accordance with Mihajlov *et al.* (1993) and Adamyan *et al.* (1994), we have that the value of the chemical potential for electron component (treated as appropriate electron gas on the positive charged background) is practically equal to the value which is obtained in the classical case. This means that the distribution function for electrons may be taken as appropriate Maxwell's function. In accordance with this, we will look for $\kappa_{i.b.}^{(\mathrm{ex})}$ in the form

$$\kappa_{i.b.}^{(\mathrm{ex})}(\varepsilon_\lambda; N_e, T) = N_i N_e \cdot \int_0^\infty \sigma_{i.b.}^{(\mathrm{ex})}(E; E') v \cdot f_T(v) \cdot 4\pi v^2 \mathrm{d}v \cdot \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \tag{8}$$

where $f_T(v)$ is the corresponding Maxwell-ova distribution function for a given temperature T, and the expression in parentheses was introduced in order to take into account the effect of stimulated emission. On the other hand, quasi classical Kramer's $k_{i.b.}^{\text{q.c.}}(\lambda, T; Ne, Ni)$ is given by the known expression (see e.g. Sobelman 1979), namely

$$k_{i.b.}^{\text{q.c.}}(\lambda, T; Ne, Ni) = N_i N_e \cdot \frac{16\pi^{5/2}\sqrt{2}e^6}{3\sqrt{3}cm^{3/2}\varepsilon_{\text{ph}}^3} \frac{\hbar^2}{(kT)^{1/2}} \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \quad (9)$$

where $\varepsilon_{\text{ph}} = 2\pi\hbar c/\lambda$. According to this, averaged Gaunt factor $G_{i.b.}(\lambda, T)$ is determined here from equation (2), where $k_{i.b.}^{(\text{ex})}(\lambda, T; Ne, Ni)$ and $k_{i.b.}^{\text{q.c.}}(\lambda, T; Ne, Ni)$ are given by equations (8) and (9).

3. Results and discussion

In this work, the calculations of the Gaunt factor $G_{i.b.}(\lambda, T)$ was carried out for the electron densities in the range from 10^{14} cm^{-3} to $2 \cdot 10^{19}$ cm^{-3} and temperatures from $5 \cdot 10^3$ K to $3 \cdot 10^4$ K, where the coupling parameter is $0.01 \leq \Gamma \leq 1.3$. The observed wavelengths cover the region 100 nm $< \lambda <$ 3000 nm. The important quantity for the process of the light plasma interactions is critical plasma density. This quantity plays an important role because the critical plasma density is the free electron density at which the absorption tends to be the maximum $n_c = 1.113 \cdot 10^{21}(1/\lambda_{\mu m})^2$ cm^{-3}. Absorption occurs at densities less than the critical density (where the plasma frequency $\omega_p = (4\pi n_e e^2/m)^{1/2}$ equals the optical frequency). In connection with the investigation of inverse Bremsstrahlung processes in different stellar atmospheres (for e.g. solar and different dwarf atmospheres) in the range of the investigated wavelengths 100 nm $\leq \lambda \leq$ 3000 nm, the critical electron densities lie in the region of densities between $\sim 10^{20}$ cm^{-3} and 10^{23} cm^{-3}.

Here the obtained results are illustrated in Figures 2, 3 and 4. Figure 2 illustrates the behavior of the Gaunt factor $G_{i.b.}(\lambda, T)$ for the electron concentrations

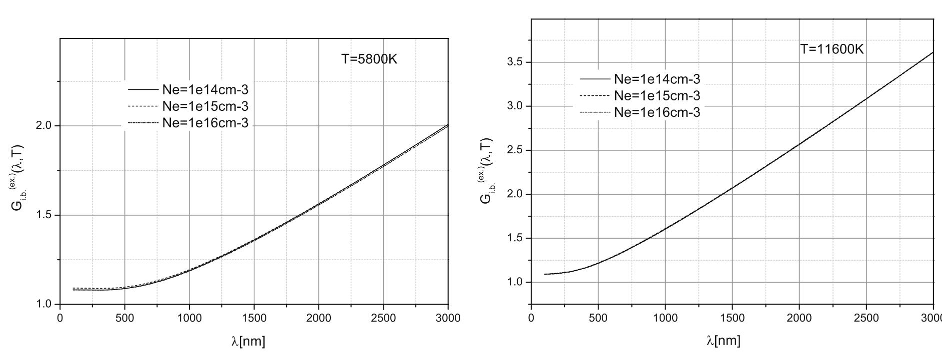

Figure 2. (**a**) Behavior of the Gaunt factor $G_{i.b.}^{(\text{ex.})}(\lambda, T)$ for temperature $T = 5800$ K and electron concentration $Ne = 10^{14}$ cm^{-3}, 10^{15} cm^{-3} and 10^{16} cm^{-3}, (**b**) Same as in Figure 2(a) but for $T = 11600$ K.

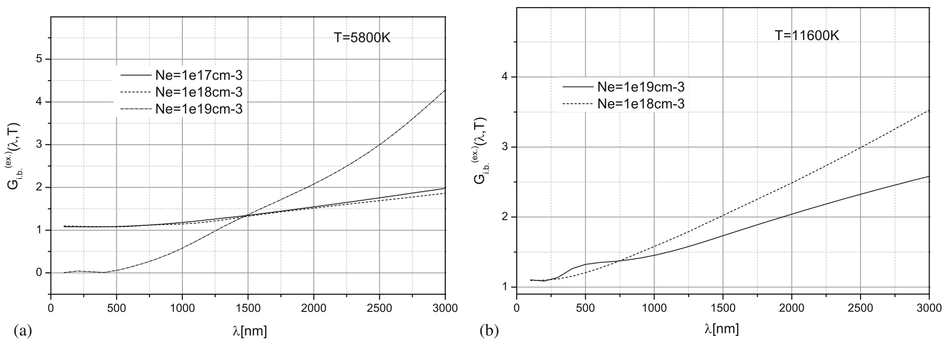

Figure 3. (**a**) Behavior of the Gaunt factor $G_{i.b.}^{(\mathrm{ex.})}(\lambda, T)$ for temperature $T = 5800$ K and $Ne = 10^{17}$ cm^{-3}, 10^{18} cm^{-3} and 10^{19} cm^{-3}. (**b**) Calculated values $G_{i.b.}^{(\mathrm{ex.})}(\lambda, T)$ at $T = 11600$ K for 10^{18} cm^{-3} and 10^{19} cm^{-3}.

10^{14} cm^{-3}, 10^{15}cm^{-3} and 10^{16} cm^{-3} and temperatures 5800 K and 11600 K, and Fig. 3 illustrates the electron concentrations 10^{17} cm^{-3}, 10^{18} cm^{-3} and 10^{19} cm^{-3} in the same temperature range as in Figure 2. Figure 4 illustrates the dynamics of the Gaunt factor change with the increase of the electron concentrations from 10^{18} cm^{-3} up to 10^{19} cm^{-3} in the case of $T = 11600$ K. Let it be noted that each of the figures shows a Gaunt factor behavior determined for the same temperature also, as in the case of an ideal plasma. It enables the estimate of the differences, bearing in mind the electron–ion influence on the inverse Bremsstrahlung in the case of non-ideal plasma. Our attention should be focused on the fact that the dependence of the Gaunt factor $G_{i.b.}^{(\mathrm{ex.})}(\lambda, T)$ on the electron density is governed by the dependence of the screening radius r_{cut} in equation (3) on the same electron density.

The data shown in Figure 5 enables the comparison of the results obtained here with the results of electron–ion inverse Bremsstrahlung processes in the case of

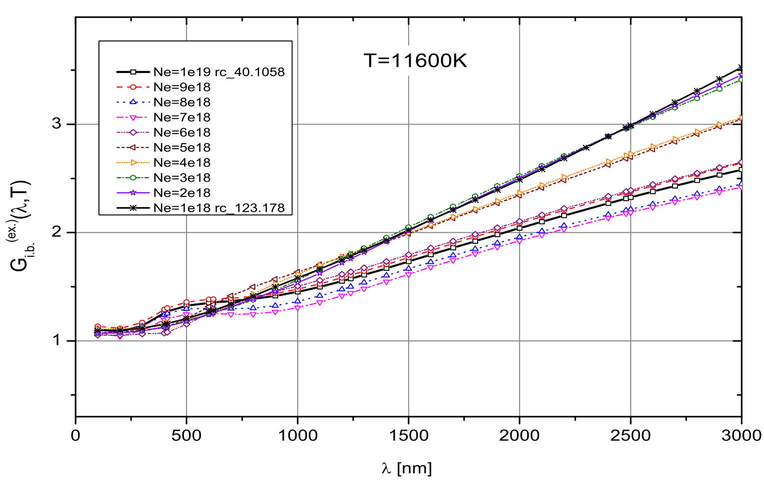

Figure 4. Dynamics of the Gaunt factor change with increase of the electron density from $Ne = 10^{18}$ cm^{-3} to 10^{19} cm^{-3} in the case of temperature $T = 11600$ K.

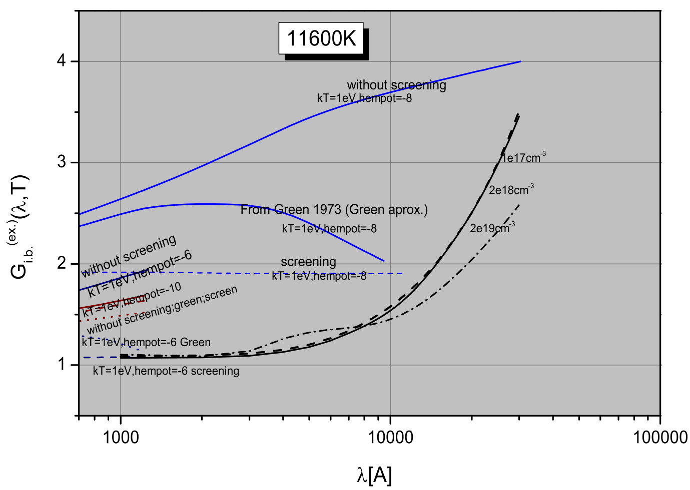

Figure 5. The behavior of the mean Gaunt factor for few cases that differ in the values of the chemical potential of electronic components ($\mu_{\rm el}$), i.e. concentration of free electrons at $T = 11600$ K (Armstrong *et al.* 2014), together with our corresponding data (solid, dashed and dotted black lines).

non-ideal plasma by other authors. This figure shows the behavior of the averaged Gaunt factor $G_{i.b.}(\lambda, T)$ determined in Armstrong *et al.* (2014) for $T = 11600$ K in several cases of different chemical potential of the electron component ($\mu_{\rm el}$), that implies different electron concentrations also. The following cases are considered: $\mu_{\rm el} = -10, -8, -6$. The same figure also shows the behavior of the Gaunt factor $G^{\rm (ex.)}_{i.b.}(\lambda, T)$ determined for the corresponding region of electron concentration and temperature. The differences of the obtained results and those from Armstrong *et al.* (2014) are evident in the figure and expected. It is clear that these differences are affected by the principal differences in the way of describing the electron–ion scattering in the rest of the plasma.

4. Conclusion

The exact quantum mechanical method presented here could be used to obtain the spectral coefficients for inverse Bremsstrahlung process for the broad class of weakly non-ideal plasmas as well as for plasma of higher non-ideality. It is expected that the cut-off Coulomb potential model results are more accurate in comparison with other methods, which is so far used for cases of non-ideal plasma. Certainly, this method can be of interest in connection with the investigation of inverse Bremsstrahlung processes in different stellar atmospheres. Also, these results can be of interest for different high energy laboratory plasma research.

Acknowledgements

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Regular Article

BEAMDB and MolD – databases for atomic and molecular collisional and radiative processes: Belgrade nodes of VAMDC*

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Abstract. We present two atomic and molecular (A&M) databases, MolD and BEAMDB, hosted by the SerVO – the Serbian virtual observatory (http://servo.aob.rs). These databases and web applications have been implemented in accordance to the standards developed by Virtual Atomic and Molecular Data Centre (VAMDC, http://www.vamdc.eu). The MolD database contains photo-dissociation cross-sections for individual rovibrational states of the diatomic molecular ions and rate coefficients for the atom-Rydberg atom chemi-ionisation and inverse electron-ion-atom chemi-recombination processes. The Belgrade electron/atom(molecule) database (BEAMDB) provides collisional data for electron interactions with atoms and molecules. Differential cross sections (DCS) are presented for both elastic and inelastic (excitation) cross sections in tabulated data tables. These DCS data are integrated over a full range of scattering angles in order to achieve integral, momentum transfer and viscosity cross sections as functions of impact electron energy. Beside these tables, energy loss spectra are presented in the graphical form.

1 Introduction

Reliable atomic and molecular data play a key role in many areas of science: atomic and molecular (A&M) physics, nuclear physics, astrophysics, laboratory plasma research, medicine, radiation damage as well as having many applications in industry (integrated circuits, lighting, etc.) [1,2]. Recently, the role of A&M induced damage in DNA and hence the damage to living cells has been investigated by both top-down approach, where thin films of supercoiled plasmid DNA or self-assembled monolayers (SAMs) of short DNA single and double strands have been objects of study, and by bottom-up approach where interactions with DNA constituents have been studied [3]. These investigations produce many relevant A&M data that are further used in modelling (radiation tracks [4]) and sophisticated radiation therapy treatments [5]. In particular our knowledge of the fundamental mechanisms of radiation damage relies on knowing the strengths of particle interactions (cf. for electrons [6], protons [7,8], γ- and X-ray and ions [9]) at the molecular level, these are usually quantified in the form of cross sections. The data obtained from space borne telescopes and the commissioning of large scale ground based arrays (e.g. ALMA) is revolutionising our knowledge of origin and evolution of interstellar medium and the genesis of stars [10–12]. Astronomical datasets are central of the interpretation of such data and therefore several databases have been compiled and recommendations made [13,14].

The recent intensive search for life in our solar system is mainly based on understanding analogous environments on Earth that may have hosted the emergence of life. The search for evidence of habitability, fossils, and molecules on the planet Mars is now a primary NASA and European Space Agency objective. Reliable molecular data are of particular importance in the area of molecular astrobiology [15,16] with knowledge of molecular spectroscopy for study of exoplanet atmospheres and identifying biosignatures on the Earth and beyond is important for our further understanding of planetary habitability.

The amount of A&M data (measured in laboratory or calculated) being generated is therefore already huge and is growing rapidly. There is therefore a need to assemble such data into accessible (on-line) databases. A very successful attempt to organise and standardise a plethora of A&M data is the Virtual Atomic and

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Molecular Data Centre (VAMDC). VAMDC started as EU FP7 e-infrastructure project with the goal of developing interoperability and communication between different A&M databases and providing a common portal for accessing all registered data. It is now maintained by the VAMDC Consortium with 30 running databases [17].

In this paper, we outline the two Belgrade nodes of VAMDC, BEAMDB and MolD, discussing their content as well as technical details of our implementation of such databases and their inclusion in VAMDC. BEAMDB and MolD are the result of data generated over many years in the research programmes of co-authors. We hope that, in time, these will become the repository of choice for generators and users of such data all over the world.

2 The Belgrade nodes of VAMDC

The Belgrade nodes of VAMDC are hosted by the Serbian Virtual Observatory (SerVO [18]) and currently consists of two databases BEAMDB (servo.aob.rs/emol) and MolD (servo.aob.rs/mold). The databases have been developed under the standards of Virtual Atomic Molecular Data Centre (VAMDC) project. The Belgrade database (BEAMDB) covers collisional data of electron interactions with atoms and molecules in the form of differential (DCS) and integrated cross sections as well as energy loss spectra. The MolD database contains photo-dissociation cross-sections for individual rovibrational states of diatomic molecular ions and rate coefficients for the atom-Rydberg atom chemi-ionisation and inverse electron-ion-atom chemi-recombination processes.

2.1 BEAMDB database

BEAMDB database is a collection of cross-sections and energy loss spectra for electron interaction processes with atoms and molecules [19]. It is hosted by Serbian Virtual Observatory (SerVO [18]) and it is a part of two consortia: Virtual Atomic and Molecular Data Centre (VAMDC [20,21]) and RADiation DAMage portal (RADAM [22]). Two types of electron collision processes are featured in the collection, elastic electron scattering and electron excitation of atoms and electronic states of molecules. The strength of the interaction is represented by double differential cross-sections (DCS) that are the probabilities for the particular process dependent on the impact electron energy and the electron scattering angle.

DCS data sets represent a 3D surface where the scattering angle and impact electron energy are displayed on the x and y axes, respectively, while the DCS ordinate is plotted on a logarithmic scale (as shown in Fig. 1). Wherever available, measured uncertainties are included in the data sets. The experimental procedure that allows determination of two dimensional relative differential cross-section surface, which can be calibrated on an absolute scale via normalization to a single point has been described in [23]. Collisional processes are also described by integrated cross sections: integral, momentum transfer and viscosity. By comparing quantities derived from DCS by integration, it is possible to evaluate the different methods used for the production of these data sets, for example crossed beam experiments and swarm analysis derived data may be compared [25].

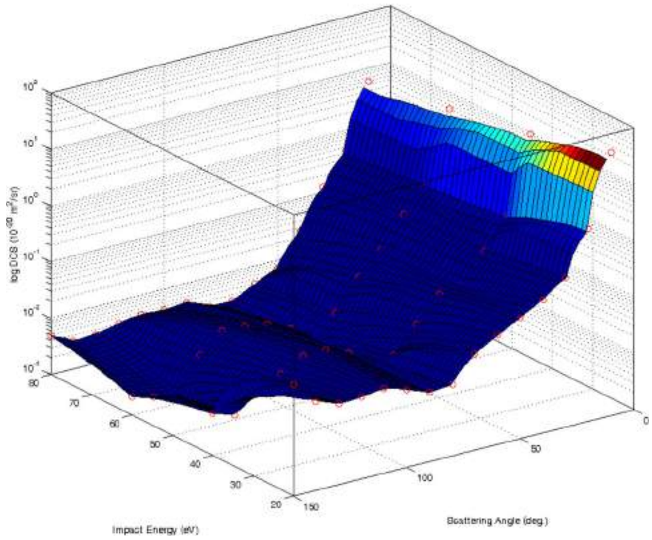

Fig. 1. Differential cross section surface for electron-impact excitation of the $4f^{14}6s6p\ ^1P_1$ state of ytterbium atom. (Data points taken from [24].)

The database contains cross sections that have been already published in peer reviewed journals and therefore have been subject to a full referring procedure. One of the aims of BEAMDB is to collect data sets that are related to the same electron interaction process but provided by different authors. This would make it possible to study the time evolution of data sets and it would facilitate a critical analysis of the different datasets with the final goal to provide a recommended set of data. All data sets are linked to the original article and are fully citable.

2.2 MolD database

MolD database is a collection of cross-sections and rate coefficients for specific collisional processes and a web service within the Serbian Virtual Observatory (SerVO [18]) and the Virtual Atomic and Molecular Data Centre (VAMDC [20,21]). This database contains photo-dissociation cross-sections for the individual rovibrational states of the diatomic molecular ions and rate coefficients for the atom-Rydberg atom chemi-ionization and inverse electron-ion-atom chemi-recombination processes.

Stage 1 of MolD development has been completed by inclusion of data for photodissociation cross-sections of hydrogen H_2^+ and helium He_2^+ molecular ions and the corresponding averaged thermal photodissociation cross-sections and by initial construction of the web interface and some utility programs [26]. We paid special attention to insert data with small temperature steps for hydrogen molecular ion photo-dissociation cross-sections as these

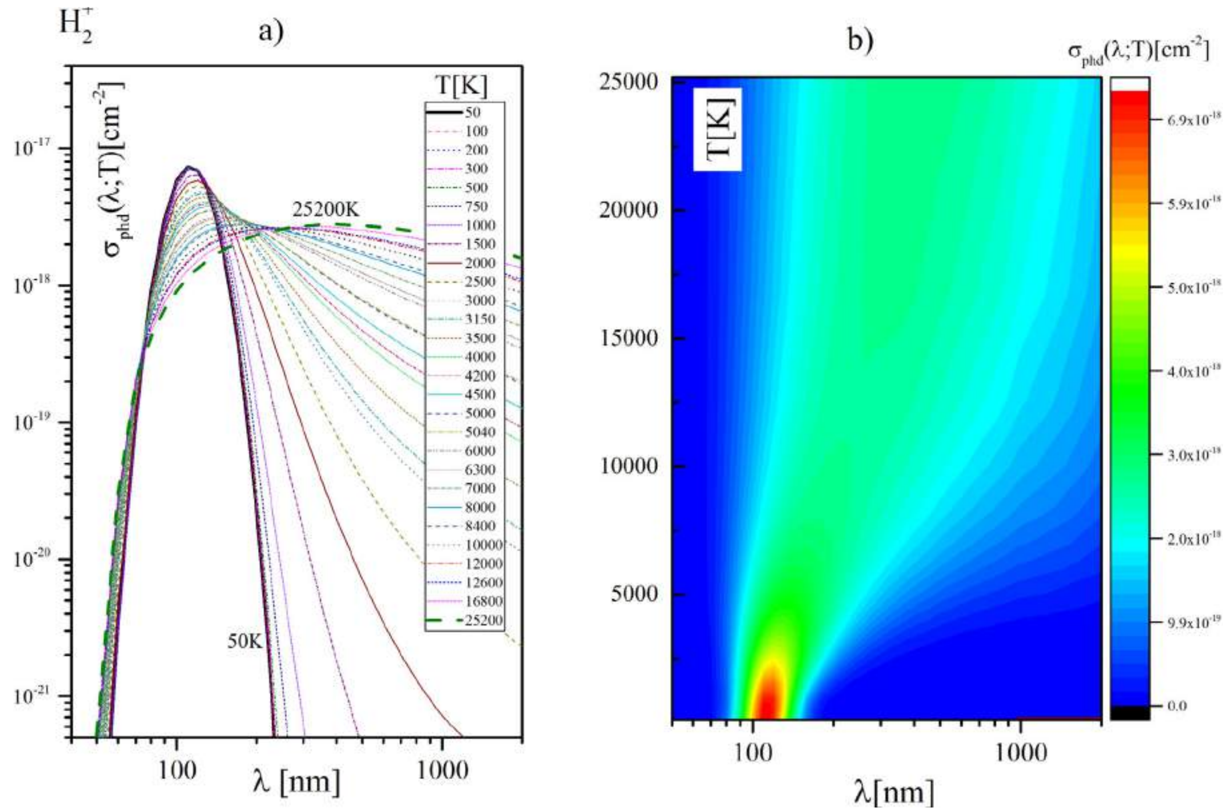

Fig. 2. (a) The behaviour of the averaged cross-section $\sigma_{\rm ph}(\lambda;\, T)$ for photodissociation of the H_2^+ molecular ion, as a function of λ and T. (b) A surface plot of average cross-section as a function of λ and T. (Data points taken from [27].)

data are very important for modelling and studying the chemistry of the early Universe [28].

The cross sections are determined using a quantum mechanical method in which the photodissociation process is assumed to be the result of radiative transitions between the ground and the first excited adiabatic electronic state of the molecular ion A_2^+ (see [27,29,30]). These transitions are the results of the interaction of the electron component of the ion-atom system with the electromagnetic field in the dipole approximation. By exploiting *utility programs* (see Sect. 4) the cross sections are given as Maxwell-Boltzmann averages of the state-to-state resolved cross sections $\sigma_{J;v}(\lambda)$ over the rovibrational distribution function at each temperature.

Figures 2 and 3 present averaged thermal cross sections for H_2^+ and helium He_2^+ molecular ions as a function of wavelengths for a wide range of temperatures. The cross-sections for the photodissociation of individual rovibration state of the considered molecular ions and the corresponding average thermal cross sections $\sigma_{\rm ph}(\lambda;\, T)$ are determined by the dipole approximation (see [26,27]) and are given by

$$\sigma_{J,v}(\lambda) = \frac{8\pi^3}{3\lambda}\left[\frac{(J+1)\left|D_{E,J+1;v,J}\right|^2 + J\left|D_{E,J-1;v,J}\right|^2}{2J+1}\right], \tag{1}$$

where $D_{E;J+1\,v;J}$ is the relevant dipole matrix element, E_{Jv} is the energy of the individual states with the angular and vibrational quantum numbers J and v, respectively, and Z is the partition function

$$\sigma_{\rm ph}(\lambda, T) = \frac{1}{Z}\sum_J\sum_v g_{J;v}\,(2J+1)\cdot e^{-\frac{E_{Jv}-E_{00}}{k_B T}}\sigma_{J,v}(\lambda), \tag{2}$$

$$Z = \sum_J\sum_v g_{J;v}\,(2J+1)\cdot e^{-\frac{E_{Jv}-E_{00}}{k_B T}}. \tag{3}$$

In this expression the product $g_{J;v}\,(2J+1)$ is the statistical weight of the individual states and the coefficient $g_{J;v}$ depends on the nuclear spin. The molecular-ion characteristics (the rovibrational energy states, etc.) are provided (see Fig. 5) as a XSAMS xml file (XML Schema for Atoms, Molecules and Solids [31]) .

The data for hydrogen are important for elaboration of atmosphere models of solar and near solar type stars and for radiative transport considerations as well as an understanding of the kinetics of stellar and other astrophysical plasmas [29,32]. The helium data are of interest particularly for helium-rich white dwarf atmospheres investigations [33–36]. Such data are also important in modelling early Universe chemistry [28,37]. The data is also useful in hydrogen and helium theoretical and laboratory plasmas research [38–40].

MolD is now in *Stage 2*, of its development adding new cross-sections and rate coefficients data for processes which involve diatomic molecular ions HX^+, where

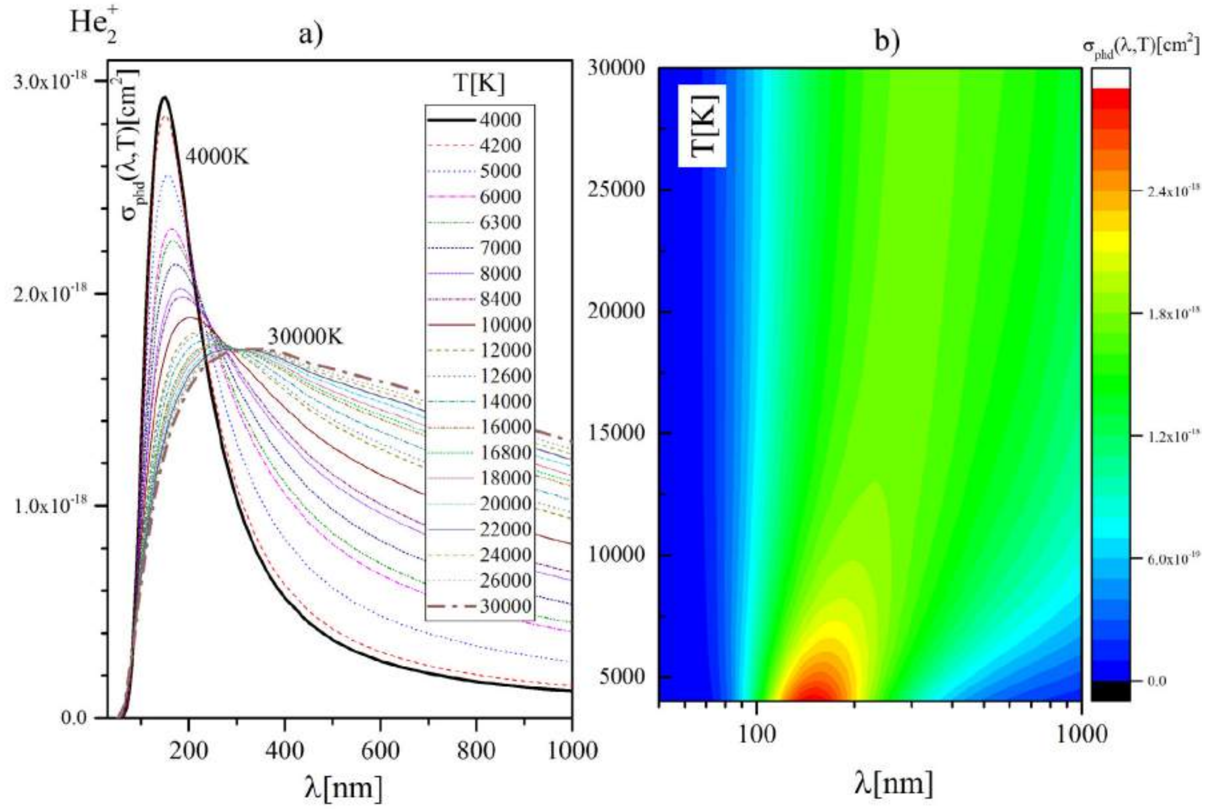

Fig. 3. (a) The behaviour of the averaged cross-section $\sigma_{\rm ph}(\lambda; T)$ for photodissociation of the He_2^+ molecular ion, as a function of λ and T. (b) Surface plot of averaged cross-section as a function of λ and T. (Data points taken from [30].)

$X = $ Mg, Li, Na, …, species such as MgH^+, LiH^+, NaH^+, HeH^+, SiH^+, AlH^+ all which are important for the exploring of the geo-cosmical plasmas, the interstellar medium as well as for studies of the early Universe chemistry and for the modelling of stellar and solar atmospheres (see, e.g. [41–43]). We also plan further development of the web interface. It should be noted that the database only contains cross sections that have been already published in peer-reviewed journals and passed the review procedure. All the data are therefore associated with original papers and can be and are cited by full references.

3 Structure and implementation of databases

3.1 Technical aspects and interoperability

Both BEAMDB and MolD services are compatible with VAMDC standards and act as a VAMDC "nodes" (for the list of nodes, see http://www.vamdc.org/structure/databases/) . They can be accessed by tools, applications or libraries which comply to VAMDC interoperability requirements, such as VAMDC portal query [44] and Astrogrid VODesktop [45]. VAMDC – compliant tools allow for distributed queries across multiple nodes. Data is accessed with a standardized VAMDC-TAP protocol (an extension of IVOA Table Access Protocol) and represented and serialized as XSAMS (XML Schema for Atoms, Molecules and Solids) documents.

BEAMDB and MolD are implemented on top of the VAMDC NodeSoftware [46] in Django [47], a Python framework for web application development. They apply custom-built data models which fit their specific datasets. An all-encompassing VAMDC model would not offer optimal performance and would be more complicated to maintain. In the process of node development customised "dictionaries" (which map VAMDC reserved keywords to local model attributes) are defined as well as query translators (which associate input queries to the local model).

Figure 5 shows sample XSAMS output from the MolD website. Key portions of data are contained under "Species" (properties of atoms, molecules, particles and their states) and "Processes" (quantifications of interactions between species) as well as "Sources" (provenance of data) tags.

A list of species and states currently included in BEAMDB and MolD are shown in Table 1. New data are being added as it becomes available.

3.2 Data models

Static models for both nodes are derived from the UML (Unified Modelling Language) diagram in Figure 4. Key

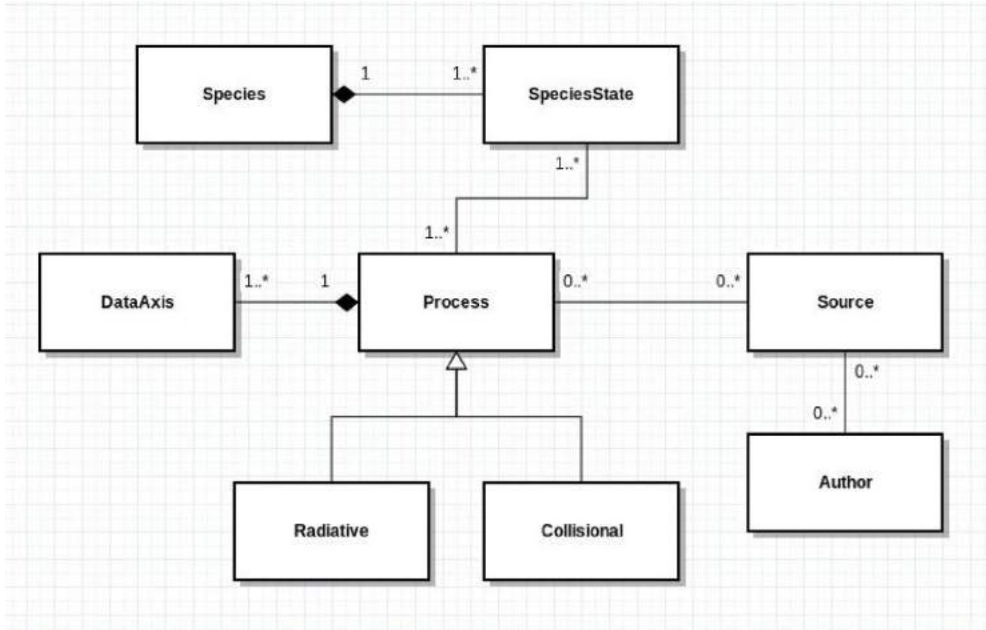

Fig. 4. UML class diagram with high level of abstraction for MolD and BEAMDB nodes.

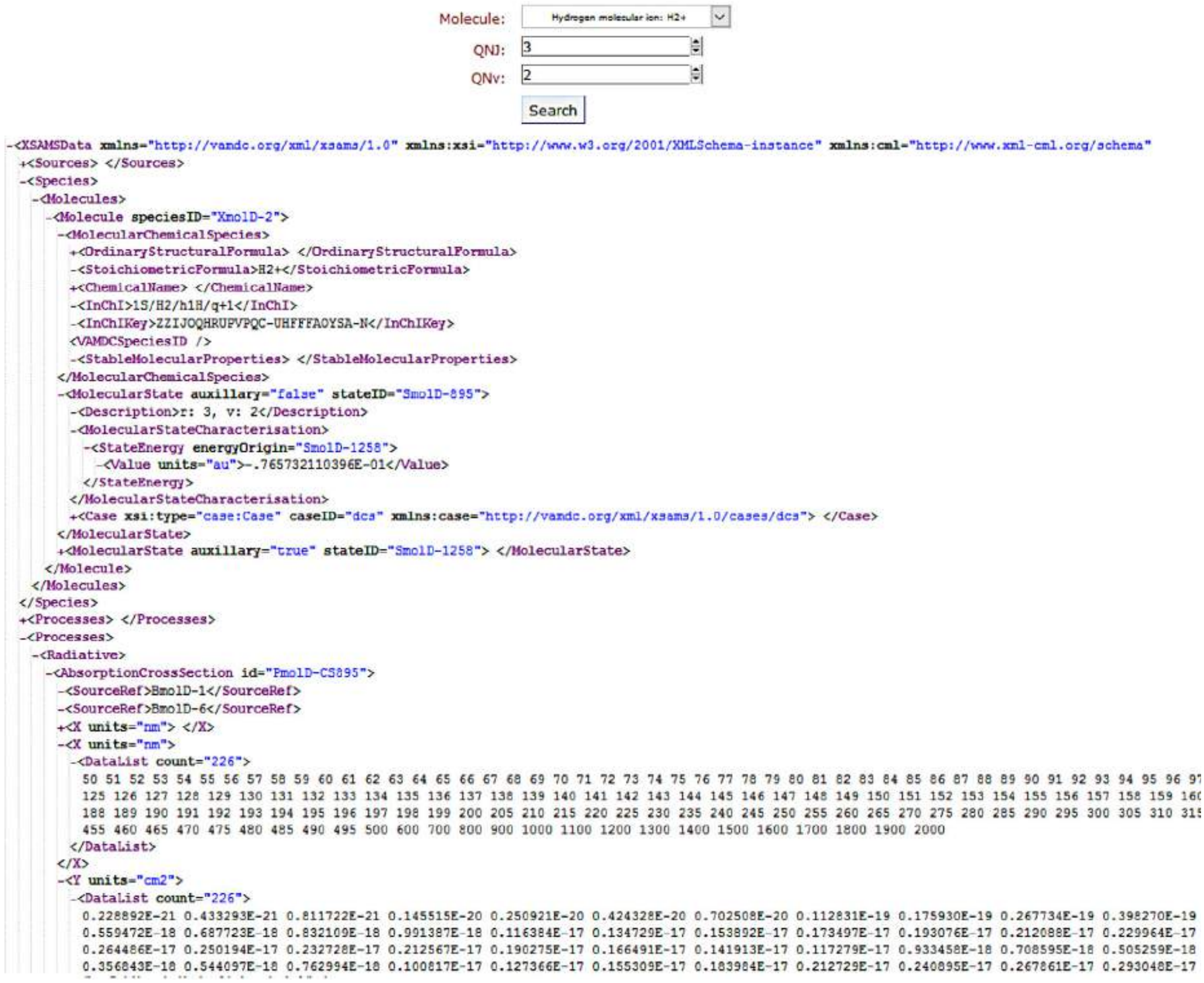

Fig. 5. Sample output from MolD. Data set, represented in XSAMS format.

Table 1. Summary of species and states included in Belgrade databases as of December 2016. Additional data will successively be added.

Species	InChI	States	Node
Ag	1S/Ag	2	BEAMDB
Ar	1S/Ar	1	BEAMDB
Ca	1S/Ca	1	BEAMDB
Cd	1S/Cd	1	BEAMDB
Hg	1S/Hg	5	BEAMDB
Kr	1S/Kr	3	BEAMDB
Mg	1S/Mg	3	BEAMDB
Na	1S/Na	1	BEAMDB
Yb	1S/Yb	1	BEAMDB
He_2^+	1S/He2/c1-2/q+1	834	MolD
H_2^+	1S/H2/h1H/q+1	424	MolD
LiH^+	1S/Li.H/q+1	60	MolD
MgH^+	1S/Mg.H/q+1	600	MolD
NaH^+	1S/Na.H/q+1	50	MolD
C2H5NO N-methylformamide	1S/C2H5NO/c1-3-2-4/h2H,1H3,(H,3,4)	3	BEAMDB
C3H7NO2 alanine	1S/C3H7NO2/c1-2(4)3(5)6/h2H,4H2,1H3,(H,5,6)/t2-/m1/s1	2	BEAMDB
C4H4N2 pyrimidine	1S/C4H4N2/c1-2-5-4-6-3-1/h1-4H	1	BEAMDB
C4H4O furan	1S/C4H4O/c1-2-4-5-3-1/h1-4H	1	BEAMDB
C4H8O tetrahydrofuran	1S/C4H8O/c1-2-4-5-3-1/h1-4H2	1	BEAMDB
CH3NO formamide	1S/CH3NO/c2-1-3/h1H,(H2,2,3)	1	BEAMDB
H2O water	1S/H2O/h1H2	4	BEAMDB
NNO Nitrous oxide	1S/N2O/c1-2-3	4	BEAMDB

Fig. 6. Homepage of BEAMB. It offers an AJAX interface for querying based on collision type, species, species state and cross section type. The interface will automatically show only species available for the selected collision type, states available for the selected species, etc.

entities in the system are Processes, which can specialize to Collisional or Radiative, Species (Atoms or Molecules) with their States and DataAxis which are usually multiple (for 2, 3 or n-dimensional data). Processes can be associated with a scientific source with corresponding authors. Specific UML diagrams and detailed descriptions of the static structure of BEAMDB and MolD nodes are shown in [19,26], respectively.

4 Software and utility programs

Apart from VAMDC-compliant web service, web applications for MolD and BEAMDB (located at http://servo.aob.rs/moldandhttp://servo.aob.rs/emol, respectively) offer on-site AJAX enabled queries and visualizations. A section of MolD website is dedicated to the calculation of Maxwell-Boltzmann averages of the

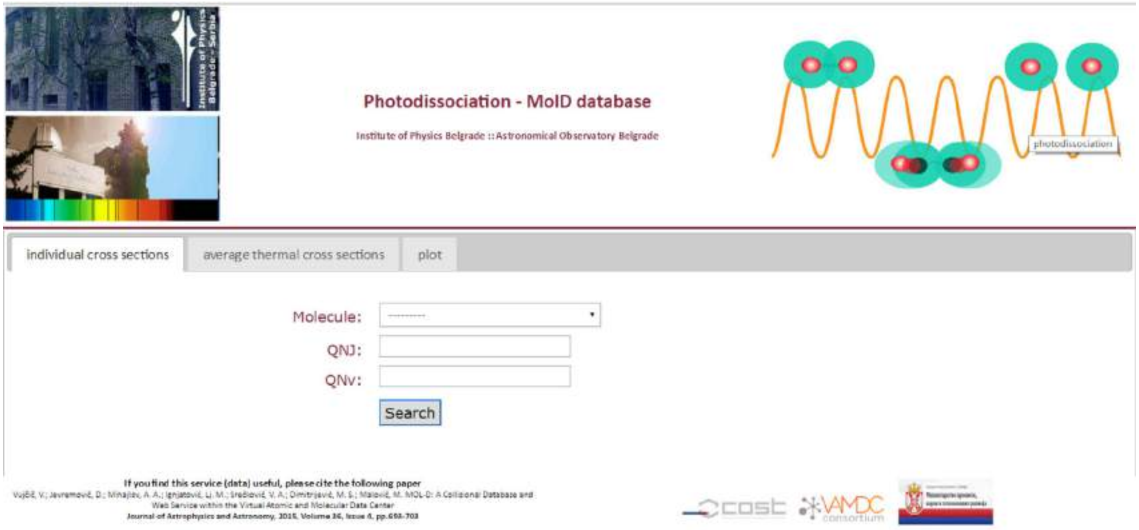

Fig. 7. Homepage of the MolD database.

state-to-state resolved cross sections $\sigma_{J;v}(\lambda)$ over the rovibrational distribution function at each temperature for H_2^+ and He_2^+. Also consumers can request a data plot of the corresponding averaged thermal photodissociation cross-sections in domain of wavelengths at a requested temperature (see Fig. 8). The data is presented both in tabulated and graphical form.

Future developments will mostly concern utilities for visualisation of 2D and 3D data. We are currently working on a manual which will contain the necessary information for using BEAMDB & MolD web interfaces.

5 Website user interface

The quest for data within BEAMBD starts with the selection of a process or type of the spectrum which can be chosen from the drop-down list in *Collision Type* (Elastic, Electronic Excitation, Energy-loss Spectrum, Total scattering, Inelastic, Threshold photoelectron spectrum). For the chosen *Collision Type*, in the combo box of *Species* the choice of available target atoms/molecules will appear. A summarized list of all species (targets) is given in Table 1, while the drop down will appear only those targets for which data are available. The same holds for *Species States (product)* and *Cross Section Type* (Differential, Integral, Momentum Transfer, and Viscosity). If all fields for search are left empty, the result of the search will be the full list of available Sources, Processes and Species.

The database is configured such that it contains the source reference where the data have been published but it does not support the search over the references (journal list or authors). This is because the primary goal of the database is to facilitate the search for specific data and give the output list of data values. Datasets can be downloaded through the VAMDC portal in XSAMS format.

MolD has a graphical interface provided on its "Homepage" (Fig. 7). First, the user clicks on the required molecular ion in the dropdown menu. The user then chooses the individual cross section and/or averaged thermal cross section he/she requires. The web interface offers access to data for photodissociation (bound-free) cross-sections of H_2^+, He_2^+, MgH^+, LiH^+, NaH^+ molecular ions as well as the corresponding averaged thermal photodissociation cross-sections of hydrogen H_2^+ and helium He_2^+ for the requested wavelength and temperature (see, e.g. Figs. 7 and 8).

6 Conclusions and perspectives

In this contribution we have summarized the current stage of development of the Belgrade molecular databases hosted by the SerVO – Serbian Virtual Observatory (http://servo.aob.rs). The databases have been developed using protocols developed by the Virtual Atomic and Molecular Data Centre (VAMDC). We hope that these databases will have an impact in laboratory and stellar plasmas modelling, technological plasmas studies and in education (graduate study level).

We hope that the e-services we have developed will make access to our data fairly easy and understandable to average user (including graduate students) and that the compilation of such data sets will be useful to data producers as well. We intend to update the current nodes/databases with newly calculated/measured data and include completely new databases into the Belgrade VAMDC node. New data entries will be inserted by the authors according to the yearly development plan as well as upon request of data producers if their data had been published in peer review journals. In the near future we aim to further improve the design of our web interface and develop more utility programs that allow online data visualization of a wide range of data.

We acknowledge the contribution of late Dr. A.A. Mihajlov who performed many of calculations and collected much

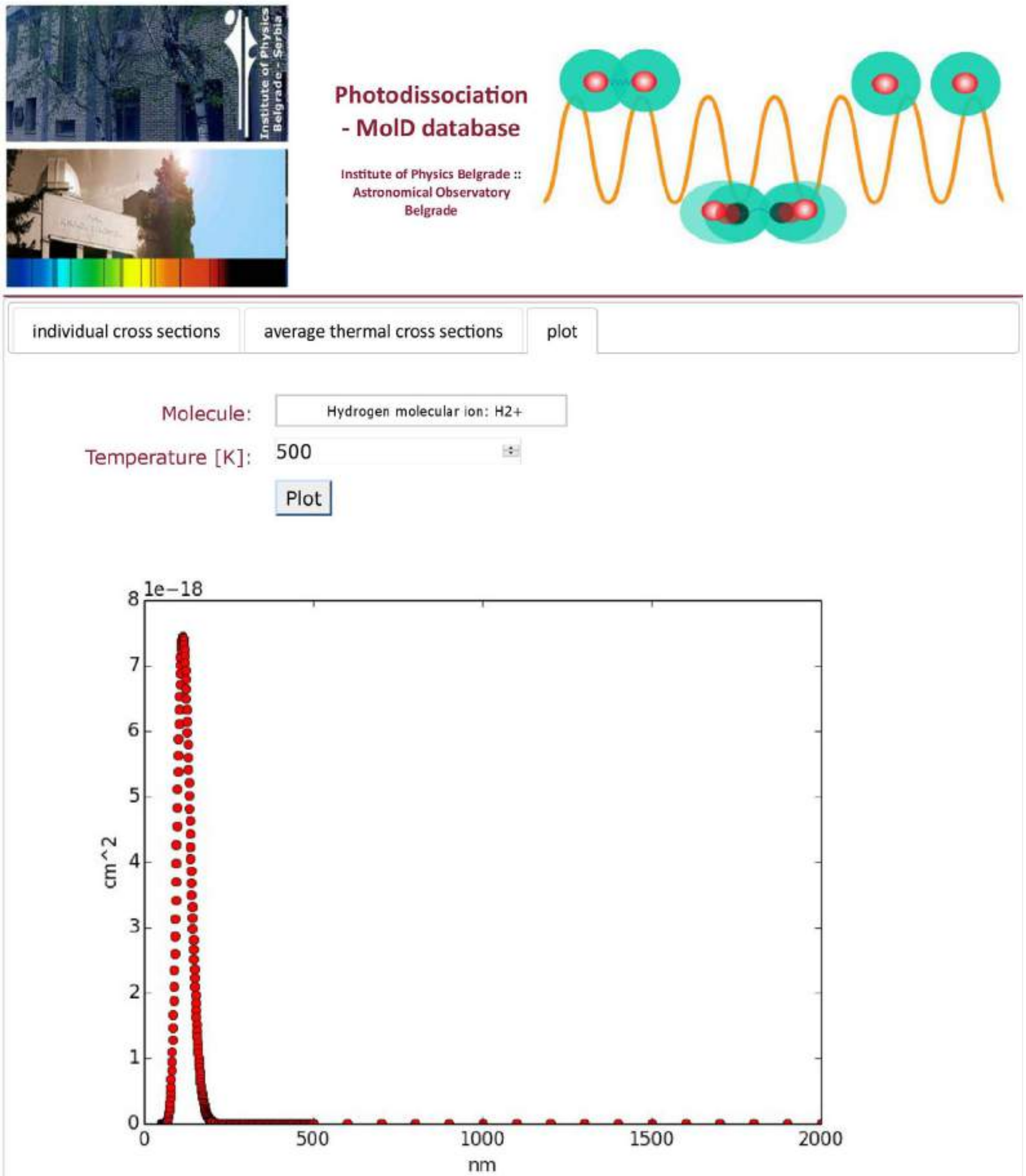

Fig. 8. A queried data plot of averaged thermal photodissociation cross-sections over a range of wavelengths at a requested temperature. The data can also be downloaded in tabulated form.

of the data that are presented within the MolD database. This work has been supported by the MESTD of the Republic of Serbia Grants OI171020, OI176002, III44002 and Nano-IBCT COST Action MP1002 (Nanoscale Insights into Ion Beam Cancer Therapy). Part of this work has been supported by the VAMDC and the SUP@VAMDC projects funded under the "Combination of Collaborative Projects and Coordination and Support Actions" Funding Scheme of The Seventh Framework Program.

Author contribution statement

M.P.B. and N.J.M. have made conceptual design of BEAMDB, V.A.S. and Lj.M.I. have made conceptual design of MolD database, D.J. and V.V. made physical realisation of both databases, B.P.M. and V.A.S. wrote the manuscript, M.S.D. and N.J.M. participated in editing and revising of the manuscript. All authors discussed the results and commented on the manuscript.

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Free-Free Absorption in Solar Atmosphere[1]

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Abstract—The free-free i.e. electron-ion inverse "Bremsstrahlung" characteristics are determined for the case of the solar atmosphere as well as solar interior where such plasma characteristics as plasma density and temperature change in wide region. We demonstrate that determination of these characteristics such as the absorption coefficients and Gaunt factors can be successfully performed in the whole diapason of electron densities and temperatures which is relevant for the corresponding atmosphere model. The used quantum mechanical method of the calculation of the corresponding spectral absorption coefficient and Gaunt factor is described and discussed in details. The results are obtained for the case of a solar photosphere and solar interior model in the wavelength region 10 nm $\le \lambda \le$ 3000 nm. The range of the physical parameters covers the area important for plasma modeling from astrophysical standpoint (white dwarfs, central stars of planetary nebulae, etc). Also, these results can be of interest and use in investigation of different laboratory plasmas.

Keywords: stars: atmospheres, atomic processes, Sun: atmosphere

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1. INTRODUCTION

Free-free i.e. Inverse Bremsstrahlung processes are important radiation mechanism in laboratory and astrophysical plasmas. Anyone interested in these processes must be fascinated by the amount of works about them (D'yachkov, 1990; Hazak et al., 2002; Grinenko and Gericke, 2009a; Mihajlov et al., 2015). For example, Grinenko and Gericke (2009b) stated that inverse bremsstrahlung is the dominant absorption mechanism for lasers with parameters typical for inertial confinement fusion. Plasma in inertial confinement fusion experiments has properties which are similar to the conditions in stellar interiors. Consequently, it is of interest to investigate the role of inverse bremsstrahlung in subphotospheric and deeper layers, and to examine its influence on radiative transfer through such layers. The contribution of inverse bremsstrahlung to the total absorption in stellar atmospheres is not crucial, but its contribution increases with density (i.e. when approaching the Sun interior), and for very dense plasmas it becomes dominant. These processes belong to the type of processes whose efficiency increases proportionally to the square of free-electron density. In addition to other factors that determine the importance of inverse bremsstrahlung, we should bear in mind the existence of a physical area where inverse bremsstrahlung is dominant compared to other processes. The examples which demonstrate this can be found in the literature (Rozsnyai, 2001; Grinenko and Gericke, 2009b; Moll et al., 2012). In the theory of stellar interiors the free-free (i.e. Inverse Bremsstrahlung) contribution to the opacity is significant in parts of the star where details about the structure are of interest i.e. regions of energy generation at the edges of degenerate cores in red giants (see Iben (1968)).

The aim of this work is determination of the corresponding spectral absorption coefficients for inverse "Bremsstrahlung" process and the corresponding Gaunt factors for a broad class of weakly non-ideal plasmas, as well as for plasmas of higher non-ideality. It is shown that this process can be successfully described by cut-off Coulomb potential model within the range of the physical parameters which covers the area important for modeling astrophysical plasma (white dwarfs, solar atmospheres, etc.). The physical sense and the properties of a group screening parameters for two-component systems which are used in this paper are discussed in details in the previous papers (Mihajlov et al., 2009a, 2009b; Ignjatović et al., 2017).

[1] The article is published in the original.

2. THEORY

2.1. Electrostatic Screening Model

In the paper of Mihajlov et al. (2011a) the model of the inner plasma screening was applied for the first time in the investigation of the optical characteristics. The investigated processes are considered as a result of radiative transition in the whole system "electron-ion pair (atom) + the neighborhood", However, as it is well known, many-body processes can sometimes be simplified by their transformation to the corresponding single-particle processes in an adequately chosen model potential.

In this screening model the potential energy of free electron $U_{\rm scr}(r)$ is strictly Coulomb: $U_{\rm scr}(r) = -e^2/r$ in the region $r < r_{\rm cut}$, where $r_{\rm cut}$ is the corresponding cut-off radius, and $U_{\rm scr}(r) = {\rm const} = U_{\rm cut}$ in the region $r > r_{\rm cut}$, where $U_{\rm cut}$ is equal to the average energy of the free electron in the considered system. In the further consideration we take $U_{\rm cut} = -e^2/r_{\rm cut}$ as the zero of energy and describe such plasma by means just of the model cut-off potential given by Eq. (1), which is especially suitable for describing electron-ion scattering within plasma. This potential is given by

$$U(r) = \begin{cases} -\dfrac{e^2}{r} + \dfrac{e^2}{r_{\rm cut}}, & 0 < r \le r_{\rm cut} \\ 0, & r_{\rm cut} < r \end{cases}, \qquad (1)$$

where r is the distance from the coordinate origin, $r_{\rm cut}$ is a parameter defined and determined further on in the text.

Certainly, we assume that the above described electrostatic screening model could be applicable in such a wide range of electron densities and temperatures that this allows to consider it as an almost universal model. For that very reason the cut-off potential Eq. (1) could also be considered as almost universal.

Let us note that in Mihajlov et al. (2011a,b) the universality of the screening model did not arise at all. However, in the case of the electron-ion inverse "Bremsstrahlung" process, which is possible in plasmas with enormous differences of the electron densities and temperature, the situation is opposite.

In order to complete the described model we have to determine the cut-off parameter $r_{\rm cut}$ and the energy parameter $U_{\rm cut}$ as functions of the electron density Ne and the temperature T. Here we will use the fact that these parameters can be determined using the data from Mihajlov et al. (2009a). Namely, the curve presented in figure 4 from Mihajlov et al. (2009a) shows the behaviour of the parameter $a_{\rm cut} = r_{\rm cut}/r_e$ as a function of the ratio $r_{s;i}/r_e$, where r_e and the ion Wigner-Seitz radius $r_{s;i}$ are given by relations

$$r_{s;i} = \left[\frac{3}{4\pi N_i}\right]^{1/3}, \quad r_e = \left[\frac{kT}{4\pi N_e e^2}\right]^{1/2}, \qquad (2)$$

where N_i is the ion density. After that the cut-of radius $r_{\rm cut}$ is determined here as the function of N_e, T by means of relations

$$r_{\rm cut} = a_{\rm cut} r_e, \qquad (3)$$

where the parameter $a_{\rm cut}$ can be directly determined as a function of the ratio $r_{s;i}/r_e$.

2.2. The Cross Section

After an introduction of the potential Eq. (1) the procedure of determination of inverse bremsstrahlung characteristic such as the spectral absorption coefficients, Gaunt factors, is possible.

For the inverse "Bremsstrahlung" cross section $\sigma_{i.b.}^{(\rm ex)}$, the standard expressions from Sobelman (1979) is used, since the potential Eq. (1) has the finite radius. Consequently:

$$\sigma_{i.b.}^{(\rm ex)}(E;E') = \frac{8\pi^4}{3}\frac{\hbar e^2 k}{q^2}\sum_{l'=l\pm1} l_{\max}\left|\hat{D}_{E,l;E'l'}\right|^2,$$
$$\hat{D}_{E,l;E'l'} = \int_0^\infty P_{E'l'}(r) r P_{E;l}(r)dr, \qquad (4)$$

where the radial functions $P_{E;l}(r)$ and $P_{E';l'}(r)$ are the solutions of the radial Schrödinger equation

$$\frac{d^2P_{E;l}(r)}{dr^2} + \left[\frac{2m}{\hbar^2}(E - U(r)) - \frac{l(l+1)}{r^2}\right]P_{E;l}(r) = 0, \qquad (5)$$

and $U(r)$ is the cut-off Coulomb potential given by Eq. (1). The radial functions $P_{E;l}(r)$ of all states which are possible in the potential $U(r)$ are described and discussed in Mihajlov et al. (1986). As the next step, using the transformation characteristics of the matrix element of the solutions $P_{E;l}(r)$ we will replace dipole matrix element $\hat{D}_{E,l;E'l'}$ in Eq. (4) by the matrix element of the gradient of potential energy $U(r)$. This procedure is described by the expressions

$$\left|\hat{D}(r)_{E,l;E'l'}\right|^2 = \frac{\hbar^4}{m^2(E-E')^4}\left|\nabla U_{E,l;E'l'}\right|^2, \qquad (6)$$

$$\nabla_r U_{E,l;E'l'} = \int_0^{r_{\rm cut}} P_{E,l}(r)\nabla_r U(r) P_{E'l'}(r)dr, \qquad (7)$$

where $U(r)$ is given by Eq. (1).

The transition from the dipole matrix element $\hat{D}_{E,l;E'l'}$ to dipole matrix element $\nabla_r U_{E,l;E'l'}$ in the case of $U(r)$ which is given by Eq. (1) means a transition from determination of the quantity $\hat{D}_{E,l;E'l'}$, which cannot be factually calculated, to determination of a quantity which can be calculated routinely. Namely, in the case of this potential the integral of two function of Coulomb continuum from 0 to ∞ gets replaced by the integral of the same two functions, but from 0 to r_{cut}.

2.3. The Absorption Coefficients

On the basses of the used solar models of Fontenla et al. (2007) and Bahcall et al. (2006) we consider here plasmas with electron densities from 10^{14} to $\sim 10^{20}$ cm^{-3} and temperatures from 6000 to 100000 K. In accordance with Adamyan et al. (1994), for such conditions we have that for the electron component, treated as appropriate electron gas on a positively charged background, the value of chemical potential is practically equal to the classical one, so that the distribution function for electrons is Maxwellian $f_T(v) = 4\pi(m/2\pi kT)^{3/2} v^2 e^{-mv^2/2kT}$, for the given temperature T. Consequently:

$$\kappa_{i.b.}^{(\text{ex})}(\varepsilon_\lambda; N_e, T) = N_e^2 \int_0^\infty \sigma_{i.b.}^{(\text{ex})}(E; E') v f_T(v) dv \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \tag{8}$$

where the expression in parentheses takes into account the effect of stimulated emission. Additionally, the quasi classical Kramer's $k_{i.b.}^{q.c.}(\lambda, T; Ne)$ we take (see e.g. Sobelman (1979)) as:

$$k_{i.b.}^{q.c.}(\lambda, T; Ne) = N_e^2 \frac{16\pi^{5/2}\sqrt{2}e^6}{3\sqrt{3}cm^{3/2}\varepsilon_{ph}^3} \frac{\hbar^2}{(kT)^{1/2}} \left(1 - \exp\left[-\frac{\hbar\omega}{kT}\right]\right), \tag{9}$$

where $\varepsilon_{ph} = 2\pi\hbar c/\lambda$, and the averaged Gaunt factor $G_{i.b.}(\lambda, T)$ is:

$$k_{i.b.}^{(\text{ex})}(\lambda, T; N_e) = k_{i.b.}^{q.c.}(\lambda, T; N_e) G_{i.b.}(\lambda, T), \tag{10}$$

where $k_{i.b.}^{(\text{ex})}(\lambda, T; Ne)$ and $k_{i.b.}^{q.c.}(\lambda, T; Ne)$ are given by Eqs. (8) and (9).

3. RESULTS AND DISCUSSION

The contribution of inverse bremsstrahlung to the total absorption in stellar atmospheres is not crucial, but its contribution increases with density (i.e. when approaching deeper in the Sun interior), and for very dense plasmas it becomes dominant. Consequently, it is of interest to investigate the role of inverse bremsstrahlung in subphotospheric and deeper layers, and to examine its influence on radiative transfer through such layers. In addition to other factors that determine the importance of inverse bremsstrahlung, we should bear in mind the existence of a physical area where inverse bremsstrahlung is dominant compared to other processes. Moreover, we expect a major contribution to inverse bremsstrahlung process in a dense highly ionized plasma (see e.g. Fig. 3, the marked region of r) in the process of transfer of radiation. Here we mean the high electron density and temperature that occur in the interior of the Sun which are in Fig. 3 presented as a function of radius (Standard Solar Models Bahcall et al. (2006)).

In Fig. 1 on left side is presented the behavior of the temperature T and N_e as a function of height h within the considered part of the solar atmosphere model of Fontenla et al. (2007). In Fig. 1 on right side is shown the surface plots of Gaunt factor as a function of wavelength and height h for the case of a solar atmosphere model from Fontenla et al. (2007). From this figure one can see that the values of the Gaunt factor strongly depend on the atmosphere parameters, mainly temperature, as well as on photon wavelengths.

In Fig. 2, are shown the plots of absorption coefficient of all considered absorption processes for the case of a solar atmosphere model from Fontenla et al. (2007) as a function of height for various values of wavelengths. Here h is the height of the considered layer with the respect to the chosen referent one. The corresponding plasma parameters are presented in Fig. 1 left panel. The electron-atom processes which are treated sometimes as the H^- continuum, are represented here by their common plot which in these figures is marked by EA (κ_{EA}). With IA i.e. κ_{ai} atom-ion symmetric and non-symmetric processes (Ignjatović et al. 2014; Srećković et al. 2014) are represented. From this figure one can see that the inverse "Bremsstrahlung" absorption coefficients are comparable with the concurrent ones especially in the region of higher electron density and temperature $h \leq -70$ km (left part of Fig. 2). Consequently, we can conclude that influence of inverse "Bremsstrahlung" process increases with temperature, density as well as with increase of wavelength.

Figure 3 left panel present the electron density and temperature in the interior of the Sun as a function of radius for the Standard Solar Models (Bahcall et al., 2006). On the right panel is presented the surface plots of Gaunt factor as a function of wavelength and radius for the Standard Solar Model (Bahcall et al., 2006). The plots of absorption coefficients of considered absorption processes for the case of a Standard Solar Model (Bahcall et al., 2006) are presented in Fig. 4. From this figure one can see that the values of the Gaunt factor strongly depend on the plasma parameters, mainly temperature, as well as on photon wavelengths. The values of the absorption coefficients in Fig. 4 increase with density and temperature increment i.e. when the value of ratio r/R decreases from 1 to 0.98 (when approaching deeper in the Sun interior). This result confirmed the increase of importance of inverse bremsstrahlung process when we go deeper into the interior of the Sun.

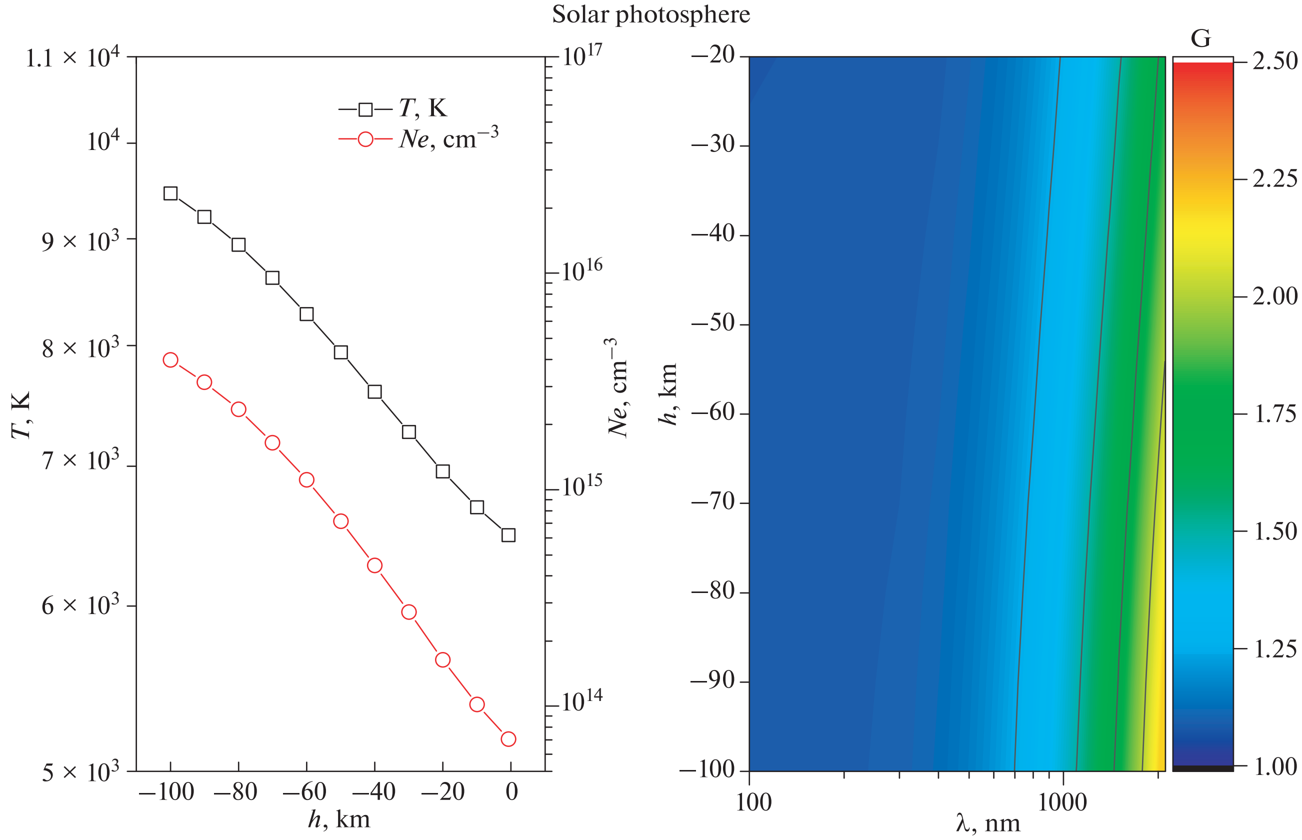

Fig. 1. Left side: the behavior of the temperature T and N_e as a function of height h within the considered part of the solar atmosphere model of Fontenla et al. (2007). Right side: the surface plots of Gaunt factor as a function of wavelength and height h for the case of a solar atmosphere model from Fontenla et al. (2007).

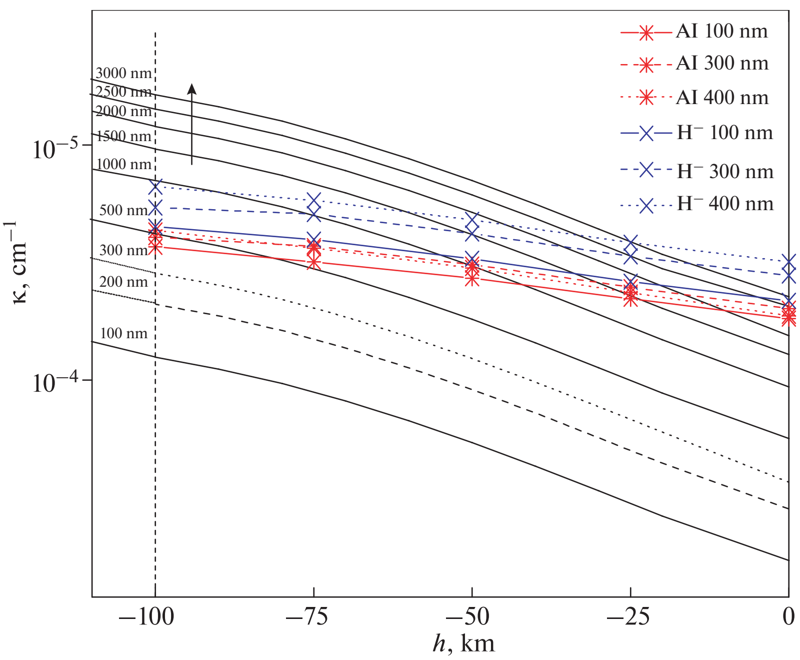

Fig. 2. The plots of absorption coefficients of considered absorption processes for the case of a solar atmosphere model from Fontenla et al. (2007). With black lines are denoted *ff* absorption processes i.e. inverse "Bremsstrahlung" absorption coefficients, with blue electron-atom i.e. H^- continuum and with red ion-atom absorption coefficients (Ignjatović et al. (2014); Srećković et al. (2014)). The extrapolated values are in the left shaded region in front of the dashed line.

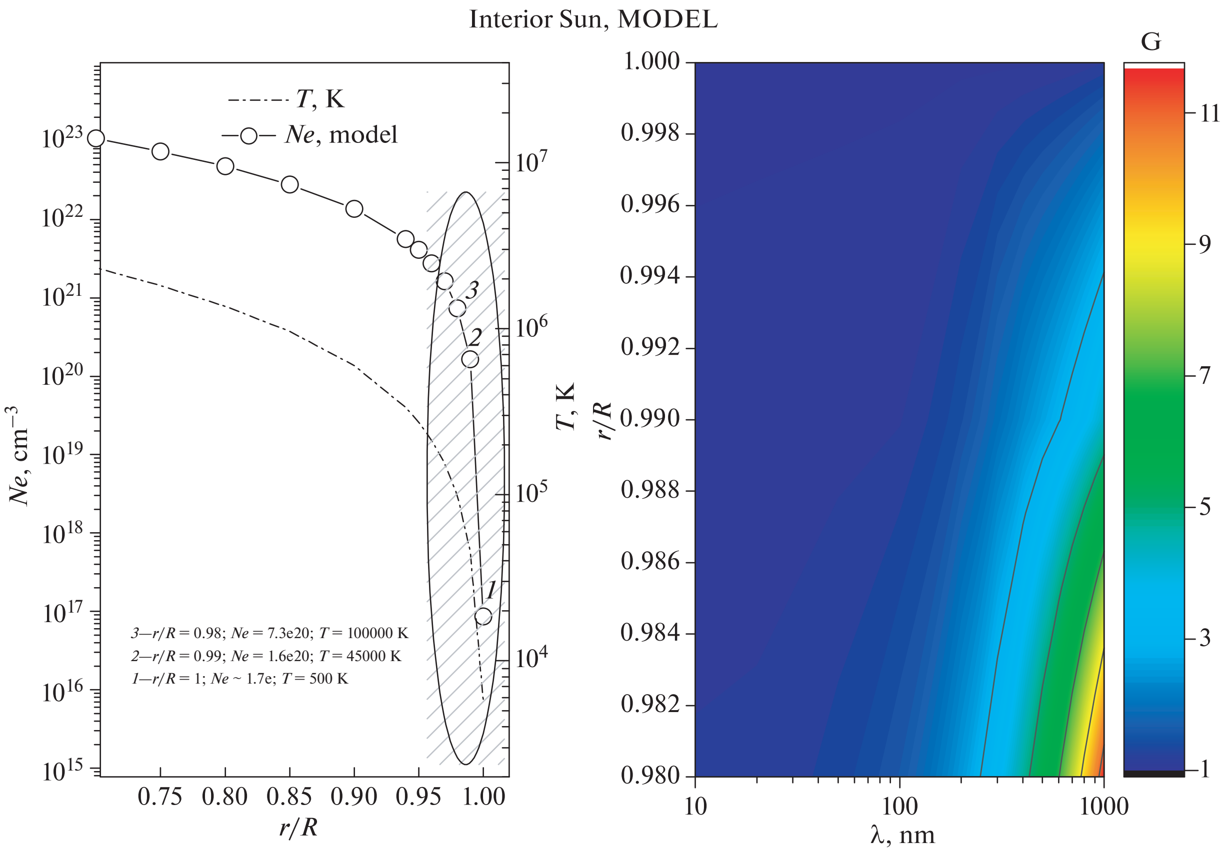

Fig. 3. Left: The electron density and temperature in the interior of the Sun as a function of radius for the Standard Solar Models (Bahcall et al., 2006). Right: the surface plots of Gaunt factors as a function of wavelength and radius for the investigated regions of solar interior.

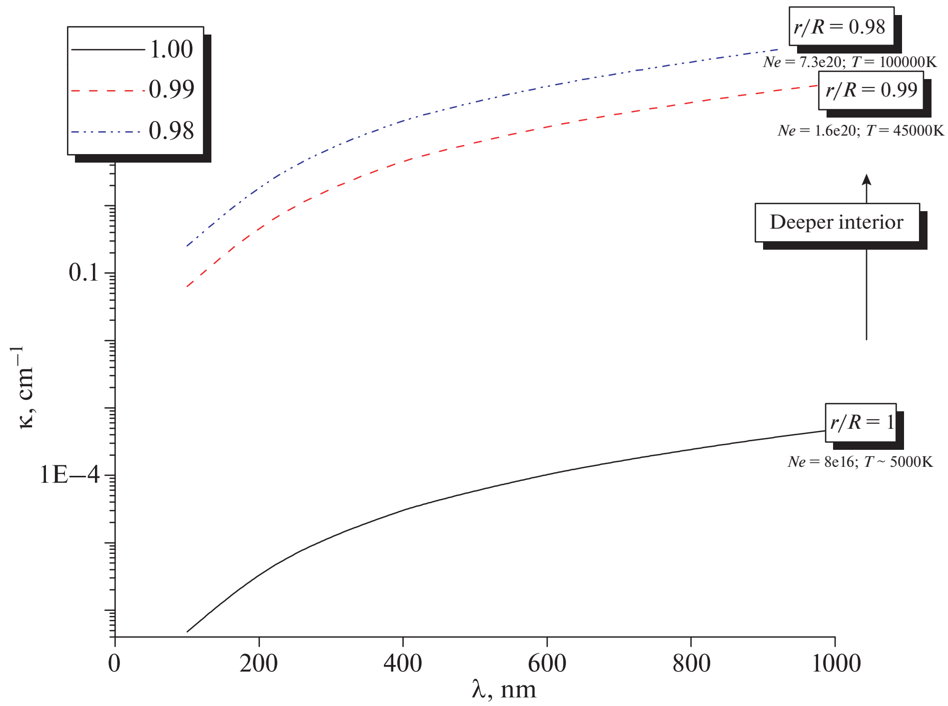

Fig. 4. The plots of absorption coefficients of considered absorption processes as a function of wavelength and radius in the investigated regions of solar interior (Standard Solar Model [2]).

The presented quantum-mechanical method is used to obtain the spectral coefficients for inverse “Bremsstrahlung” process and the corresponding Gaunt factors for a broad class of moderately non-ideal plasmas, as well as for plasmas of higher non-ideality. The range of the physical parameters covers the area important for plasma modeling from astrophysical standpoint (stellar atmospheres, central stars of planetary nebulae, etc.). The contribution of inverse bremsstrahlung to the total absorption in stellar atmospheres increases with density, and for very dense plasmas it becomes dominant. Finally, we are also able to notice that the data are highly sensitive to change of the temperature. Also, the data depend on the wavelength region i.e. absorption coefficients increase with increase of wavelength.

Further directions of development of the method would be determination of absorption coefficients and Gaunt factors for two-component systems (ions with an arbitrary charge Z and electron component) Mihajlov et al. (2009b) as well as for three-component systems (two kinds of ions with different charges and electron component) Ignjatović et al. (2017).

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Review

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Dynamics Resonances in Atomic States of Astrophysical Relevance

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Abstract. Ionized geocosmic media parameters in a thermal and a subthermal range of energy have a number of unique features. The photoresonance plasma that is formed by optical excitation of the lowest excited (resonance) atomic states is one example of conversion of radiation energy into electrical one. Since spontaneous fluorescence of excited atoms is probabilistic, the description of the radiating quantized system evolution along with photon energy transfer in a cold atom medium, should include elements of stochastic dynamics. Finally, the chaotic dynamics of a weakly bound Rydberg electron over a grid of the energy level diagram of a quasi-molecular Rydberg complex provides an excitation migration of the electron forward to the ionization continuum. This work aims at discussing the specific features of the dynamic resonances formalism in the description of processes involving Rydberg states of an excited atom, including features in the fluorescence spectrum partially caused by the quantum defect control due to the presence of statistic electromagnetic fields.

Key words. Rydberg quasi-molecule—stochastic dynamics—spectral lines emission.

1. Introduction

Publications on astrophysics have traditionally paid attention to the processes involving highly excited (Rydberg) atom: in stellar atmospheres of late spectral types, interstellar nebulae and other space objects, including our solar system. The concentration of periodic table elements in geocosmic entities can exceed their average concentration in the Universe by many orders of magnitude. The examples include the clouds of alkali atoms K and Na in the atmosphere of the Galilean satellite Io of the planet Jupiter and chemi-ionization processes that result in the formation of a wide range of molecular ions. The constants of these processes in the thermal interval of energy can reach values of the order of $10^{-9}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ (see, for example, Klyucharev *et al.* 2007). Since the characteristics of Rydberg states of atoms and quasi-molecular complexes are with certain exceptions (which are described in terms of a quantum defect theory) close to those of a hydrogen atom, they are nowadays widely used in solving current problems of nonlinear dynamics of quantized systems.

Physics and chemistry of low-temperature plasma are most interested in the processes where a transition of an optical electron into ionization continuum changes the nature of particles and occurs in thermal collisions. These processes are traditionally considered as an effective channel of molecular ion formation. According to publications, the maximum values of effective constants of the formation of a stable charged complex in binary collisions correspond to the value range of principal quantum numbers $5 \leq n \leq 25$ (see, for instance, Mihajlov *et al.* 2012).

Enrico Fermi made the fundamental contribution into the physics of atomic collisions involving Rydberg atoms (RA). He suggested treating the structure of the Rydberg diatomic quasi-molecular complex as the system of two Coulomb centers and a quasi-free Rydberg electron (RE) on the trajectory orbit (Fermi 1934). Cold ($\sim 90\,\mu$K) molecules of alkali atoms were observed in magneto-optical traps.

Today, the study of phenomena that determine evolution and stochastic properties of deterministic Hamiltonian systems is an important branch of nonlinear mechanics with potentially interesting applications in atomic and molecular physics. Research in the field of non-linear mechanics (Zaslavsky *et al.* 1991; Sagdeev *et al.* 1988) indicates that dynamic chaos conditions should be treated as a typical rather than an exceptional situation for the dynamics of Hamiltonian systems with small number of degrees of freedom. In the physics of atomic collisions under the semi-classical treaty, chaos conditions arise as a result of unstable trajectory orbits of optical electrons. Generally, there are always regions of phase space and parameters of a system of interacting particles, where the Hamiltonian system dynamics is stochastic. The transition from integrable problems of classical dynamics to a system with chaos is accompanied by the emergence of areas in the phase space that are the centers of chaos and form 'stochastic layers' and a 'stochastic web' (Zaslavsky *et al.* 1991). Even in a one-dimensional problem with a time-variable external disturbance, the effects of dynamic chaos may occur.

A complete review of data (more than 280 references) obtained before 1995 with regard to the dynamics of the optical electron in an excited hydrogen atom in external microwave and alternating electric fields can be found in Koch & van Leeuwen (1995). The work of Delone *et al.* (1983) is noteworthy as it influenced the development of theoretical and experimental research in the field of dynamic chaos phenomena in excited atom systems. This research grounded the applicability of quasi-classics in describing the development of dynamic chaos phenomena in a quasi-hydrogen Rydberg alkali atom and showed the difference of the arising process of 'stochastic diffusion' from multiphoton and tunnel ionizations in a diatomic quasi-molecular complex. In the diffusion case, the stochasticity domain in the principal quantum number space is $n_{\min} < n < n_{\max}$, where $n < n_{\min}$ are states with the outer electron regular motion, and $n > n_{\max}$ belong to continuous spectrum states defined by Chirikov criterion (Chirikov 1979).

Today quasi-classical approximation of quantum mechanics (Sagdeev *et al.* 1988) involving Bohr–Sommerfeld quantum conditions with its visual interpretation is widely and practically applied in atomic physics. Within its framework, the main results have been obtained so far with regard to the problem of associative ionization occurring in the intermediate state of a Rydberg quasi-molecular diatomic complex (Mihajlov *et al.* 2012).

Importantly, the stochastic ionization treaties for quasimolecular collision complexes or under situations when ionization is stimulated by external microwave fields are essentially one-dimensional since they are based on the assumption that the RE orbital momentum $\vec{L}$ remains invariant in the process of RE diffusion. The issue how $\vec{L}$ evolves in the case of the actual three-dimension quantum systems and whether this evolution can significantly affect the results of one-dimensional approaches is briefly outlined in the present paper. Another important issue is related to the influence of the external statistic electromagnetic fields on the atomic quantum states structure and, as a consequence, on the values of dipole matrix elements. The latter determines the rate constant values in the equations describing radiation/impact kinetics of geocosmic media, so that the quantum defect control by external fields can serve as a means to manipulate both the Rydberg complexes emission spectra and the collision ionization. It is known that direct analogies exist between the processes in the laboratory (Earth's) plasma and geocosmic plasma. In the atmospheres of helium-rich cooling white dwarfs stars, as well as in Earth conditions in the temperature range of $(12-16) \cdot 10^3$ K with ionization degree of the order of 10^{-3}, chemi-ionization plays a major role in the balance of ionization-recombination processes with $n \geq 10$ (Ignjatović *et al.* 2008). Hereinafter the system of atomic units (at. u.) is used.

2. Dipole resonance ionization model for Rydberg quasi-molecular complexes (DRM-theory)

The atoms in the upper excited states with values of effective quantum numbers $n^* \geq 5$ have unique characteristics conditioned by the strong dependence of their parameters on n^*: polarizability $\sim n^{*7}$, dipole moment $\sim n^{*2}$ etc., making them effective partners in inelastic atomic and molecular collisions. The dipole resonance ionization mechanism is briefly described below according to Mihajlov *et al.* (2012). So far the absolute majority of calculations of ionization processes occurring in the intermediate state of a Rydberg quasi-molecular complex have been performed within the framework of that ionization model. The Rydberg quasi-molecular complex A_2^{**} stabilization or decay with the formation of charged fragments are determined by the set of such parameters as peculiarities of interaction potentials, the nature and the level of particle excitation, and the relative collision energy. The main contribution into the ionization occurs in the range of internuclear distances R at which the weakly bound (outer) electron becomes shared within the parent complex A_2^+. Charge exchange in that complex induces the generation of a time varying dipole moment $\sim R(t)$ that, in turn, causes the emergence of a quasi-monochromatic microwave electric field perturbing Rydberg electron (RE) motion in the Keplerian orbit. The corresponding charge exchange frequency $\omega(R)$ appears to be equal to the exchange interaction $\Delta(R)$ or, equivalently, to the frequency of complete rotations of the low-bound electron orbital motion. The probability of autoionization decay of the complex A_2^{**} is proportional to R^2 and depends on the value of the RE photoionization cross-section, i.e. on the probability of the RE stimulated transition from the bound state with the binding energy $E_i^*(n) < 0$ into the states of a continuous spectrum with the electron kinetic energy $\varepsilon_k = p_k^2/2 \geq 0$. The emitted electron energy coincides with the energy released during the transition of the initial state of $A_2^{**}(R)$ into the state $A_2^+(R)$, that is reflected in the 'dipole resonance mechanism' of the process.

It should be noted that today, the interest in chemi-ionization of Rydberg atoms is experiencing a renaissance due to the need to take them into account in the quantum electronics physics, on the one hand, and on the other hand, due to the negative impact of Rydberg complexes induced by geomagnetic disturbances in the Earth's ionosphere on our biosphere, including the human being per se. Deterministic DRM-theory has played a major role in understanding the processes that underlie ionization mechanisms involving Rydberg atoms. Moreover, the model is valid for both a symmetrical and an asymmetrical process (Smirnov & Mihailov 1971). A new feature of the DRM-theory largely stimulate the development of experimental research, for example, the use of synchrotron radiation to excite molecular clusters (Krainov 2010).

3. Non-linear dynamic resonances in atomic systems in an external time-depending electric field

In the literature, the term 'dynamic chaos' in atomic systems refers to the result of the evolution of deterministic (causal) quantized atomic systems, which dynamics over time cannot be accurately predicted. As an example, consider three options:

(i) Rydberg hydrogen atom or quasi-hydrogen alkali atom in an external electric (electromagnetic) field (Delone *et al.* 1983; Krainov 2010).
(ii) Rydberg collisional quasi-molecular complex, i.e. Rydberg quasi-molecule.
(iii) The diffusion ionization of Rydberg collision complexes with a strong non-adiabatic connection between electron motion and nuclear motion.

The above-cited papers by Delone *et al.* (1983) and Krainov (2010) formulate the traditional approach to the problem of the excited atom behavior in an external microwave electric field, show the applicability of a quasi-classical description for RE dynamics which starts with the initial energy ε_0. The field perturbation causes the main change $\Delta n = n - n_0$ in the principal quantum number n_0 of the initial state of the atom when the external field angular frequency ω_L coincides with the circular frequency of the electron motion in the Keplerian orbit $\omega_c = n^{*-3}$ (resonance). In the case of alkali atoms, the effective quantum number n^* differs from the principal one n on the value of the quantum defect δ_l: $n^* = n - \delta_l$. Essentially, the authors of Delone *et al.* (1983) (see also Gontis & Kaulakys 1987) suggested a stochastic ionization mechanism unparalleled in tunnel ionization or multiphoton ionization, i.e. the diffusion ionization mechanism. In quantum mechanics, this is explained within the model of 'multiphoton' resonance, under which the m-photon energy coincides with the energy level separation of an excited particle. Quasi-classical approach connects the stochastization effect with the emergence of a stationary term $U_{k,m}(\varepsilon)$ in the perturbing series that formally corresponds to the m-photon resonance when the product $m\omega_L$ coincides with the RE k-overtone: $m\omega_L = k\omega_c$, where m and k are integer numbers. In this case the value of the excited atom energy ε begins to oscillate in the vicinity of its 'undisturbed' value ε_0 with the width of the nonlinear resonance $\delta\varepsilon$.

$$\delta\varepsilon^2 \sim \omega_c U_{k,m}(\varepsilon)/(d\omega_c/d\varepsilon), \quad \varepsilon = \varepsilon_0 = -1/(2n_0^{*2}). \tag{1}$$

Two fixed energy levels that have the quantum numbers n_0 and $n_0 + k$ mix most effectively when m-photon resonance is realized,

$$m\omega_L = \Delta\varepsilon = \varepsilon(n_0 + k) - \varepsilon(n_0) \approx k\omega_c(n_0), \tag{2}$$

i.e. the m-photon energy $m\omega_L$ coincides with the energy spacing $\approx k\omega_c$ between the levels. In the literature, this situation is called the implementation of dynamic nonlinear resonance for the 'resonance' energy $\varepsilon_{k,m} = \varepsilon(n_0)$. Only in this case, the external perturbation can significantly distort the initial (unperturbed) motion of the electron. Note also the root (non-linear) dependence of $\delta\varepsilon$ on the value of the disturbing potential.

The emergence of the finite width of nonlinear resonance for nonlinear systems ($d\omega_c/d\varepsilon \neq 0$) is crucial for the formulation of global (strong) chaos conditions. Generally speaking, in the energy space with a given external excitation, a discrete set of 'resonant' energies $\varepsilon_{k,m}$, which are conditioned by nonlinear resonances of different orders, can be realized (along with the corresponding quantum numbers $n_{k,m}$). In the case of a weak excitation, the widths $\delta\varepsilon$ of neighboring resonances do not overlap, i.e. $\delta\varepsilon < \Delta\varepsilon$. If the system motion starts with the initial energy value $\varepsilon = \varepsilon_0$, the system always remains 'bound' within the width $\delta\varepsilon$. The situation changes radically when the regions of neighboring nonlinear resonances begin to overlap, i.e. $\delta\varepsilon > \Delta\varepsilon$. Now the electron can 'diffuse' in the neighborhood of any nonlinear resonance and go away from its initial position as far as can be in the energy space. The resonance overlap condition is known in the literature as Chirikov criterion for the onset of the global chaos (Chirikov 1979).

The ratio $K = \delta\varepsilon/\Delta\varepsilon$ (Chirikov parameter) equals one was shown to be the threshold of the global chaos realization. Note that the widths of dynamic resonances and, consequently, the effects of stochastic dynamics are directly related to the matrix elements of perturbation operators. This observation is confirmed by the data in Bezuglov *et al.* (2002), where the coefficients of the light-induced RE diffusion equation in an external microwave field are explicitly expressed using dipole matrix elements of an external field. Some results of the theory of dynamical chaos, which are useful for carrying out relevant assessments may be found in the works of Koch and van Leeuwen (1995), Delone *et al*. (1983), Krainov (2010), Kaulakys & Ciziunas (1987), Bezuglov *et al*. (2001), Kaulakys & Vilutis (1999) and Bezuglov *et al*. (2014).

Studies of the dynamic chaos in quantized systems place high demands on the numerical algorithms stability at large times. Efimov *et al*. (2014a, b) and Balaraman and Vrinceanu (2007) suggest to use geometric integration methods of Hairer (1999) in describing evolution of a Rydberg atom in external fields. These methods combine the enhanced stability of symplectic methods of differential equations numerical solution with the efficiency (calculation speed). The improved method of split evolutions was also applied in calculations on the base of Floquet technique (Chu & Telnov 2004) that allows extending the algorithms used for nonstationary problems. As a result, an algorithm for calculating RE trajectories in the Coulomb potential perturbed with a microwave electrical field was elaborated (Efimov *et al.* 2014a, b).

We show in Figure 1 numerical results on the chaotic diffusion dynamics of RE in a hydrogen atom which evolves from the initial state 10p (with the principal $n_0 = 10$ and orbital $l = 1$ quantum numbers) to the ionization continuum in the presence of the external microwave field $\vec{E} = \vec{E}_0 \cos(\omega_L t)$. The field frequency is taken as $\omega_L = 3/10^3$ at. u. The field amplitude $E_0 = |\vec{E}_0|$ is chosen to exceed the critical value $E_c = 2/(49n_0^4)$, (Delone *et al.* 1983; Krainov 2010) for the onset of the dynamic chaos regime. When the amplitude $E_0 > E_c$, all dynamic resonances occurring in the region $n > n_0$ overlap, so that RE may free-diffuse into continuum. Under the semi-classical approach the description of the wave-function evolution is carried out in terms of the RE classical trajectories characteristics such as the energy ε and the angular momentum $\vec{L}$. The initial value L_0 of $L = |\vec{L}|$ is determined, for instance, via the initial orbital quantum number l with the semi-classical formula $L_0 = l + 0.5 = 1.5$ (Delone *et al.* 1983; Reetz-Lamour *et al.* 2006) while the initial energy ε_0 of the trajectory is obtained via equation (1). We are concerned mainly with the situations when L tends to change significantly, i.e. the states with various l mix. Data of Figure 1 correspond to two basic configurations resulting in the maximum possible variations of L: (i) RE plane motion ($\vec{L}_0 \perp \vec{E}_0$, figures (a) and (b)) with the amplitude $E_0 = 16.4/(49n_0^4)$ and (ii) RE three-dimensional motion ($\vec{L}_0 \parallel \vec{E}_0$, figures (c) and (d)) with $E_0 = 12.9/(49n_0^4)$.

However, data in Figure 1 do not negate the results of the initial one-dimensional diffusion ionization theory of Delone *et al*. (1983) and Krainov (2010) that takes into account the chaotic migration of RE only along the energy spectrum without regard to changing L. Importantly, it is well seen that L variations in the process of diffusion remains below its critical value $L_c \sim l = 10$, exceeding of which results in deviations from one-dimensional theory (Delone *et al.* 1983; Krainov 2010). As it turns out with lower values of $L < L_c$, the diffusion rate constants calculated using the equations of Fokker–Planck type practically does not depend on L (Krainov 2010), so that L variations with amplitude less than L_c do not affect the one-dimensional approach for RE stochastic ionization.

4. Specific features of stochastic and radiative processes under double Stark resonance

Today the research in spectral composition of Rydberg atoms is one of the main trends in physics of Earth's atmosphere and astrophysics. In the literature, the case where one of the levels of l-series of an atom is located in energy space exactly between the two levels of adjacent series $(l-1)$ or $(l+1)$ is called Föster resonance or double Stark resonance (Walker & Saffman 2005). This configuration corresponds to a two-photon resonance for a cascade transition $(l-1, n) \rightarrow (l, n) \rightarrow (l-1, n+1)$ (see Fig. 2). Such situation occurring when $\delta_{l-1} - \delta_l = 0.5$ in terms of the

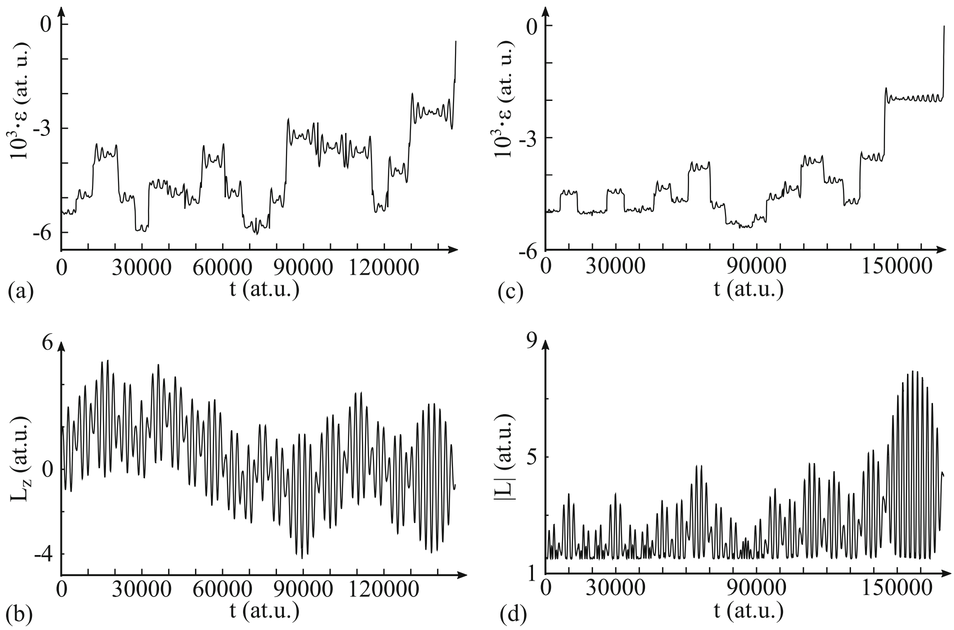

Figure 1. Evolution of the Rydberg electron energy ε ((**a**) and (**c**)) and its angular momentum $\vec{L}$ ((**b**) and (**d**)) for 10p state ($n_0 = 10$, $l = 1$) of hydrogen atom. In the case of RE plane motion ((a) and (b)), (b) exhibits the projection L_Z of $\vec{L}$ on the direction $\vec{L}/|\vec{L}|$ orthogonal to the plane of RE motion. (d) corresponds to three-dimensional RE motion and shows the length $\vec{L} = |\vec{L}|$ of the angular momentum.

quantum defect δ is typical for Rydberg alkali atoms (in the case of Na, for instance, $\delta_{l=0} - \delta_{l=1} \approx 0.493$), while it is absent in the hydrogen atom. Today, the literature on spectroscopy considers this phenomenon as a prospective option for manipulating cold atoms in a laser field (Shore 2011; Reetz-Lamour *et al.* 2006). The configuration of atomic levels that meets the case of double Stark resonance presented in Fig. 2 is similar to that of a three-dimensional quantum oscillator according to the second Bohr correspondence rule (Sommerfeld 1934), where 'long' optical transitions are forbidden (see Fig. 2). In other words, it is a matter of most of the transitions being blocked due to a significant decrease in the values of their dipole matrix elements. Both electron diffusion over the grid of quasi-crossing energy curves of a Rydberg complex and radiative processes should be damped under the realization of Föster resonance.

As an illustration, we consider RE features in alkali atoms which can be modeled with Sommerfeld potential $U_\alpha(r) = -1/r + \alpha/(2r^2)$ (Sommerfeld 1934), where α is a parameter of our model. In the case of Hydrogen atom the parameter α is zero. For alkali atoms α-values should be found from spectroscopic data using the following relation between the quantum defect δ_l of l-atomic series and the parameter α: $\delta_l = l + 0.5 - [(l + 0.5)^2 + \alpha]^{1/2}$. The conditions of Föster resonance implementation $\delta_{l-1} - \delta_l = 0.5$ for a Sommerfeld atom corresponds to the parameters α values $\alpha_l = 3(l^2 - 1/16)$ (Zakharov *et al.* 2011). In the particular case of the $\{p, s\}$ series it yields $\alpha_p = 2.81$, whereas $\alpha_d = 11.8$ for the $\{d, p\}$ series. The particularities

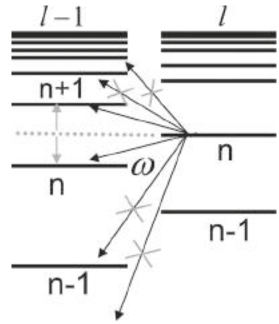

Figure 2. Schematic energy levels diagram for two series {l − 1} and {l} that realize the Föster resonance. The levels structure is identical to that for a three-dimensional oscillator and in accordance with the oscillator selection rules (Sommerfeld 1934) allow dipole optical transitions between adjacent levels only.

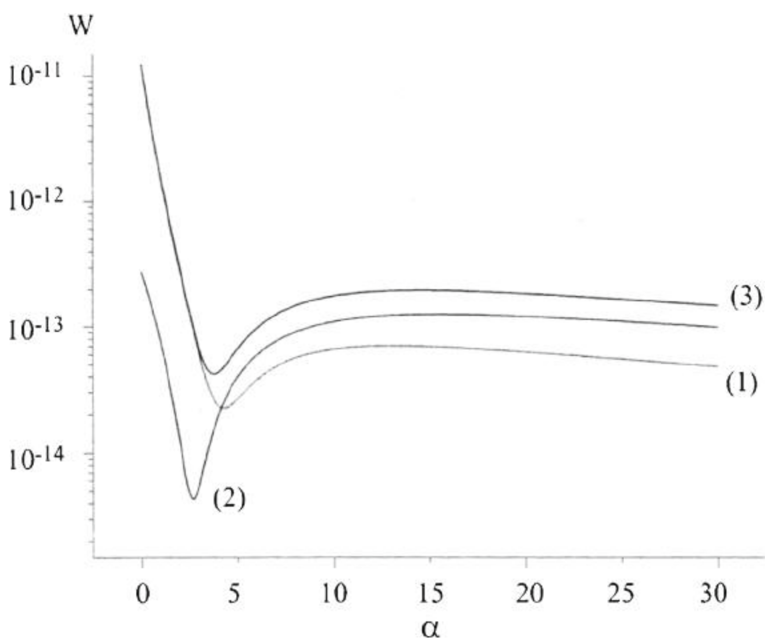

Figure 3. Partial probabilities $W_{p\to s}$ (curve (1)) and $W_{p\to d}$ (curve (2)) (atomic units) of spontaneous transitions for the state 13p ($n = 13$, $l = 1$) as functions on the model parameter α entering into Sommerfeld potential $U_\alpha(r)$. Curve (3) shows the behavior of the total spontaneous decay rate $W_p(n) = W_{p\to s} + W_{p\to d}$.

of stochastic ionization were discussed in work of Zakharov *et al.* (2011) where it was demonstrated a threefold increase in the time of the diffusion ionization in the vicinity of the double Stark resonance. Here we present calculations (see Fig. 3) for the total probabilities $W_{l\to l'}(n)$ of the spontaneous transitions of nl-state at all lower lying levels of the fixed l'-series ($l' = l \pm 1$). We choose the initial Rydberg state of p-series ($l = 1$) with $n = 13$. It is well seen a significant decrease (at three orders of magnitude) of spontaneous transitions probabilities in the vicinity of the critical value $\alpha_p = 2.81$, where blocking the dipole matrix elements takes place due to Föster resonance (see Fig. 2). Those important facts should be properly accounted for in the radiation-collisional kinetics in the atmospheres of celestial objects under the presence of quasi-static electric/magnetic fields resulting in essential Stark/Zeeman shifts of atomic levels. One of the consequences, for instance, may be dramatic redistribution of Rydberg states ($n \sim 10$) populations with the subsequent changes in IR emission spectra.

5. Conclusion

In the literature, the term 'chaotic' refers to quantum-mechanical or quasi-classical ensembles. It implies a probabilistic description of physical phenomena which cannot be reduced to a conventional notation of an individual wave functions or a trajectory. The main reason for the conversion of a regular atomic system into chaotic one under the influence of external time-varying forces is mainly connected with the emergence of the so-called 'dynamic nonlinear resonances'. Their mutual overlapping results in the emergence of a global dynamical chaos. In this paper, the stochasticity is considered with regard to diffusion ionization, arising due to complicated energy levels of a Rydberg quasi-molecular collisional complex or stimulated by an external weak microwave field. We discussed as well a possibility of blocking dipole optical transitions in a Rydberg atom due to the quantum states shifts under the presence of statistic electromagnetic fields and described the corresponding dramatic changes in both the dynamic chaos regime and kinetics of radiative processes. Important specific futures of the double Stark resonance are outlined that are of interest for the interpretation of the observed fluorescence spectra in astrophysics.

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Changes of atmospheric properties over Belgrade, observed using remote sensing and in situ methods during the partial solar eclipse of 20 March 2015

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ABSTRACT

Measurements of atmospheric parameters were carried out during the partial solar eclipse (51% coverage of solar disc) observed in Belgrade on 20 March 2015. The measured parameters included height of the planetary boundary layer (PBL), meteorological parameters, solar radiation, surface ozone and air ions, as well as Very Low Frequency (VLF, 3–30 kHz) and Low Frequency (LF, 30–300 kHz) signals to detect low-ionospheric plasma perturbations. The observed decrease of global solar and UV-B radiation was 48%, similar to the solar disc coverage. Meteorological parameters showed similar behavior at two measurement sites, with different elevations and different measurement heights. Air temperature change due to solar eclipse was more pronounced at the lower measurement height, showing a decrease of 2.6 °C, with 15-min time delay relative to the eclipse maximum. However, at the other site temperature did not decrease; its morning increase ceased with the start of the eclipse, and continued after the eclipse maximum. Relative humidity at both sites remained almost constant until the eclipse maximum and then decreased as the temperature increased. The wind speed decreased and reached minimum 35 min after the last contact. The eclipse-induced decrease of PBL height was about 200 m, with minimum reached 20 min after the eclipse maximum. Although dependent on UV radiation, surface ozone concentration did not show the expected decrease, possibly due to less significant influence of photochemical reactions at the measurement site and decline of PBL height. Air-ion concentration decreased during the solar eclipse, with minimum almost coinciding with the eclipse maximum. Additionally, the referential Line-of-Sight (LOS) radio link was set in the area of Belgrade, using the carrier frequency of 3 GHz. Perturbation of the receiving signal level (RSL) was observed on March 20, probably induced by the solar eclipse. Eclipse-related perturbations in ionospheric D-region were detected based on the VLF/LF signal variations, as a consequence of Lyα radiation decrease.

1. Introduction

Abrupt change in the incoming solar radiation flux during solar eclipse induces disturbances in different atmospheric layers (Gerasopoulos et al., 2008; Aplin et al., 2016). These disturbances are not necessarily similar to those during sunset/sunrise, because of different time scales and initial conditions. They depend on a number of factors, including the percentage of sun obscuration, latitude, season, time of the day, synoptic conditions, terrain complexity and surface properties. Since solar energy impacts the atmosphere primarily by convection of heat from the ground, lower atmospheric layers are more influenced by changes in solar radiation. The layer of the atmosphere in direct interaction with the surface, thus directly influenced by the Earth's surface forcing, is called the planetary boundary layer (PBL). Since surface is also a source of humidity and pollutants, turbulence within the PBL is responsible for mixing and dispersion of pollutants, while air pollution concentrations in the PBL are generally higher than those in the free troposphere (Stull, 1988).

A number of studies have focused on the effect of solar eclipse on various atmospheric properties, mainly in PBL. Changes in meteorological parameters near the ground level were most extensively investigated, for several eclipse events (Anderson, 1999; Ahrens et al., 2001; Kolarž

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et al., 2005; Founda et al., 2007; Nymphas et al., 2009). The studies reported decrease in temperature and wind speed, changes in wind direction and increase in relative humidity, as a result of solar eclipse. The magnitude of these changes varied in different studies. Decrease in height of the PBL during solar eclipse was also observed (Kolev et al., 2005; Amiridis et al., 2007). The PBL quickly responds to surface forcing and its height can range from as low as a few hundred meters to a few kilometers. Diurnal cycle of the PBL height starts with the sunrise by heating of the surface and development of a convective boundary layer (CBL), reaching a steady state in the afternoon. The CBL remains as a residual layer until the development of a new mixing layer on the following day. A region of statically stable layer – the entrainment zone forms at the top of the PBL. It closely follows the PBL development, being shallow in the morning and thickening during the day due to intense turbulence and vigorous convection (Stull, 1988). During a solar eclipse, the change in the incoming radiation is more abrupt and affects the evolution of the PBL (Amiridis et al., 2007; Kolev et al., 2005), thus providing opportunity for investigating mechanisms involved in PBL evolution.

Some studies investigated eclipse-related changes in ozone concentration (Zerefos et al., 2001; Kolev et al., 2005; Zanis et al., 2001, 2007), due to its strong dependence upon the magnitude of UV flux (Bian et al., 2007). Tropospheric ozone (O_3)is the result of chemical reactions, mostly between nitrogen oxides (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs), helped with UV radiation via process of photo-dissociation of O_3. Surface ozone concentrations were reported in literature to decrease during solar eclipse, with exception of unpolluted sites (Zanis et al., 2001, 2007).

Reported observations suggest increase in air ion (Kolarž et al., 2005; Aplin and Harrison, 2003 and references therein) and air radon concentrations (Gaso et al., 1994 and references therein) during solar eclipse, mainly attributed to PBL height decrease. Air ions are natural constituents of the atmosphere produced mostly by cosmic rays (20% of overall ionization) and natural radioactivity from soil (gamma decay of ^{40}K)and the air (^{222}Rn). The first two ionization sources mentioned above are nearly constant in time, and consequently changes of air ion generation areprimarily related to changes in Rn concentration. The background concentration of cluster air ions in lower troposphere vary from a few hundred to a few thousand ions cm^{-1}, with an average near-ground ionization rate of 10 ion pairs $cm^{-3}s^{-1}$. Air ions are neutralized mostly by ion-to-ion recombination and ion-aerosol attachment (Dolezalek, 1974). Their concentration changes diurnally: during the night, when the boundary layer conditions are stable concentrations are high, with maximum at dawn. During the day, with the development of convective boundary layer, air ion concentration decreases with minimum in the afternoon (Blaauboer and Smetsers, 1996). Radon and aerosol-carried Rn progenies are powerful air ionizers (energy of α particle decay is more than 5 MeV, while average ionization energy of air is 34 eV/ion pair) and thus the main source of cluster air ion pair production in the troposphere. Radon exhalation from the ground is determined by concentration of uranium, diffusion coefficients and porosity of soil layers on the way to surface (Ishimori et al., 2013). Average Rn concentration over the continents is 10 Bq m^{-3} (UNSCEAR, 1993).

The solar eclipse also influences ionosphere. In the upper part of this area variations in plasma frequencies are detected (Verhulst et al., 2016). Also, there are detected plasma variations in the lower ionosphere (see e.g. Guha et al., 2010; Maurya et al., 2014). One of the ways to register the variations of solar radiation impact within upper atmosphere is based on technology of radio waves which are reflected in ionosphere during propagation between emitters and receivers. Namely, the signal reflection height in the ionosphere and, consequently, parameters describing signal characteristics (propagation geometry, altitude distributions of refractive index and attenuation) depend on local plasma properties (primarily on electron density) (Bajčetić et al., 2015). Electron density declines during solar eclipse, similarly to sunset, resulting in increase of the reflection height of radio signals reflected on relevant atmospheric layer (Guha et al., 2010), as well as the occurrence of hydrodynamic waves (Nina and Čadež, 2013; Maurya et al., 2014). Because of that, the registered wave variations reflect the non-stationary physical and chemical conditions in the medium, along the considered wave trajectories, in real time. In addition to plasma parameters related to low ionosphere, several parameters describing signal propagation, like distance between transmitter and receiver, influence temporal changes in recorded signal characteristics. Because of that, the electron density decrease (or increase) can result in either increase and decrease of recorded amplitude (Grubor et al., 2008). Thus, only variation from the expected values is important for detection of influences of an event on low ionosphere.

The aim of this paper is to study atmospheric disturbances detected in Belgrade, induced by partial solar eclipse (51% coverage of solar disc) on March 20, 2015. Focusing on troposphere (mainly PBL) and ionosphere (D-region). For that purpose, four experimental setups were used to collect data, including lidar (Light Detection and Ranging) for measurement of PBL height and heights of elevated layers, AWESOME (Atmospheric Weather Electromagnetic System for Observation Modelling and Education) VLF/LF receiver (Cohen et al., 2010) and instruments for measurements solar radiation, meteorological parameters, concentrations of ozone, air ions and radon, and propagation of radio signals in troposphere.

The paper is organized as follows. In Section 2 we describe measurements and methods used in the study, and give overview of background conditions. The results are described in Section 3, and a conclusion of this study is given in Section 4.

2. Measurements and methods

2.1. UVradiation, ozone and air-ion measurements

UV-B erythemal radiation was measured using 501 biometer made by Solar light company, USA. Instrument was set on the roof of the Institute of Physics Belgrade (IPB), so that no obstacles entered the field of view. During the eclipse, data acquisition was set to 10 min. Global Sun radiation was measured by Republic Hydro-meteorological Service in Belgrade using Kipp&Zonen CMP6 pyranometer (http://www.kippzonen.com/Product/12/CMP6-Pyranometer), with 1-min data acquisition. Surface ozone measurements were conducted using Aeroqual monitor, series 500 (http://aeroqual.com/product/series-500-portable-air-pollution-monitor), made in New Zealand. The instrument was placed near UV 501 biometer and acquisition was set to 6 min. Air ions, temperature, pressure and relative humidity were measured using a Cylindrical Detector and Ion Spectrometer CDIS (Kolarž et al., 2011), made at IPB. The CDIS was placed 1 m above grassy surface (where the soil allows the radon exhalation), at IPB (44.86° N, 20.39° E, 89 m a.s.l.). Only positive air ion concentrations were measured since they have lower mobility than negative ions and consequently lower ion-to-aerosol attachment coefficient. Thus, they are less sensitive to air pollution and provide better picture of atmosphere processes. Radon was measured using continual radon measuring instrument RAD7, Durridge company, USA. Quality of continual Rn measurements is related to level of radon concentration and measuring period, i.e. counting events. The instrument was placed next to CDIS at the same level.

2.2. Measurements of meteorological parameters

The meteorological measurements were obtained at two semi-urban sites in Belgrade. One measurement site was located at IPB. At the site, temperature, relative humidity and atmospheric pressure at altitude 1 m above ground were measured. The meteorological measurements were also available from an automatic weather station collocated with a SYNOP station at Košutnjak, Belgrade (WMO no. 13275, 203 m a.s.l.), about 10 km away from the IPB site.

2.3. Detection of PBL height

A variety of methods can be used to quantify the PBL height, depending on available measurements (Emeis et al., 2008). Differences between PBL and free troposphere can be observed using vertical profiles of thermodynamic quantities and wind from radiosounding measurements. Lidar observations, using atmospheric aerosol as a tracer, can be used to determine heights of both PBL and elevated aerosol layers if present in the atmosphere.

In this study radiosounding and lidar measurements were used to determine PBL height. While radiosoudings are regularly available at 00UTC and 12UTC at the WMO station, providing meteorological data on mandatory and significant pressure levels, the advantage of lidar measurements is that they can be performed continuously with high vertical andtemporal resolutions. Data derived from lidarmeasurements can be used for detection and characterization of aerosols and PBL evolution, and allow for the detection of abrupt and smaller scale changes in the layer structure.

The lidar system at IPB, is a bi-axial system with combined elastic and Raman detection designed to perform continuous measurements of suspended aerosol particles in the PBL and the lower free - troposphere. It is based on the third harmonic frequency of a compact, pulsed Nd:YAG laser, emitting pulses of 65 mJ output energy at 355 nm with a 20 Hz repetition rate. The optical receiver is a Cassegrain reflecting telescope with a primary mirror of 250 mm diameter and a focal length of 1,250 mm. Photomultiplier tubes are used to detect elastic backscatter lidar signal at 355 nm and Raman signal at 387 nm. The detectors are operated both in the analog and photon-counting mode and the spatial raw resolution of the detected signals is 7.5 m. Averaging time of the lidar profiles during the March 2015 solar eclipse case was 1 min corresponding to 1,200 laser shots.

Lidar measurements can be used to estimate PBL height using different approaches (Sicard et al., 2006; Baars et al., 2008). In this study, the gradient method was used to determine the position of the strongest gradient of the aerosol vertical distribution, associated with the PBL height (Flamant et al., 1997). The height of a strong negative peak which can be identified as the absolute minimum of the range corrected signal's (RCS) derivative, determines the PBL top height. A strong negative gradient in lidar RCS is a result of decrease in aerosol backscatter due to decrease in aerosol concentration and humidity (Matthias et al., 2004). Our estimate of PBL height is based on lidar measurements at 355 nm. However, when available, measurements at larger wavelengths (i.e. 532 nm and 1,064 nm) are more appropriate for analysis of PBL height due to smaller relative contribution of molecular backscatter compared to 355 nm. Other local minima in the signal derivative, with absolute values above a specified threshold and with transition intervals including a minimum of five points, are associated with elevated aerosol layer top heights in the free troposphere (Flamant et al., 1997).

The Richardson number is used for PBL height estimation from radiosounding measurements. Radiosoundings are performed two times each day, at 00 and 12 UTC, at a weather station (Belgrade Košutnjak, WMO number 13275), 10 km away from the lidar measurement site at 203 m altitude. The Richardson number is defined as (Stull, 1988):

$$R_{ib} = \frac{g[z - z_0][\theta(z) - \theta(z_0)]}{\theta(z)\left[u(z)^2 + v(z)^2\right]} \tag{1}$$

where g is acceleration due to gravity, z_0 is the altitude of the weather station, $\theta(z)$ is the potential temperature and $u(z)$ and $v(z)$ are zonal and meridional components of the wind. The layers in which R_{ib} is above a critical value of 0.21 (Vogelezang and Holtslag, 1996; Menut et al., 1999) are considered to be above the PBL.

Since the data are available at discrete heights, at standard and significant pressure levels, the bulk Richardson number is used (Stull, 1988). Successful estimation of the PBL height from radiosounding measurements from stations in the WMO network, has been previously reported (Jeričević and Grisogono, 2006; Amiridis et al., 2007). Average uncertainty of the PBL height was estimated for March for a 10-year period from 2006 to 2015, from radiosounding profiles retrieved at 12 UTC. Typical resolutions varied from 100 m to 1,000 m, and the uncertainty of PBL height H was estimatedusing the following formula:

$$H = H_{estimated} \pm \frac{\Delta z}{2} \tag{2}$$

where Δz is the measurement resolution (Jeričević and Grisogono, 2006). It was calculated to be 180 m corresponding to the average vertical resolution of 350 m. On the eclipse day, the resolution and the uncertainty were estimated to be 150 m and 80 m, respectively.

2.4. Terrestrial line-of-sight radio communication measurement setup

The referential Line-of-Sight (LOS) radio link was set in the area of Belgrade, using the carrier frequency of 3 GHz, with the purpose of investigating solar eclipse contribution to receiving signal level (RSL) instability.

The transmitter was emitting non-modulated carrier, having the radio frequency (RF) output power level of 0 dBm. LOS link was established at the distance of 70 m. The signal was transmitted using the signal generator with the frequency stability of TCXO $\leq \pm 0.5$ ppm and signal level stability $\leq \pm 0.7$ dB which was housed at constant temperature. Antenna emitted horizontally polarized electromagnetic (EM) wave. The receiving system (Rx) was formed with Tektronix SA2600 spectrum analyser that was programmed to perform 1 kHz width spectral recording into 500 points. In this way, the generated signal spectrum at the receiving side could be reconstructed with an accuracy of 2 Hz, which made it possible to monitor temporal changes in the level of the received signal peak.

The measuring samples of the received signal level were recorded every 45 s equidistantly during continuous operation of the LOS link. On 20 March 2015, we made 480 recordings through 6 h, includingthe solar eclipse period.

2.5. Ionospheric observations

Global experimental setup for the low ionospheric observation is based on continuously emitting and receiving the VLF/LF signals by numerous worldwide-distributed VLF/LF transmitters and receivers, respectively. In this study, we based our analysis on D-region monitoring using the 37.5 kHz LF signal emitted by the NRK transmitter located in Grindavik (Iceland) and received at IPB by the AWESOMEVLF/LF receiver. This transmitter was chosen because the path of this signal passes through an area that was affected by a total eclipse.

2.6. Background conditions

The eclipse on March 20, 2015 started at 8:40 UTC, ended at 10:58 UTC, reaching maximum coverage of 51% at 9:48 UTC. In the days prior to the eclipse, the synoptic conditions were influenced by a cyclone moving to the east, over Balkans, followed by an increase in geopotential. Wind field was characterized by northwesterly flow shifting to northerly. On the day of the eclipse surface conditions were influenced by weak-gradient anticyclonic field. On the previous day, overcast skies with light rain in the evening were reported. From the morning of the March 20 and during the day, the sky was clear. The calm meteorological conditions provided good opportunity to observe possible eclipse-related changes in meteorological parameters near surface.

3. Results

3.1. Global and UV radiation

Primary effect of solar eclipse is reduction of solar radiation reaching the surface. In Fig. 1 diurnal variation of global sun radiation and UV-B erythemalradiation are shown for the day of the solar eclipse, and for three clear days after the eclipse. Solar eclipse on March 20 occurred during morning increase of both global and UV-B radiation due to sun elevation. Their attenuation was 48%, slightly smaller than the obscuration of the solar disc (51%). This difference could be due to diffuse solar irradianceknowing that UV-B radiation is the shortest wavelength reaching the surface and thus most prone to scattering. While the direct solar irradiance is reduced proportionally to the obscuration of solar disc during the eclipse, the diffuse irradiance is less affected due to contribution of multiple scattering from less shadowed part of the sky (Zerefos et al., 2001). They reported that the difference in reduction of diffuse and direct irradiance was more pronounced at shorter wavelengths.

3.2. Meteorological parameters

Meteorological measurements were analyzed to investigate the response of the air temperature, relative humidity and pressure at near-surface level to the eclipse. As mentioned in the previous section, the meteorological measurements were conducted at two locations: at IPB lidar measurement site and at Košutnjakstation, about10 km away. Diurnal cycle of the temperature was interrupted by the eclipse at both measurement sites (Fig. 2). Change in temperature increase rate was observed at both sites, with similar delay after the first contact. Higher temperatures were measured, and temperature decrease was more pronounced at IPB station, probably due to lower altitude and as a result of lower measurement height above ground. At this station, the temperature decreased during the eclipse, by 2.6 °C, at the rate of 0.043 °Cmin^{-1}, reaching minimum about 15 min after the maximum of the eclipse. At Košutnjakstation the temperature was almost constant after the first contact until the maximum of the eclipse, with an increase rate of 0.003 °wCmin^{-1}. After the eclipse maximum, it started increasing with increased downward radiation, at a higher rate of0.03 °C/min.To further investigate the effect of the eclipse on temperature, measurements available from Košutnjakstation on days following the eclipse were used. The rate of temperature change during the eclipse was compared to the rates recorded during the same period of day on three cloud-free days after the eclipse – March 21, 23 and 24. Increasing trend of maximum daily temperature was measured in this period. On the eclipse day, the increase rate from the first contact to the eclipse maximum (0.003 °Cmin^{-1})was very low in comparison to the rates of 0.016 °C min^{-1}, 0.025 °Cmin^{-1} and 0.032 °Cmin^{-1} for the same period on March 21, 23 and 24, respectively. After the eclipse maximum until the end of the eclipse, temperature increase rate of 0.025 °Cmin^{-1}was comparable to the corresponding rates on the three following days. Total increase in temperature during the eclipse was 2.0 °C, while the corresponding measured increase on March 21, 23 and 24, was 2.3 °C, 3.3 °C and 4.0 °C, respectively.

Relative humidity showed decreasing trend, typical for the beginning of the day and morning increase of temperature. During the eclipse, humidity was almost constant until the maximal obscuration of solar disc, and then it decreased by 10% at both locations (IPB and Košutnjak), in consistence with temperature increase. Until the maximal obscuaration, at IPB, the temperature was decreasing while the relative humidity was almost constant. It remains unclear whether its behaviour is an effect of eclipse.

The wind speed measured at the Košutnjak station followed atypical diurnal cycle, until the maximum of the eclipse, when both wind speed and gustiness dropped, and started increasing after the event (Fig. 3). Wind speed decreased from a maximum of 2.7 ms^{-1} to about 1.1 ms^{-1}at the end of the eclipse. The absolute minimum of wind speed and gusts was reached about 35 min after the last contact. Wind direction changed from northerly to northeasterly for the duration of the eclipse.

Pressure drop during the eclipse at Košutnjak station was 0.9 hPa (not shown here), which is most probably the consequence of the temperature

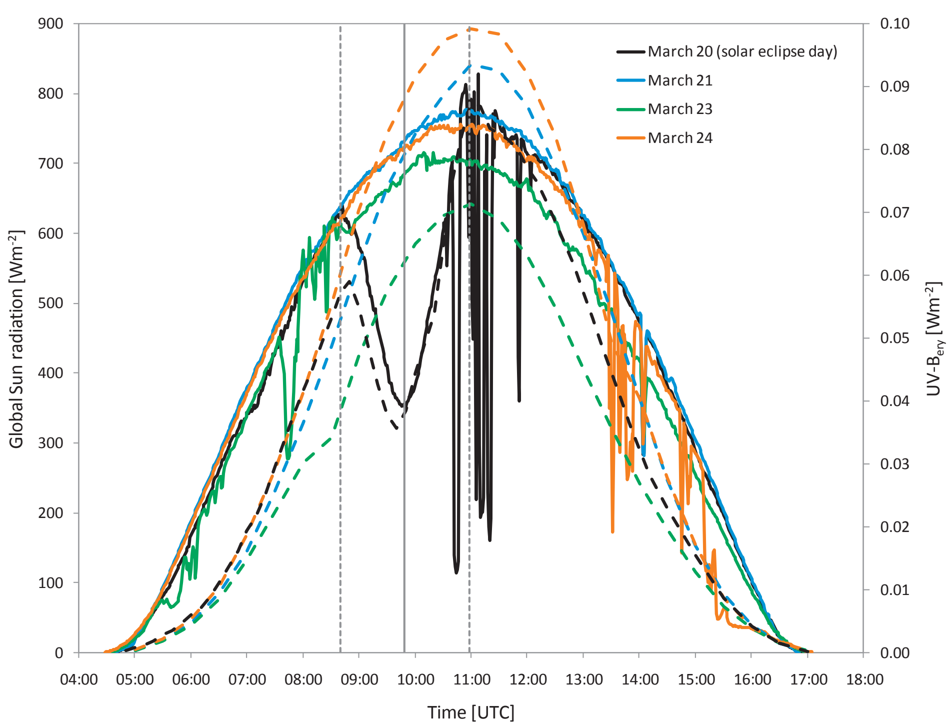

Fig. 1. Global Sun radiation (solid lines) and UV-B erythemal radiation (dashed lines) during partial Solar eclipse (March 20, 2015) and three clear days after the eclipse. Dotted vertical lines indicate beginning, maximum and end of the eclipse.

drop (Fig. 2). The pressure minimum was reached about 30 min after the eclipse maximum. Additional data, from radiosounding, provided information on vertical profiles of meteorological variables 1 h after the event. Up to the top of the PBL, the northerly wind speeds were relatively low, from 2 to 3.5 ms^{-1}. Air in the PBL was not very humid, with relative humidity of 35–60%.

These observed changes are generally in agreement with those reported in previous studies, related to eclipse events with larger obscuration of solar disc. The exception is relative humidity, which was almost constant until the eclipse maximum in this work, while it was reported to increase in previous studies. Anderson (1999) compiled data on near-surface temperature during selected total eclipse events, given in literature. These data showed temperature decrease of 2.0–3.6 °C, with minimal value coinciding with mid-eclipse (in one case), or reached with the time lag of 7–17 min. Foundaet al. (2007) presented observations at several sites in Greece, with different degrees of sun obscuration (74–100%) during solar eclipse in March 2007. Their results showed that temperature (measured at altitudes varying from 1.5 m to 17 m at different sites) decreased by 1.6–2.7 °C (3.9 °C at a site affected by low clouds), reaching minimal value 12–14 min after the mid-eclipse. Following the temperature response, the relative humidity was reported to increase by about 20% (Founda et al., 2007; Kolev et al., 2005). A decline in wind speed, after mid-eclipse, as a result of cooling the boundary layer and reduction of turbulent transport (Girard-Ardhuin et al., 2003) was also reported in literature (Anderson, 1999; Founda et al., 2007).

3.3. PBL evolution assessment from meteorological and lidar measurements

The presence of the residual layer, evolution of the PBL and aerosol layers in the free troposphere during the solar eclipse were observed using lidar measurements in Belgrade. For that purpose, the vertical profiles of the range-corrected analog signal at 355 nm, obtained from 10:15 UTC until 15:25 UTC with temporal resolution of 1 min, were analyzed, using the gradient method. The time series of range corrected signal (RCS) vertical profiles, along with heights of PBL and elevated aerosol layers are presented in Fig. 4.

The eclipse occurred before local noon, during the development of the mixing layer. In the morning, with surface heating, PBL started increasing from 600 m height to about 800 m above ground during the time period of about 2 h until the start of the eclipse at 8:40 UTC. The increase of the PBL height before the eclipse was steady and gradual. During this period, a layer was identified at height of about 1 km. This layer can be identified as the residual layer. With the beginning of the eclipse, the amount of solar radiation reaching the surface started

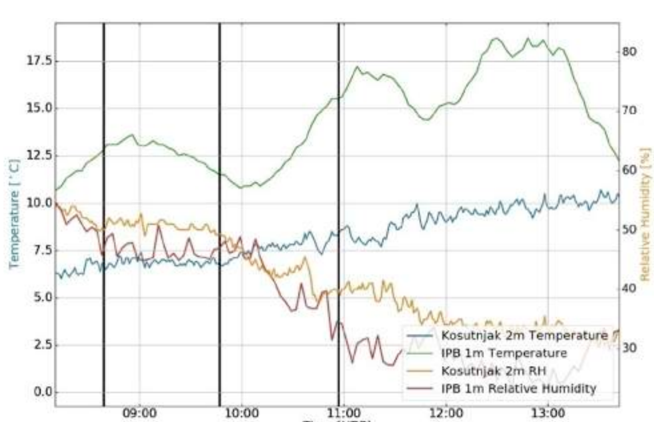

Fig. 2. Temperature and relative humidity. Vertical lines indicate beginning, maximum and end of the eclipse.

decreasing (Fig. 1). This affected the change in surface temperature (Fig. 2), and therefore convective motion, with the effects diminishing with height. The PBL height decreased by about 200 m during the solar eclipse, reaching minimum 20 min after the maximum of the eclipse. This decrease in PBL height is similar to those reported in previous research (Amiridis et al., 2007; Kolev et al., 2005), for solar eclipse with larger solar disc obscuration. With passing of the eclipse, the PBL started gaining height until reaching the height of about 1700 m around 13 UTC. Stronger variations of PBL height observed after the eclipse can be attributed to stronger convective motions. In first minutes after the eclipse, shallow cumulus clouds formed with their base at the top of the PBL. A peak in PBL height, coinciding with peaks in temperature and wind speed measurements was observed during the later phase of the event. Depth of the entrainment zone followed the development of the PBL. It showed gradual increase before the eclipse, from low values of about 30 m, to variations in height of several tens of meters after the eclipse as a result of strong convective motions.

The PBL height value calculated as an hourly average around 12 UTC (soon after the end of the eclipse), was 1 500 ± 100 m, in agreement with the one estimated from radiosounding:1 600 ± 80 m.Small differences of results obtained from radiosounding and lidar measurements can be due to local effects at two measurement sites and differences in the methods used. The gradient method uses gradient in lidar RCS due to decrease in aerosol backscatter while the bulk Richardson number approach relies on thermodynamic properties. Different surface properties and elevations of measurement sites influence the heat and momentum fluxes contributing to the PBL development. Lidar is operated on a fixed location during the whole measurement period, providing information on vertical column of air directly above the instrument. Radiosounding profiles are affected by the horizontal drift of the instrument caused by wind and depend on whether the ascent is made in a thermal or between thermals (Stull, 1988). To further estimate impact of eclipse on PBL height we compared these values with the PBL heights calculated for March for a 10-year period from 2006 to 2015 from the radiosounding profiles taken at 12 UTC (excluding the profile on the day of the eclipse). The values estimated both from lidar (around 12 UTC) and radiosounding measurements made on the day of the eclipse fall within the inter-quartile range of the values for the 10-year reference period (Fig. 4).

The lidar measurements during solar eclipse also showed presence of aerosol layers in free troposphere, at altitudes up to 4 km.

3.4. Ozone and air-ion concentrations

Surface ozone measurements showed no significant decrease, as opposed to most other measured parameters, possibly indicating less significant influence of photochemical reactions at the IPB semi-urban measurement site (see Fig. 5). While a decrease of surface ozone concentration during solar eclipse is expected, this effect could be missing in less polluted areas, or it could be masked by air transport or decline of PBL height (Zanis et al., 2001, 2007). For an urban station in Thessaloniki, Zanis et al. (2001) reported that surface ozone concentration decreased by 10–15 ppbv during the solar eclipse in August 1999 (maximum sun obscuration 90%), with a half-hour delay in starting time of the decrease after the first contact. However, they did not observe any effect on surface ozone in an elevated rural station at Hohenpeissenberg (99.4% sun coverage). Measurements during the solar eclipse in March 2006, conducted in Greece, showed decrease of 5–10 ppb surface ozone in an urban site in Thessaloniki (about 70% sun obscuration), while no effect was observed in relatively unpolluted sites in Finokalia and Kastelorizo, with 82% and 86% solar obscuration, respectively (Zanis et al., 2007). In our study, the measurements were taken at semi-urban site, during solar eclipse event with 51% sun obscuration. It is also noteworthy that measurements conducted for few other days, after the solar eclipse, in the present study showed high time lag of ozone concentration peaks compared to UV radiation peak. This was also reported in Tie et al. (2007) and Bian et al. (2007).

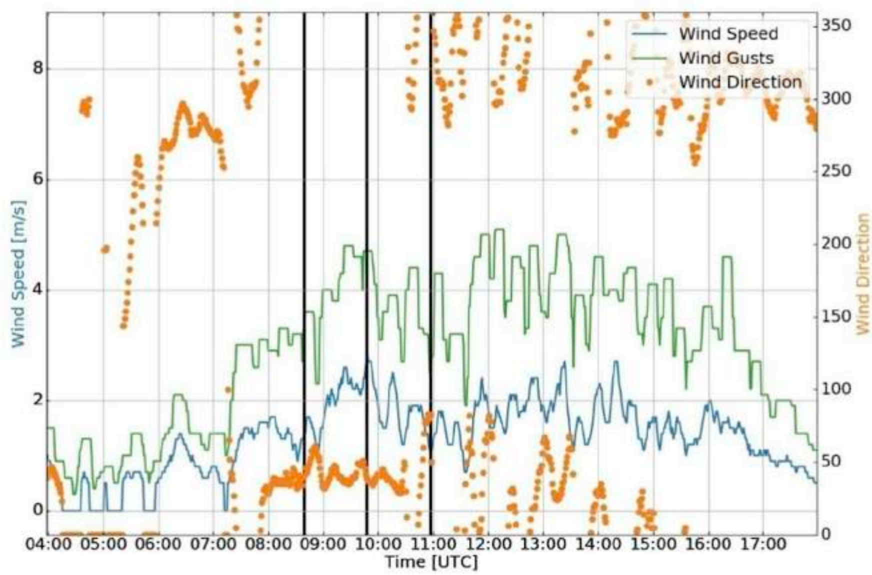

Fig. 3. Wind speed, gusts and direction. Vertical lines indicate beginning, maximum and end of the eclipse.

Radon concentrations measured during the eclipse (not shown here) were in the range between 0 and 15 Bq m^{-3} which is typical background for this part of the day. As shown in Fig. 6, air ion concentration decreased during the course of the day. The decrease was more intensive during the eclipse. After the eclipse, air ion concentration returned to its usual diurnal path to afternoon minimum. This could be explained by decrease of diffusion processes that are responsible for radon exhalation from the soil, as a result of cease of heating the surface during the eclipse. Differences were noted in air ion change during the eclipse in 1999 (97.7% sun obscuration), described in Kolarž et al. (2005) and that described in this study (51% sun obscuration).

3.5. Line-of-Sight radio communication receiving signal change

The observed RSL change during the time of solar eclipse was compared with the RSL change in few following days. The usual change of RSL in morning hours presented in Bajčetić et al. (2013) was confirmed during regular days, while, the pattern of signal level variation was quite different during the solar eclipse (Fig. 7, left panel).

Additionally, the observed meteorological variables were used to calculate the value of the air refractivity parameter (R) using (3), with the aim of the correlation between variation of that parameter and microwave RSL change (Fig. 7, right panel).

$$R = 77,6\frac{P}{T} + 3,73 \cdot 10^5 \frac{P_{vp}}{T^2}. \quad (3)$$

R is the value which describes the overall influence of the tropospheric medium on the radio wave propagation and depends on relative air pressure P, absolute temperature T and partially on water vapour pressure P_{vp} (Debye, 1957; Falodun and Ajewole, 2006).

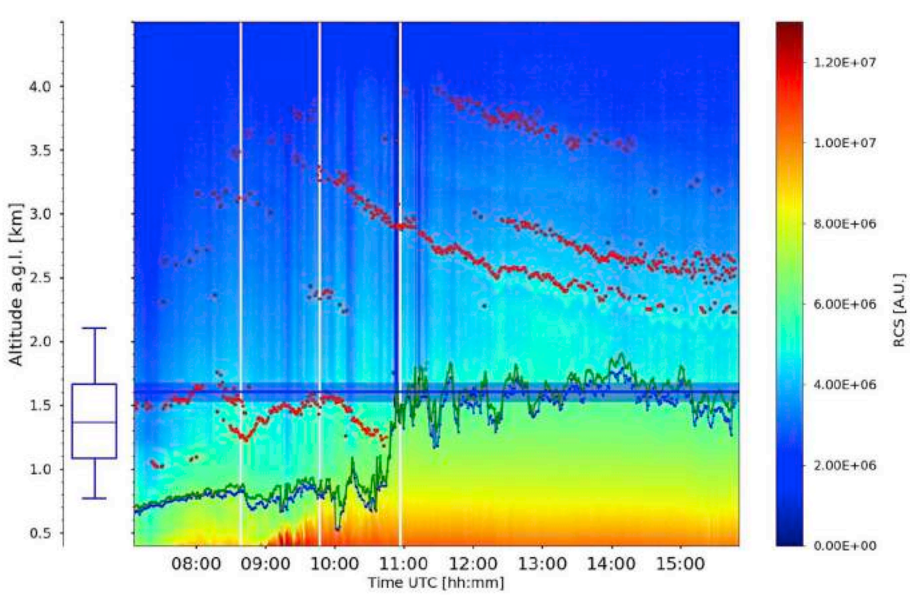

Fig. 4. Temporal evolution of PBL (blue line) and elevated aerosol layers (red dots). Colormaps represent the lidar RCS at 355 nm on March 20, 2015. White vertical lines indicate beginning, maximum and end of the eclipse. Box plot shows the median, first and third quartiles and 5th and 95th percentiles of PBL heights in March for period 2006–2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

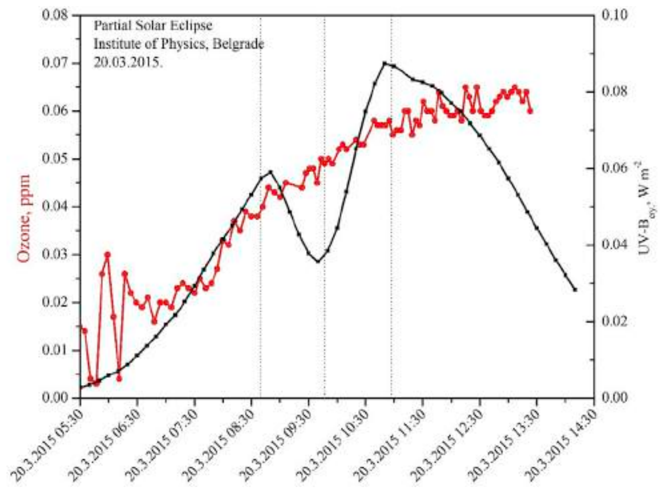

Fig. 5. Ozone and UV-B erythemal radiation during partial solar eclipse. Dotted vertical lines indicate beginning, maximum and end of the eclipse.

We normalized the measured values R_{xi} (i = 1,…, 480) of the air refractivity parameterto its mean value during the related day ($\overline{R}_x$), using Eq.2measured values R_{xi} of the air refractivity parameter, in order to emphasize the level of variation.

$$RSL = 100 \cdot \frac{R_{xi} - \overline{R}_x}{|\overline{R}_x|}. \tag{4}$$

Following the presented data in Fig. 8, it can be seen that there was meaningful correlation between RSL and R during the days after the solar eclipse, while their values change fairly independently on the day of the solar eclipse.

Analysing data presented in Fig. 8, it can be seen that before the period of solar eclipse, the disturbance manifested through the unusual *R* constant value until 08:40 is well correlated with the constant value of *RSL*. At the moment of solar eclipse maximum, the considerable *R* disturbance can be noticed, while this phenomenon does not reflect to the *RSL*. From 10:00, until the end of the solar eclipse, value of *R* varied within expected usual values, however *RSL* changed unusually.

This unusual RSL variation was possibly triggered by the solar eclipse event. In ordinary periods of measurements, the relative air pressure, absolute temperature and partially the pressure of the water vapour directly influence the permittivity of the air, causing the refraction of the electromagnetic wave, so the effects are noticeable as the RSL variation. However, during a solar eclipse event, it is not possible to consequently relate RSL and R. Considering the absolute amplitude variation of RSL, which was in the domain of 2,5 dB for the presented time periods, the sudden not so intense air permittivity perturbation within the area where LOS link was established did not have direct influence on the radio propagation at 3 GHz frequency. While RSLwas evidently slightly perturbedduring solar eclipse, there is not clear evidence that this perturbation is related to solar eclipse. The observed phenomena are not well presented in the literature for this particular scenario, and will be a subject of future analyses.

3.6. Effects on the ionosphere and LF radio signal propagation

The ionospheric perturbations were detected as variations of recorded NRK signal from Iceland. Generally, the temporal evolution of recorded signal can be used for detection of low ionospheric plasma perturbations; these changes in medium through which signal propagates affect wave reflection height, and consequently, propagation geometry and attenuation, resulting in variations of recorded signal characteristics.

The shapes of the temporal change depend on numerous parameters. Namely, in addition to periodic and sudden variations in the ionospheric plasma conditions, characteristics of signals like mutual locations of transmitter and receiver, power of transmitted signal, and geographical area through which the signal propagates, affect the recorded signal properties. For these reasons the dependencies between the ionospheric changes of electron density induced by radiation increase and VLF/LF signal amplitude are not monotonous, e.g. growth in the electron density does not necessarily cause amplification of recorded signal amplitudes (for detailed explanation see Nina et al., 2017). Thus, for detection of some sudden perturbationit is sufficient toobservechanges in temporal

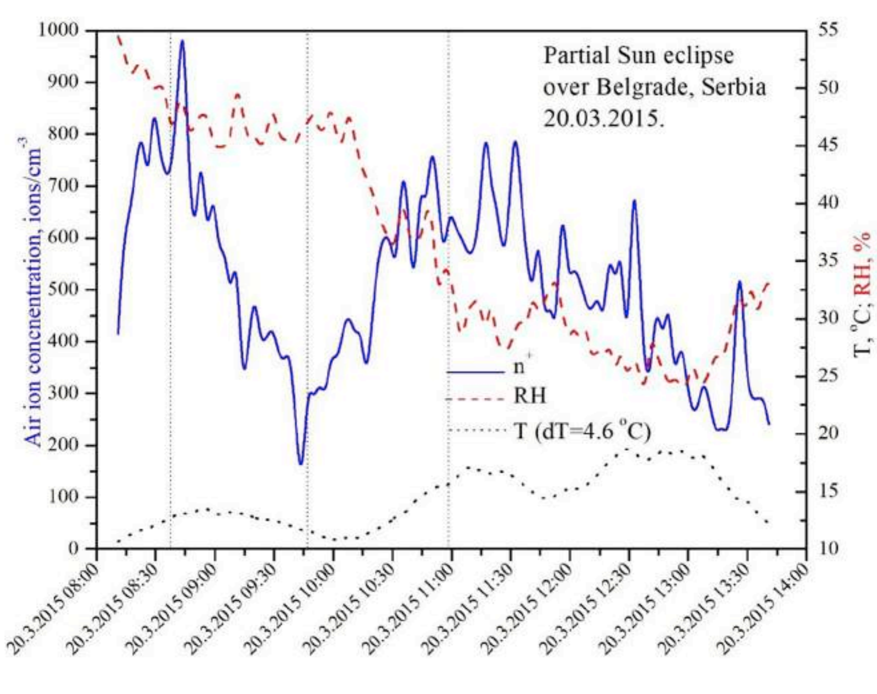

Fig. 6. Air ion concentration, temperature and relative humidity during partial solar eclipse. Dotted vertical lines indicate beginning, maximum and end of the eclipse.

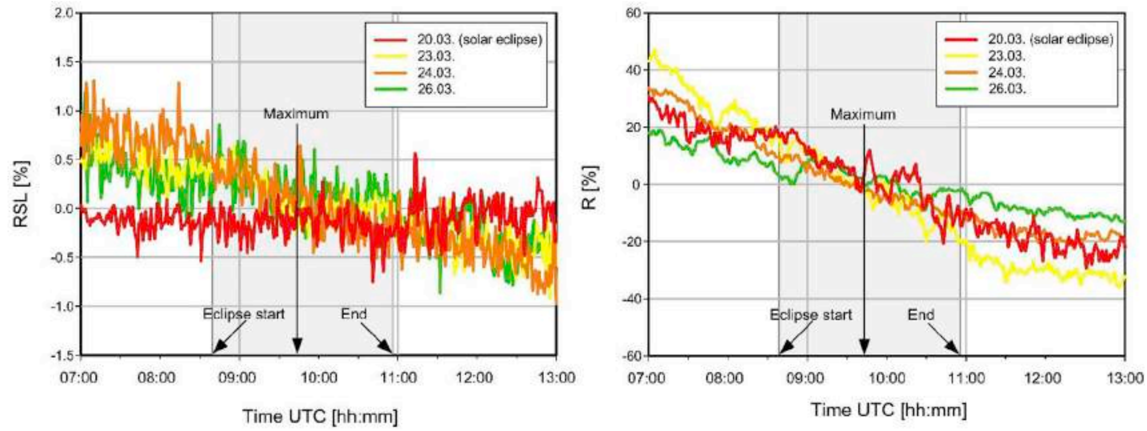

Fig. 7. Receiving signal level (*RSL*) and refractivity (R) variation. Shaded domains represent the time period when eclipse occurred.

evolution of signal characteristics.

Fig. 9 shows temporal variations of amplitude difference from its initial considered values, recorded by the AWESOME system at the Belgrade station on March 20, 2015 when solar eclipse occurred, and three days after that. The additional days are shown to visualize amplitude variation in solar eclipse period with respect to its shapes in other relevant periods without influence of the eclipse. The reason for choosing these particular days was relatively quiet conditions without significant traveling ionospheric disturbance resulting from atmospheric lightnings, and solar flares among other events. While amplitude variations are pronounced during the solar eclipse, they are practically within noise domains on the other three days. In the first period, a decrease in amplitude was observed, with the minimum occurring before the eclipse maximum. Further, the amplitude increased, exceeded the amplitude values during the first contact and reached the larger value approximately coincidently with the eclipse maximum time (indicated by a vertical line). Finally, it returned to the expected values, which are around initial values (this can be concluded from the three referent signals).

As explained in Section 1, electron density variation is most important for changes of plasma parameters which influence signal propagation. Its time variations depend on different electron gain and loss processes. The constituents of the low ionosphere can be ionized by γ, X and a part of UV photons. The most important solar influences on the ionization processes in the D-region in absence of large radiation increase, primarily as consequence of solar X-flares (Nina et al., 2012a,b) is coming from the solar Lyα line (121.6 nm) radiation (Swamy, 1991) whose presence is periodically intensified during the day. Bearing in mind that satellites did not register significant increase of intensity of X radiation, we can conclude that the signal variations are a consequence of Lyα radiation decrease. http://en.wikipedia.org/wiki/Solar_eclipse.

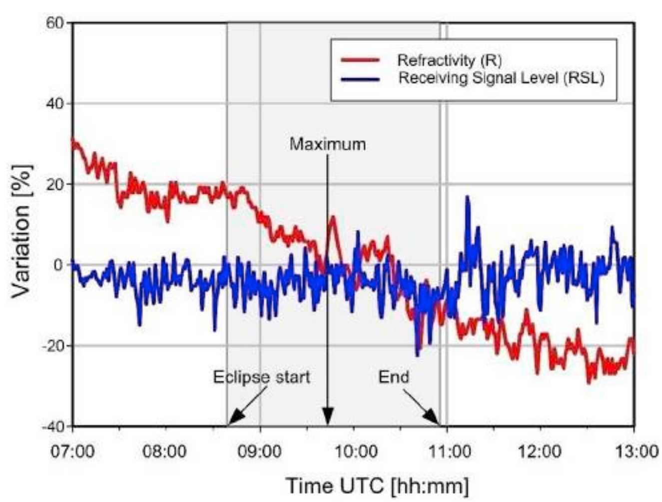

Fig. 8. *RSL* and R variation during solar eclipse. Shaded domains represent the time period when eclipse occurred.

4. Conclusions

Changes in atmospheric properties were observed during a partial solar eclipse (51%) on March 20, 2015 in Belgrade. For that purpose, four experimental setups were used to collect data, including lidar to derive PBL height and heights of elevated layers, AWESOME VLF/LF receiver (Cohen et al., 2010) and instruments for measurements of solar radiation, meteorological parameters, concentrations of ozone, air ions and radon and propagation of radio signals in troposphere. Although the solar eclipse was only partial, its influence on atmospheric properties in troposphere and ionosphere was noticeable. The detected changes in atmospheric parameters were generally similar, but weaker in intensity, to those reported in literature for solar eclipse events with larger obscuration of solar disc.

In troposphere, the influence of the eclipse was observed in meteorological surface parameters, and it was evident up to the top of the PBL. Eclipse-induced decrease in PBL height was 200 m, comparable to that reported in literature, with minimal value occurring 20 min after the eclipse maximum. The PBL height determined from 12 UTC radiosounding measurements (soon after the eclipse), showed that it was within the usual values for this location at that time of year. The meteorological parameters showed similar behavior at two measurement sites Košutnjak and IPB, respectively. The temperature change was more pronounced and abrupt at the –IPB station, probably due to lower measurement height, where it decreased by 2.6 °C, reaching minimum 15 min after the eclipse maximum. This temperature change is similar to those reported in literature for solar eclipse with larger obscuration of solar disc. At the Košutnjakstation the temperature was almost constant, until the eclipse maximum. Relative humidity was almost constant at both sites from the first contact until the eclipse maximum, as opposed to the increase reported in literature. The diurnal cycle then continued, with the increase in temperature and decrease in relative humidity at both sites. The 10-m wind speed and gusts decreased, reaching a minimum about 30 min after the eclipse. The wind direction changed from northerly to northeasterly for the duration of the event. Decrease of PBL height and the entrainment zone thickness were also observed during the eclipse, as a result of diminished surface heating. Ozone concentrations showed no decrease, as opposed to most results reported in literature, except for those reported for rural measurement sites. The possible reasons are less significant influence of photochemical reactions, decrease in PBL height or advection by changing wind during the event. Measured

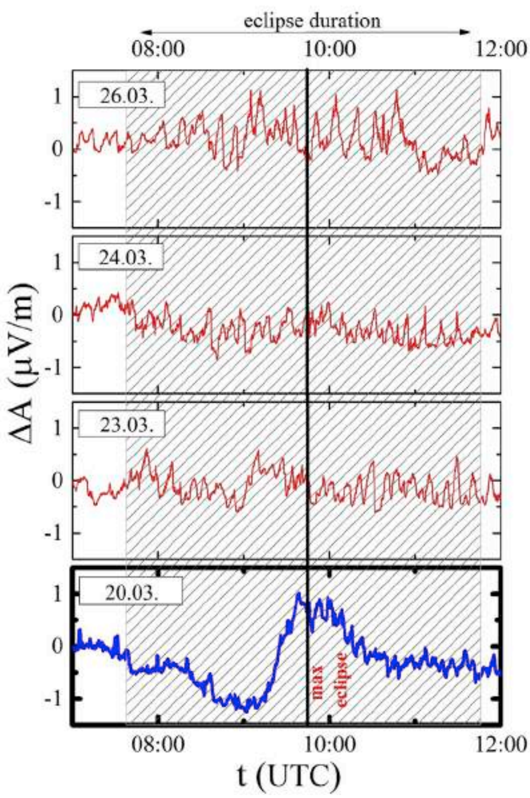

Fig. 9. The variations of amplitude difference from its initial considered values against the universal time (UT), recorded by the AWESOME system at the Belgrade station on March 20, 2015 when solar eclipseoccurred (lower panel) and three days after that (top panels). Shaded domains represent the time period when eclipse occurred (here we consider a whole period of eclipse because of long signal propagation path from Iceland to Serbia).

radon concentrations were typically low for this time of the day, while the air ion concentration sharply decreased.

The referential Line-of-Sight (LOS) radio link was set in the area of Belgrade, in order to investigate influence of the event on RSL instability. During the solar eclipse, an unusual pattern of the signal level variation was observed and different relationship between the RSL and the air refractivity parameter (R). Further analysis is needed to clearly relate the perturbation with solar eclipse which affected the atmospheric variables and therefore R.

Impact of the solar eclipse on the ionosphere was registered through changes of characteristics of radio waves which are reflected in ionosphere. The amplitude variations, were pronounced during the solar eclipse, and were at the expected values on the days after the event. Since satellite measurements did not show significant increase of intensity of X radiation, it was concluded that the signal variations are consequence of Lyα radiation decrease.

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A study of VLF signals variations associated with the changes of ionization level in the D-region in consequence of solar conditions

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Abstract

In this paper we confine our attention to the analysis of amplitude and phase data acquired by monitoring VLF/LF radio signals emitted by four European transmitters during a seven-year period (2008–2014). All the data were recorded at a Belgrade site (44.85° N, 20.38° E) by the Stanford University ELF/VLF receiver AWESOME. Propagation of VLF/LF radio signal takes place in the Earth–ionosphere waveguide and strongly depends on ionization level of the D-region, which means that it is mainly controlled by solar conditions. Some results of amplitude and phase variations on GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals measurements at short distances ($D < 2$ Mm) over Central Europe and their interpretation are summarized in this paper. Attention is restricted to regular diurnal, seasonal and solar variations including sunrise and sunset effects on propagation characteristics of four VLF/LF radio signals. We study VLF/LF propagation over short path as a superposition of different number of discrete modes which depends on the variations of the path parameters. Although the solar X-ray flare effects on propagation of VLF/LF radio signals are well recognized on all paths, similarities and differences between them are defined under existing conditions over the paths. Statistical results show that the size of amplitude and phase perturbations on VLF/LF radio signal is in correlation with the intensity of X-ray flux. We present the calculations of electron density enhancements in the D-region caused by different classes of solar X-ray flares during the period of ascending phase and maximum of the solar cycle 24.

Keywords: Solar activity; Solar flare response; D-region; VLF; Ionospheric disturbances

1. Introduction

The lowest region of the ionosphere, the D-region, is important as a reflecting layer for the longwave communication and navigation systems. The Very Low Frequency (VLF, 3–30 kHz) and Low Frequency (LF, 30–300 kHz) bands are below the critical frequencies of the D-region. VLF/LF radio waves from transmitters propagate through waveguide bounded by the Earth's surface and the D-region. This propagation is stable both in amplitude and phase and has relatively low attenuation. VLF/LF radiation tends to reflect from electron densities (strictly conductivities) at altitudes of 70–75 km during daytime and 80–90 km during nighttime. Also VLF/LF radiation is reflected by the conducting Earth's surface and this means that the radio waves propagate over Earth trapped between the imperfect mirrors of the ground and the ionosphere (Wait and Spies, 1964; Mitra, 1974). The effective reflection height depends on the ionization levels of the D-region. The lowest region of the ionosphere (<90 km altitude) is formed during quiet conditions primarily by the action of solar Lyman-α radiation (121.6 nm) on nitric

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oxide. Daytime electron density in this region is about or less than $Ne \sim 10^8\ m^{-3}$. During the nighttime the ionization rate drops and recombination processes continue. Even at night there is a sufficient ionization in the lowest region of ionosphere to affect VLF/LF radio signals (Goodman, 2005; Kelley, 2009).

A range of dynamic phenomena occur in the D-region and cause diurnal and seasonal variations in connection with solar activity (11-year sunspot cycle). The phenomenon such as solar X-ray flare illuminating the daytime ionosphere induces unpredictable effects that are associated with space weather. When the solar X-ray flares appear, the X-ray fluxes suddenly increase and the ones with the appreciable wavelength below 1 nm are able to penetrate down to the D-region and increase the ionization rate there (Thomson et al., Nov. 2001). A lot of work has been done regarding the correlation between X-ray fluxes and VLF perturbations as well as D-region electron density profile (Thomson, 1993; Thomson et al., Nov. 2001; Žigman et al., 2007). The changes in the conditions of the D-region at these altitudes cause the changes in the received amplitude and phase at the receiver, allowing us to compare experimental observations of received radio signals with the simulations based upon the predicted changes in the D-region to understand what is happening.

2. Data analysis method

2.1. Description of experimental data

In this paper we confine our attention to the analysis of amplitude and phase data acquired by monitoring VLF/LF radio signals emitted by four European transmitters during a seven-year period (2008–2014). This period covers the ascending phase and maximum of the solar cycle 24. All the data were recorded at a Belgrade site (44.85° N, 20.38° E), Serbia by the Stanford University ELF/VLF Receiver Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME). Narrowband data can be recorded in a continuous fashion, even in case when as many as 15 transmitters are being monitored (Cohen et al., Jan. 2010).

VLF/LF radio signals received at Belgrade site include: GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz. These VLF/LF radio signals propagate in the Earth–ionosphere waveguides over Central Europe. Great Circle Paths (GCPs) for those signals are short and we divide them in two groups: D <1 Mm and 1 Mm < D <2 Mm. The transmitters of radio signals: DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz are located in the same time zone (local time: UT + 1 h) as a receiver site. The transmitter of GQD/22.10 kHz is located in the UK, but a radio signal propagates over great segment of path in the same time zone where the receiver is.

The details of the VLF/LF transmitting and receiving sites and the path geometries are provided in Table 1. Locations of the transmitters and receiving site are presented in Fig. 1.

The analysis of VLF/LF data was done together with the examination of the corresponding solar X-ray fluxes. This work deals with a typical X-ray irradiance I_X in Wm^{-2} recorded by GOES-15 satellite in the band 0.1–0.8 nm, available from National Oceanic and Atmospheric Administration USA, via the web site: www.swpc.noaa.gov/ftpmenu/lists/xray.html.

2.2. Background ionospheric condition

The accuracy in the description of the ionospheric medium is crucial and the electron density profile, as an important part of its description, is worth of our attention. The background daytime exponential profile of electron density in general use for VLF modeling (Wait and Spies, 1964) is given by:

$$N_e(h, \beta, H') = 1.43 \cdot 10^{13} e^{(0.15H')} e^{[(\beta-0.15)\cdot(h-H')]}\ m^{-3}, \quad (1)$$

with H' in km and β in km^{-1}. This equation has been successfully used in VLF measurements (Thomson, 1993;

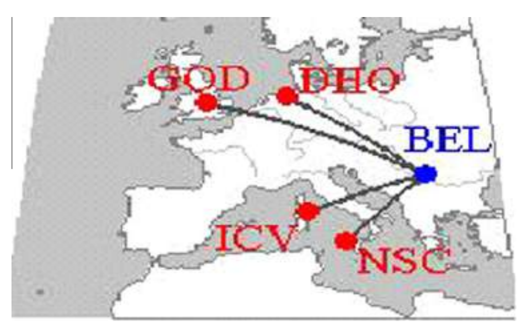

Fig. 1. Great Circle Paths (GCPs) of subionospherically propagating VLF/LF radio signals recorded at Belgrade site.

Table 1
VLF/LF transmitting and receiving sites.

	Freq [kHz]	Country	Geographic Latitude [deg]	Geographic Longitude [deg]	GCP [km]	Orientation of propagation path
Transmitter: GQD	22.10	UK	54.73 N	2.88 W	1982	Northwest to southeast
Transmitter: DHO	23.40	Germany	53.08 N	7.61 E	1300	Northwest to southeast
Transmitter: ICV	20.27	Italy	40.92 N	9.73 E	976	Southwest to northeast
Transmitter: NSC	45.90	Italy	38.00 N	13.50 E	953	Southwest to northeast
Receiver: AWESOME		Serbia	44.85 N	20.38 E		

McRae and Thomson, May 2000; McRae and Thomson, 2004; Thomson et al., Nov. 2001). The D-region electron density profile is characterized by the two Wait's parameters: H', as a measure of the reflection height and β as a measure of the sharpness or rate of changes of electron density with height. We also use Eq. (1) in our work to calculate the altitude density profile in the range 50–90 km.

2.3. Method of simulations VLF/LF radio signals propagation

The Long Wave Propagation Capability waveguide code, LWPC program package (Ferguson and Snyder, 1990) is used for simulation of VLF/LF propagation along any particular great circle path under different diurnal, seasonal and solar cycle variations in the ionosphere. The LWPC program typically performs the calculations for ten or more modes and has been tested against experimental data. Also, the LWPC program can take arbitrary electron density versus altitude profiles supplied by the user to describe the D-region profile and thus the ceiling of the waveguide.

Using the LWPC code the propagation path of VLF/LF signal was simulated in normal ionospheric condition, with goal to estimate the best fitting pairs of Wait's parameters β_{nor} and H'_{nor} (where, *nor* means normal condition) to obtain values of amplitude and phase closest to the measured data for selected day (Thomson, 1993; Thomson et al., May 2000; McRae and Thomson, May 2000; Žigman et al., 2007). The next step was to simulate propagation of VLF/LF radio signal through the waveguide in the perturbed D-region induced by additional X-ray radiation for selected moments during the flare duration. In our study we have accepted the presented method and used the observed VLF/LF data to examine the amplitude and phase perturbations during the solar X-ray flare. We used the RANGE model of the LWPC code for examination the single propagation path and specified a range-dependent ionospheric variation. Electron densities were determined from the observed amplitude and phase perturbations by a trial and error method in which electron density profile was modified until the calculated amplitude and phase perturbations matched with observed data. In this manner, the obtained Wait's parameters β_{per} and H'_{per} (*per* means perturbed condition) were used for our further calculations.

3. Investigations on diurnal and seasonal amplitude variations on VLF/LF radio signals

In literature, the first results about diurnal amplitude variations on VLF signals were published in 1933. Yokoyama and Tanimura (1933) studied propagation of 17.7 kHz and 22.9 kHz, over long distances $D > 5$ Mm. They gave explanation for amplitude fading based on single-ray geometrics optics. Budden (1961) and Wait (1962) suggested that many rays are needed to explain VLF propagation over long paths. Crombie and Jan. (Jan. 1964) and Walker (1965) put forward an explanation based on the use of modes in the Earth–ionosphere waveguide in which two modes are presented in the nighttime part of the path and only one mode in daylight. Later Clilverd et al. (1999) presented studies of VLF propagation over long path, NAA/24 kHz radio propagating from Cutler Maine, USA to Faraday, Antarctica during period 1990–1995. VLF radio signal propagated from North to South. They found the times of the amplitude minima were consistent with modal conversation taking place as the day-night boundary crossed the propagation path at specific locations.

Volland (1964) presented the studies of diurnal phase and amplitude variation of VLF radio signal at medium distances where the propagation of VLF radio signal did not take place predominantly by one mode. The results were obtained on measurements of VLF data over propagation paths with distances in the range between 300 km and 3000 km at daytime medium, and at nighttime medium this range was larger. The focus was restricted to regular changes including sunrise effects and solar flare effects. At medium distances the sunrise effects were very regular and marked in phase and amplitude of VLF radio signals. The sunset effects were much weaker and not so regular.

3.1. Diurnal amplitude variations

Diurnal behaviors have been examined at different frequencies all monitored at Belgrade site. For this purpose day 18 April 2010 was selected as representative day of normal ionospheric conditions under low solar activity. The Earth-facing side of the Sun was blank, without sunspots. During that day at 02:05 UT the maximum of X-ray irradiance $I_{Xmax} = 10^{-7}$ Wm^{-2} in the band 0.1–0.8 nm, was recorded. Diurnal variation of amplitude on GQD/22.10 kHz, DHO/34.40 kHz, ICV/22.27 kHz and NSC/45.90 kHz radio signals over 24 h are shown in Fig. 2a. Characteristic events of amplitude minima that occurred during the sunrise and sunset were identified for each path and marked with SR and SS on Fig. 2a. There is a data gap between 13:00–14:00 UT on each trace caused by data archival. Also, there is data gap between 07:00 and 08:00 UT on amplitude variations of DHO/23.40 kHz radio signal, because in that period the transmitter is off-air. The shape of the expected signal curve varies dramatically over the path with time.

For comparison, we calculated monthly averaged amplitude values of GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals for April 2009, 2010 and 2011. Fig. 2b shows the monthly averaged amplitude values for four VLF/LF radio signals against universal time over 24 h. In the averaged data for ICV there are spikes at ~10:40 UT in both the April 2010 and April 2011 curves. Sporadically amplitude of

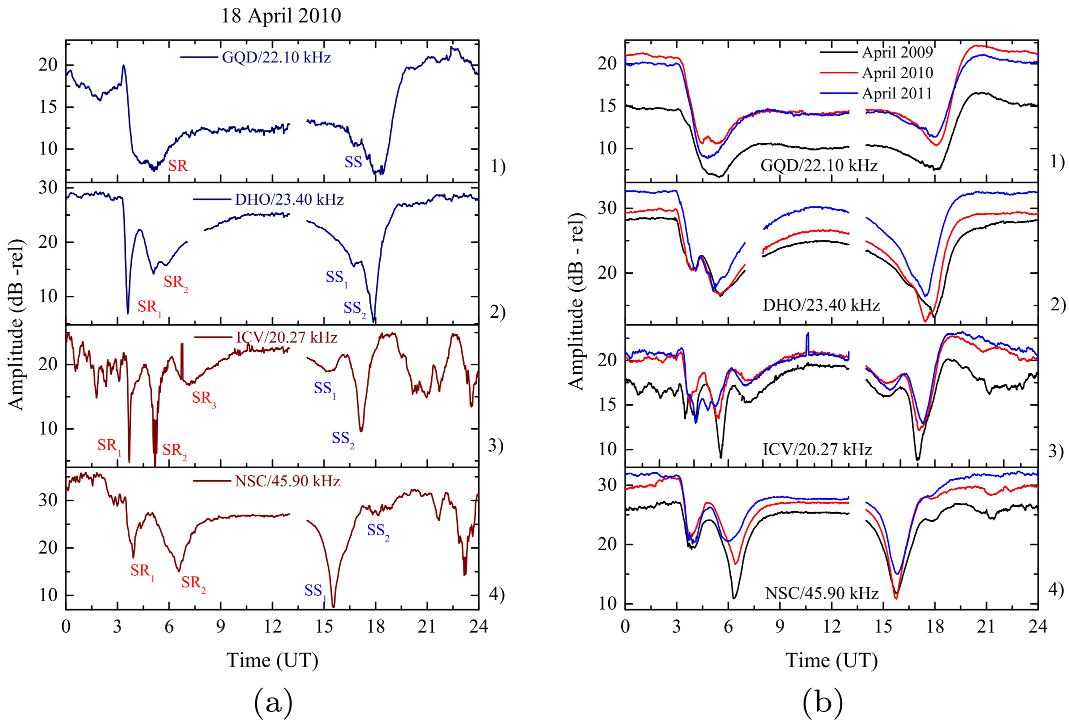

Fig. 2. (a) Diurnal variation of amplitude on VLF/LF signals at GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz monitored on 18 April 2010, (b) Variations of monthly averaged amplitude of VLF/LF signals obtained for April 2009, 2010 and 2011.

ICV/20.27 kHz increases by ∼2 dB in duration of few minutes. As this appearance is repeatable always at ∼10:40 UT, the source of it is artificial (Fig. 2b, panel number 3). In April 2011 the solar X-ray flares occurred during a few days, and these days were eliminated from calculations. To present development of solar activity during the current solar cycle 24 we cite smoothed sunspot numbers (SSN) for April 2009, 2010 and 2011 and they are: 2.2, 15.4 and 41.8, respectively (http://www.ips.gov.au/Solar/1/6).

GQD/22.10 kHz radio signal propagates from Skelton UK to Belgrade and this path is far apart in longitude in comparing with other paths analyzed in this paper. This is West-East propagation and the distance between transmitter and receiving site is $D = 1982$ km. The first panel of Fig. 2a shows the observed diurnal variation of the amplitude on VLF radio signal at 22.10 kHz. There is well evidence between amplitude recorded during nighttime and daytime conditions. The variation of amplitude has larger values during nighttime than in daytime condition, because of lower absorption in the D-region. During the transition between nighttime/daytime propagation conditions, two not sharp minima in amplitude, labeled by SR and SS are seen in Fig. 2a panel number 1.

The first panel of Fig. 2b shows monthly averaged amplitude values of GQD/22.10 kHz radio signal over 24 h by order of succession three years. The shapes of the curves are very similar to each other. On each curve, there are well defined two amplitude minima. The time of development the amplitude minima are repeatable from year to year. Monthly averaged amplitude values for April 2010 and 2011 are greater in comparing with values for April 2009, and we assume it was induced by the changes in solar activity.

Grubor et al. (2008) presented measured and calculated diurnal variations of amplitude and phase on GQD/22.10 kHz radio signal recorded at Belgrade site for one summer day in 2005. Considering the results, it is evident that the diurnal phase variation of GQD/22.10 kHz radio signal is generally in the form of a trapezium, where all night conditions over the path correspond to one steady-phase level and all day conditions over the path correspond to the other steady-phase level. In all our examinations of diurnal phase variations on GQD/22.10 kHz recorded at Belgrade site from 2008 to 2014 we obtained a similar shape of curves with the example presented in the paper (Grubor et al., 2008). The idealized transition from one phase level to the other during sunrise and sunset completes the straight sides of the trapezium. In this paper we will present the phase steps during transition periods for recorded data on 18 April 2010. Observed variations of amplitude and phase on GQD/22.10 kHz radio signal over three hours are presented on Fig. 3a and b.

We accepted the results obtained by Volland (1964) that VLF radio signals propagating from transmitter to receiver over paths with distance ∼2000 km reflect once on the middle of the paths. By the LWPC code we simulated the propagation of GQD/22.10 kHz radio signal and obtained coordinates 50.30° N, 10° E for the middle of

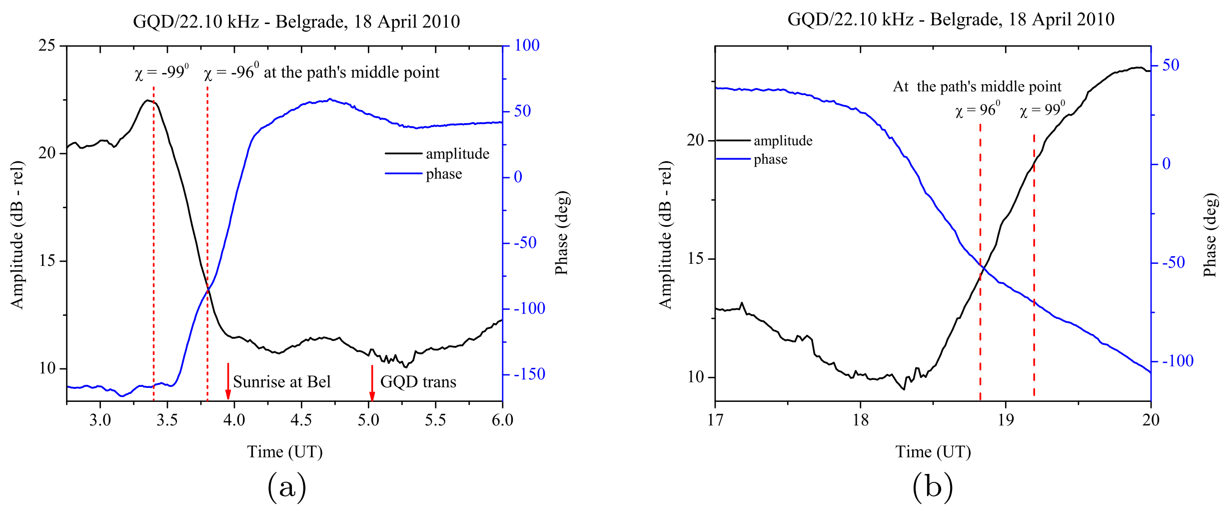

Fig. 3. (a) Amplitude and phase on GQD/22.10 kHz during sunrise recorded at Belgrade on 18 April 2010, (b) Amplitude and phase on GQD/22.10 kHz during sunset at Belgrade on the same day. For convenience, morning solar zenith angles are shown as negative while those for the afternoon are positive.

the propagation path, and number of discrete modes under different diurnal condition over path. For convenience, morning solar zenith angles are shown as negative while those for the afternoon are positive. The process of ionization in the D-region begins when solar zenith angle has value $\chi = -99^\circ$, and sunrise terminator reaches a height $h = 95$ km. The next important moment is when sunrise terminator reaches a height $h = 35$ km that occurs for $\chi = -96^\circ$. In time interval that corresponds to values of the solar zenith angle $\chi = -99^\circ$ and $\chi = -96^\circ$ there are changes of the altitude profile of ionospheric conductivity against time. By changing the time as input parameter with the step of one minute we defined the times of solar zenith angles $\chi = -99^\circ$ and $\chi = -96^\circ$ at the middle of the propagation path. In this way we got the information about the time of sunrise at $h = 95$ km and $h = 35$ km in the D-region. Changes in the conductivity of the D-region cause variations in amplitude and phase of the VLF/LF radio signals propagating across the terminator line. These moments are marked with red dashed lines on Fig. 3a. Also, the sunrises at Belgrade site and GQD transmitter (on ground level) are marked with red arrows. VLF radio signal propagates from nighttime to daytime conditions, with number of discrete modes $n_n = 17$ and $n_d = 7$, respectively. Fig. 3a shows the transition from phase level during nighttime to phase level during daytime, starting after the sunrise occurs at $h = 95$ km. Simultaneously with phase step the development of the amplitude minimum is presented on Fig. 3a.

In confirmation of our assumption that GQD/22.10 kHz radio signal once reflects from the ionosphere (one-hop) along path, $D = 1982$ km is in correlation timing of the creating the first minimum with time interval of the illumination ionosphere in the altitude range, 95–35 km in the middle of the path.

During sunset the opposite changes occur in the D-region. Fig. 3b shows the transition from phase level during daytime to phase level during nighttime and the development of amplitude minimum. We defined the times when sunset terminators reaches height at $h = 35$ km and $h = 95$ km at the middle of the propagation path. Red dashed lines indicate these times on Fig. 3b. The amplitude minimum occurred at ~18:15 UT about one hour earlier than sunset is at $h = 95$ km.

DHO/23.40 kHz radio signal propagates from Rhauderhent, Germany to the Belgrade site across an all land path. VLF radio signal propagates Northwest-Southeast and the distance between transmitter and receiver site is $D = 1300$ km. The second panel of Fig. 2a shows the observed variations of amplitude on DHO/23.40 kHz radio signal against time over 24 h. The amplitude of VLF radio signal varies in a characteristic way that is defined by geophysical parameters of transmitter and receiver site. The differences in amplitude values recorded during nighttime and daytime conditions are evident. Four amplitude minima labeled as SR_1, SR_2, SS_1 and SS_2 are observed, respectively during sunrise and sunset transition along the propagation path. The amplitude of the signal is generally dependent on a superposition of discrete modes (nighttime: $n_n = 18$ and daytime: $n_d = 7$), which depends on the variations of the waveguide parameters. The amplitude minima are produced by modal interference generated at the sunrise and sunset height discontinuities in reflection height as they move along the path (Walker, 1965).

At the middle of the path (49° N, 14.5° E) sunrise reaches height $h = 95$ km at 03:13 UT and $h = 35$ km at 03:33 UT on 18 April 2010. From recorded data it is evident that amplitude started to fall from nighttime level at ~03:15 UT and had minimum value at 03:36 UT. Development of amplitude minimum SR_1 is in good correlation with changes of illumination at the middle of the path. The amplitude had minimum value SS_2 at 17:55 UT. The sunset reaches height $h = 95$ km at 18:46 UT and than amplitude value is very close to values of nighttime level. During daytime condition over DHO-BEL path there are two amplitude minima SR_2 (morning) and SS_1 (afternoon) developed under solar zenith angles $\chi = -81°$ and $\chi = 80°$, respectively.

The second panel of Fig. 2b shows monthly averaged values of amplitude on DHO/23.40 kHz for April 2009, 2010 and 2011. The shapes of curves which presented monthly average variations of amplitude over 24 h are very similar. There are some differences in values from year to year. Also four amplitude minima are noticeable.

Radio signals with frequency ICV/20.27 kHz and NSC/45.90 kHz propagate from Southwest to Northeast over short paths 976 km and 953 km, respectively. Both radio signals propagate over sea, land, sea and land, which implies to very similar conductivity properties of the waveguide bottoms. The third panel of Fig. 2a shows amplitude variation on ICV/20.27 kHz radio signal against universal time. For this VLF radio signal the differences in amplitude values recorded during nighttime and daytime conditions are not well recognized (nighttime: $n_n = 16$ and daytime: $n_d = 7$). Three amplitude minima labeled as SR_1 SR_2 and SR_3 are observed during sunrise transition and morning over the propagation path. Two of them are very sharp. Two minima amplitude labeled by SS_1 and SS_2 are observed during afternoon and sunset transition, respectively. The first amplitude minimum SR_1 is very sharp and occurs in time interval close to time interval during which sunrise terminator reaches middle of the propagation path (42.96° N, 14.77° E).

For studying diurnal variations on ICV/20.27 kHz radio signal against time during three year period we calculated monthly averaged amplitude values and the results are shown on the third panel of Fig. 2b. All the curves for April 2009, 2010 and 2011 have similar shape with well defined five amplitude minima on each of them.

The fourth panel of Fig. 2a shows diurnal variations of amplitude on NSC/45.90 kHz radio signal against time recorded on 18 April 2010. The amplitude has larger values during nighttime than in daytime condition, due to lower absorption during night. Also four amplitude minima were developed during that day. The fourth panel of Fig. 2b shows monthly averaged amplitude data against time. In all the curves it is possible easily to define the amplitude minima. Also, the times of their development are repeatable from year to year.

Along with the study of diurnal variation of amplitude we have examined the diurnal variation of phase on NSC/45.90 kHz radio signal. This LF radio signal propagates from Southwest to Northeast over short path, $D = 953$ km. By the LWPC code we simulated the propagation of NSC/45.90 kHz radio signal and obtained times of sunrise/sunset at heights: $h = 95$ km and $h = 35$ km in the D-region for middle part of the propagation path (41.53° N, 16.75° E). Our numerical results show that LF radio signal propagates from nighttime to daytime condition as a superposition of discrete modes $n_n \leqslant 34$ and $n_d = 10$, respectively. Sunrise effects on LF propagating cause a gradual fall of number of discrete modes over a short path. Data of amplitude and phase on NSC/45.90 kHz radio signal recorded on 19 May 2011 are given on Fig. 4. The first panel of Fig. 4 shows amplitude variation on LF radio signal against universal time with well developed four amplitude minima. The second panel of Fig. 4 presents monitored phase data for the same day. During dawn and dusk time sector there are not smoothly transitions of phase from one stable level to another.

Timing of development the first amplitude minimum, SR_1 is in good correlation with time when sunrise terminator reaches the middle part of the propagation path. The phase transition from nighttime to daytime condition passes through the peak, while the amplitude drops to lower values. In the process of changing daytime to nighttime condition, when sunset terminator reaches middle part of path there is occurrence of the last amplitude minimum, SS_2. Development of the amplitude minimum SS_2 is followed with well recognized peak in phase values.

During daytime condition over path, two amplitude minima labeled as SR_2 (morning) and SS_1 (afternoon) are observed. The lowest values of these amplitude minima are recorded under solar zenith angle $\chi = -74°$ and $\chi = 71°$, respectively. The amplitude minimum SR_2 is followed with suddenly decreasing of phase values, while the amplitude minimum SS_1 is in correlation with increasing phase values.

DHO-BEL, ICV-BEL and NSC-BEL paths and great segment of GQD-BEL path are in the same time zone. Middle of GQD-BEL and NSC-BEL propagation paths are far apart in longitude for 7°. All the paths are similarly illuminated during daytime condition while there are differences in the level of illumination during dawn and dusk in accordance to geographic coordinates of transmitter. Based on these facts, our results are as follows:

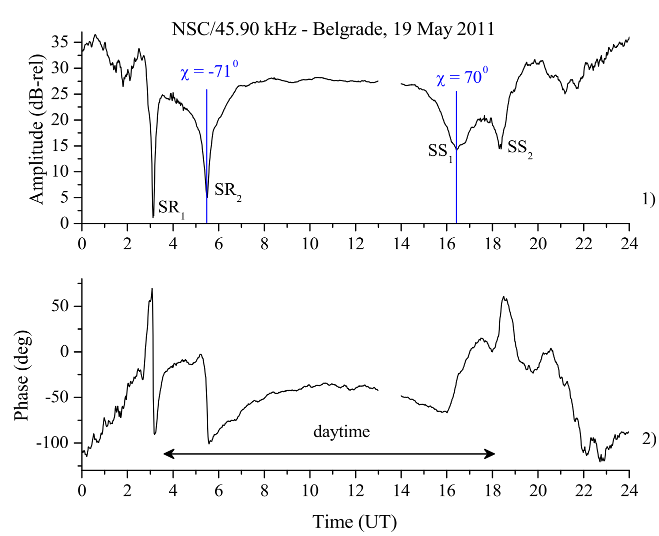

Fig. 4. Diurnal variations of amplitude and phase on NSC/45.90 radio signal against universal time recorded at Belgrade site during 19 May 2011.

1. The process of ionization in the D-region begins when solar zenith angle reaches value $\chi = -99°$, and sunrise terminator reaches the height $h = 95$ km. When this process starts in the middle of the path, it causes the changes of altitude profile of ionospheric conductivity and the appearance of the first amplitude minimum.
2. Our results based on the simulation of the VLF/LF propagation over short paths (D <2 Mm) show that 20.27 kHz, 22.10 kHz and 23.40 kHz radio signals propagate under nighttime condition as a superposition of 16, 17 and 18 discrete modes, respectively. Under daytime condition all of these VLF radio signals propagate as a superposition of 7 discrete modes. Our numerical results show that LF radio signal propagates from nighttime to daytime condition as a superposition of discrete modes $n_n \sim 34$ and $n_d = 10$, respectively. Sunrise effects on LF propagating over a short path cause a gradual fall of number of discrete modes.
3. How many amplitude minima and at what time they would be developed are based on specifications for each path. The occurrences of amplitude minima depend on the interferences of various number of discreet modes. All possible combinations of conditions: *sunrise and sunset, position of terminator on propagation path, relative positions of transmitter and receiver, distance, ground conductivity and transmitted frequency* are responsible for the occurrence of amplitude minima.
4. The main point of our result is that the amplitude minima could be divided in two types: The amplitude minima that are developed in time intervals during transition of nighttime/daytime and daytime/nighttime conditions on the middle of the propagation path belong to the first type. The second type of amplitude minima occurs under daytime condition over all short paths. Amplitude minima of second type usually appear as a pair, one during morning and other during afternoon and their timings are symmetrical arrange in a according to a local noon. Timings of their occurrences continuously change from day to day.

3.2. Seasonal amplitude variations

We examined four VLF/LF radio signals recorded at Belgrade site to follow main propagation characteristics induced by different levels of illumination over 24 h and over one year. For this purpose we analyzed the measurements obtained in the years of low solar activity. Fig. 5a shows the averaged amplitude variations against time for winter month, January and summer month, June 2009. There is a gradual shift between winter and summer amplitude levels on radio signals: DHO/34.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz. Monthly averaged amplitudes on GQD/22.10 kHz have larger values during winter than summer months. All VLF propagation paths are differently illuminated under winter and summer conditions causing time differences in the appearances of amplitude minima.

Fig. 5b shows monthly averaged amplitude on VLF/LF radio signals for equinox months: April and October 2009. As for these two months, on the basis of comparing the curves for monthly average amplitude values during the

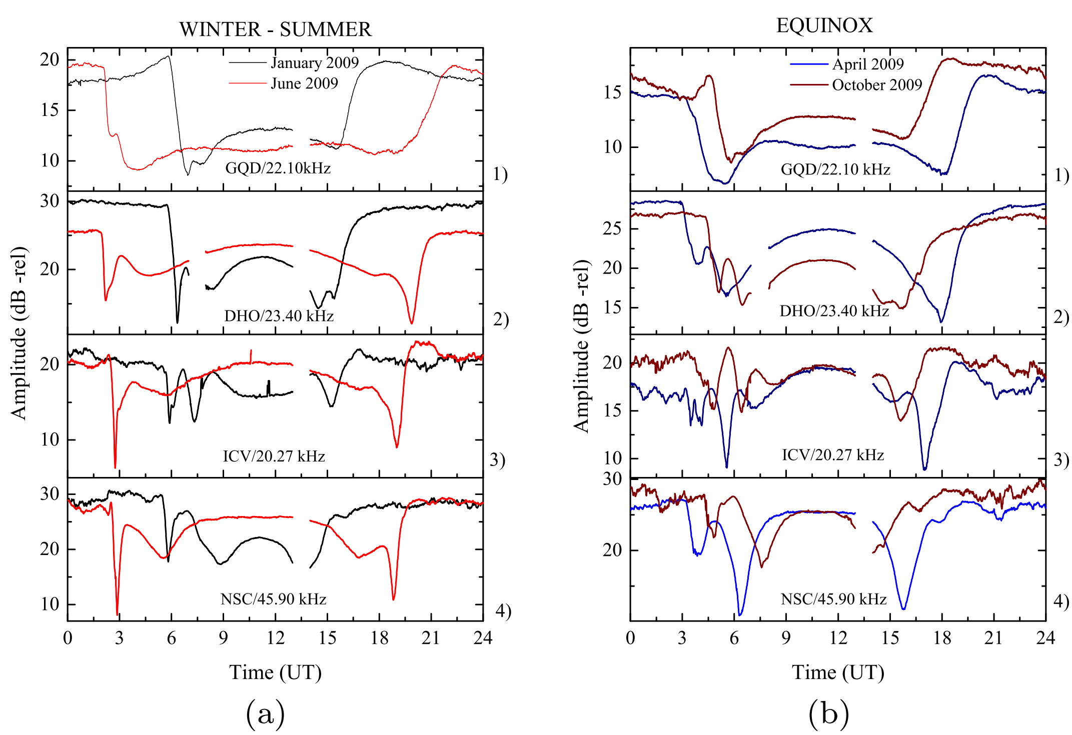

Fig. 5. The monthly averaged amplitude on GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals versus time over 24 h (a) for January and June 2009, (b) for April and October, 2009.

period of 24 h, it is obvious that the shapes of these curves are similar to each other. There is a time difference when it comes to the moment of appearance and development of amplitude minima in April and October 2009.

On the basis of measured VLF/LF data our results for short paths, $D < 2$ km are:

> Timings of development the amplitude minima when sunrise and sunset terminators reach middle of the propagation path are in correlation with seasonal effects on the D-region. During daytime there are one or two pairs of amplitude minima whose creation is a consequence of destructive interference of modes. The temporal variability in their creation is correlated with number of light hours for each day during year. The amplitude minima in dawn and morning are sharper than in afternoon and dusk and are the sharpest during summer.

4. Typical amplitude and phase changes of VLF/LF radio signals induced by solar flares

A characteristic of the radiation emission in the EUV, X-ray and radio signals is that it is not uniformly distributed in the Sun's corona, but mostly concentrated in localized emission centers. These emission centers belong to a class of phenomena known collectively as *active regions*. A solar flare is a sudden, rapid and intensive phenomenon in solar activity, releasing a large amount of energy (up to about 10^{25}J) in the solar atmosphere (Prölss, 2004; Bothmer and Daglis, 2007). However, when a solar X-ray flare occurs, there is a major increase in the flux of X-rays from the Sun and those with wavelengths appreciable below 1 nm are able to penetrate down to the D-region heights and cause there additional ionization. The rapid increase in the electron density leads to several phenomena grouped together under the name *sudden ionospheric disturbance* (SID). The increased electron density lowers the effective reflection height H' and causes a very strong influence on propagation characteristics of VLF/LF radio waves (Mitra, 1974).

4.1. Amplitude variations due to solar activity cycle

There are times when the active regions are rare or only weakly defined. Under these conditions the Sun is designated as "quiet". An "active" Sun is characterized by numerous strong active regions. A seven-year period (2008–2014) includes the minimum of solar cycle 23 in December 2008 and the maximum of solar cycle 24 in April 2014, with 82 SSN. Solar cycle 24 belongs to the category of moderate cycles (http://www.ips.gov.au/Solar/1/6). In Table 2 there are some characteristics of solar cycle 24. Following the development of X-ray flares in solar cycle 24 it shows that no flares were observed in January 2009, while 282 solar X-ray flares of C, M and X class were observed in February 2014 (www.tesis.lebedev.ru).

VLF/LF propagation as noted above provides some insight on the way ionization builds up and decays, and provides a routine monitor for the detection and time change of solar-geophysical disturbances. The Figs. 6a and 6b illustrate the diurnal-seasonal variations of amplitude on DHO/23.40 kHz radio signal in Belgrade for three-month period during "quiet" (2009) and "active" (2014) solar condition. White areas were missing data caused by: transmitter off-air, archival data or failures at the receiver site.

The diurnal-seasonal variations of amplitude are caused by variation of the equivalent reflection height and the reflection characteristics of the D-region during 24 h. The Fig. 6a shows that amplitudes of signal are typically higher and more variable at night (different shades of blue color) than during the day (equal turquoise color). At dawn and dusk amplitude on DHO/23.40 kHz radio signal passes through the minimum producing sharp border between nighttime and daytime amplitude values (green gradually turns to turquoise color). The dawn crossing (left sides of Fig. 6a and 6b) is sharper than the dusk crossing. The recorded VLF amplitude can be higher or lower at night, depending on the path, due to the summation of the modes. It is characterized by periodic and repeatable variations of amplitude as the dawn-dusk terminator moves along a DHO-BEL path.

For better interpretation of measured data we simulated VLF propagation under normal ionospheric condition. We selected date: 20 January 2009 and time 06:16 UT to calculate main propagation parameters of DHO/23.40 kHz radio signal from transmitter along path to Belgrade using the LWPC code. The modeling of VLF radio signal propagation in the Earth–ionosphere waveguide in which the illumination smoothly changes is carried out and results are given in Table 3. Numerical values of: *ground conductivity σ, solar zenith angle χ, sharpness β, reflection height H', electron density at H' and number of modes as a function of distance from transmitter along path to receiver* are presented in Table 3. Analysis of data shows that electron density increases, reflection height moves down in the D-region and the number of discrete modes reduces from $n_n = 18$ to $n_d = 7$. The consequence of the occurrence of all these processes in the waveguide is that amplitude of VLF signal during daytime has smaller value than during the night.

Table 2
Main characteristics of solar cycle 24.

Cycle	Sol. start year month		Sol. max. year month		Max SSN	Rise to max years months	
24	2009	Jan	2014	April	82.0	5.3	64

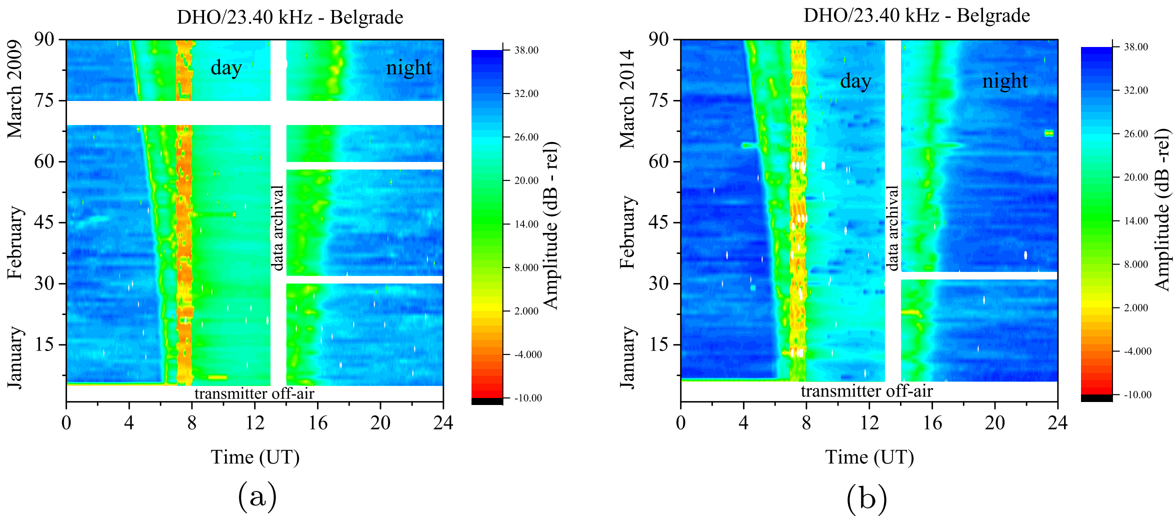

Fig. 6. Amplitude measurements on DHO/23.40 kHz radio signal at Belgrade site during: (a) January–March 2009 (b) January–March 2014.

Table 3
Main propagation parameters of DHO/23.40 kHz radio signal from transmitter along path to receiver at Belgrade, for 20 January 2009 at 06:16 UT.

	D (km)	σ (Sm^{-1})	χ (deg)	β (km^{-1})	H' (km)	Ne (m^{-3})	*mds*
1	0	0.01	−100.9	0.43	87	3.09E7	18
2	240	0.01	−98.9	0.41	84.8	4.31E7	17
3	460	1E−3	−97.1	0.39	82.7	5.78E7	16
4	560	0.01	−96.2	0.39	82.7	5.78E7	16
5	600	1E−3	−95.9	0.39	82.7	5.78E7	16
6	660	1E−3	−95.4	0.37	80.5	8.08E7	15
7	820	0.01	−94	0.37	80.5	8.08E7	15
8	880	0.01	−93.5	0.34	78.3	1.13E8	13
9	1100	0.01	−91.7	0.32	76.2	1.56E8	10
10	1300	0.01	−90	0.30	74	2.18E8	7

The ionospheric effects of X-ray flares provide one major additional source of interest – *the reaction of the ionospheric medium to an impulsive ionization*. Disturbances in the D-region induce increase of amplitude on DHO/23.40 kHz radio signal. Fig. 6b shows recorded amplitudes on DHO/23.40 kHz radio signal against universal time over 24 h during January–March 2014. Perturbations of amplitudes during daylight hours appear as blue streaks on Fig. 6b. To present changes in the daytime D-region during SIDs we modeled VLF propagation by changing Wait's parameters β and H' in RANGE model of LWPC code. The modeling of VLF propagation in the waveguide under normal ionospheric condition and during two SIDs were carried out and results are presented in Table 4. Recent collections of data provide even more detailed insight into variation of signal amplitude and consequently into ionospheric variability. During a SID, the D-region becomes highly ionized, the altitude profile of ionospheric conductivity changes and VLF radio signal reflects from a lower height and all of these changes result that VLF signal propagates as a superposition of more discrete modes than in normal ionospheric condition. The signal strength of the wave increases and in our modeling amplitude of VLF signal changes from $A_{nor} = 31.5$ dB to $A_{per} = 36.5$ dB.

4.2. Path dependent

For studying solar flare events at similar conditions we have examined only those events that occurred in the time

Table 4
Calculated parameters of normal and disturbed D-region and variation of signal amplitude.

Calculated parameters	Normal ionosphere	SID	
β (km^{-1})	0.30	0.42	0.52
H' (km)	74	70.5	67
Ne (m^{-3}) at H'	$2.18 \cdot 10^8$	$3.93 \cdot 10^8$	$6.23 \cdot 10^8$
Number of modes	7	8	9
Amplitude dB above 1 μV/m	31.5	34.3	36.1

sector for solar zenith angle $-60^\circ \leqslant \chi \leqslant 60^\circ$. As for the above mentioned facts, we have already examined 250 solar flare events in period 2009–2014, and analyzed their effects on propagation characteristics of VLF/LF radio signals.

Behaviors of amplitude and phase perturbations on VLF/ LF radio signals induced by different intensity of solar X-ray fluxes, observed on Belgrade site, were examined and these results are presented in recent papers: Grubor et al. (Dec. 2005), Grubor et al. (2008), Žigman et al. (2007), Nina et al. (May 2012), Šulić et al. (2014). Also we studied results about the modeling of VLF wave propagation over long paths ($D < 12$ Mm) under normal and disturbed ionospheric conditions (McRae and Thomson, May 2000; Devi et al., 2008; Thomson et al., 2011; Chakrabarti et al., 2012; Basak and Chakrabarti, 2013; Kumar and Kumar, 2014). As our work is based on monitoring and modeling VLF/LF wave propagation over short paths we studied results obtained by Todoroki et al. (Feb. 2007), Grubor et al. (2008), Schmitter (2013), Kolarski and Grubor (2014). In the next subsection are given our results for used Wait's parameters in the RANGE model of the LWPC code, compared with the published results.

Simultaneous observations of amplitude (A) and phase (ϕ) on VLF/LF radio signals during solar X-ray flares could be applied for calculations of electron density profile. Therefore, the amplitude perturbations were estimated as a difference between values of the perturbed amplitude induced by X-ray flare and amplitude in the normal ionospheric condition: $\Delta A = A_{per} - A_{nor}$. Phase perturbations were estimated as: $\Delta\phi = \phi_{per} - \phi_{nor}$.

Although the solar X-ray flare effects on the propagating VLF/LF radio signals are well recognized on all paths, similarities and differences between them are defined under existing ionospheric conditions over the paths. According to that we will present our results of amplitude and phase perturbations on VLF radio signals observed during March 2011.

Twenty-three solar X-ray flares occurred on 6 March 2011, which is unusually large number for medium solar activity. Fig. 7a gives an instructive example of four successive solar flares that induced amplitude perturbations on GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals observed in Belgrade site. In Fig. 7b there are phase perturbations on same four VLF/LF radio signals versus universal time from 08:45 UT to 12:45 UT. The top panels of Fig. 7a and 7b show the solar X-ray flux against universal time as monitored by GOES-15 satellite.

Table 5 provides measured values of amplitude and phase perturbations on GQD-BEL, DHO-BEL, ICV-BEL and NSC-BEL paths induced by C2.65 ($2.65 \cdot 10^{-6}$ Wm^{-2} of X-ray flux in the band 0.1–0.8 nm), C3.13 ($3.13 \cdot 10^{-6}$ Wm^{-2}), C7.53 ($7.53 \cdot 10^{-6}$ Wm^{-2}), and C5.14 ($5.14 \cdot 10^{-6}$ Wm^{-2}) class solar X-ray flares.

Based on the observed and presented data on Fig. 7a and 7b it is easily to summarize the following:

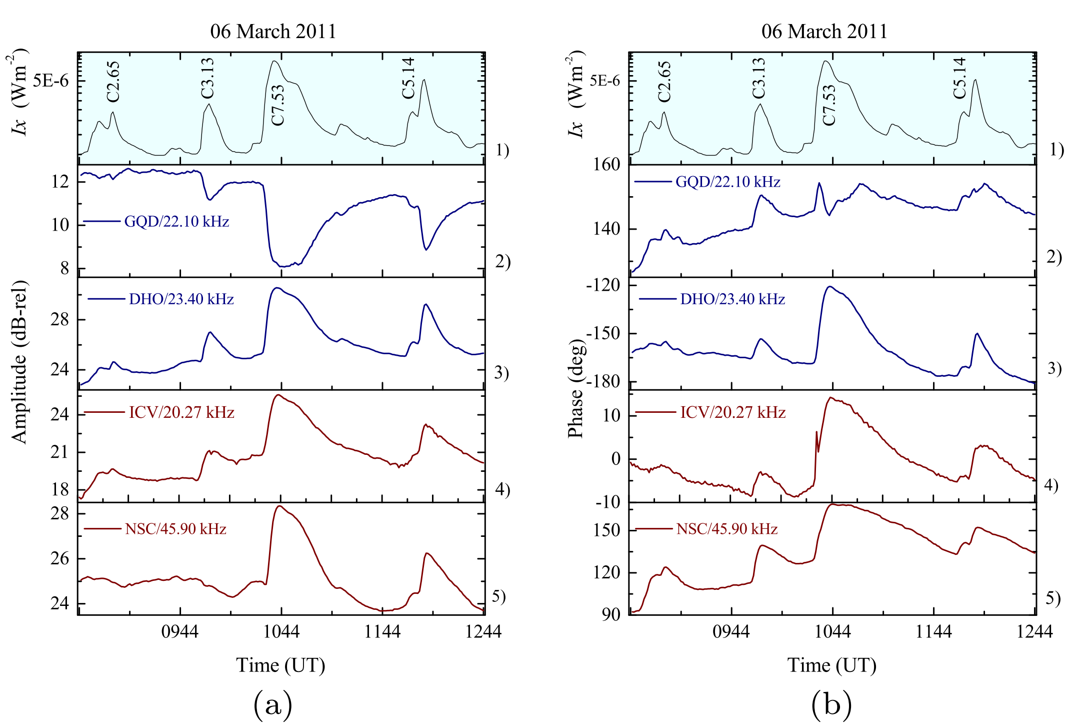

Fig. 7. Simultaneous variations of X-ray flux, amplitude and phase of GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals against universal time (a) perturbation of amplitudes during four successive flares on 6 March 2011 (b) perturbation of phases during four successive flares on the same day.

Table 5
Measured values of amplitude and phase perturbations on four radio signals induced by small class solar X-ray flares.

Solar X-ray flare		GQD 22.10 kHz		DHO 23.40 kHz		ICV 20.27 kHz		NSC 45.90 kHz	
class	$I_{X\,max}$ Wm^{-2}	ΔA dB	$\Delta\phi$ deg	ΔA dB	$\Delta\phi$ deg	ΔA dB	$\Delta\phi$ deg	ΔA dB	$\Delta\phi$ deg
C2.65(09:04 UT)	2.65E−6	−0.4	7	1.43	6	1.2	2	0	25
C3.13(10:01 UT)	3.13E−6	−1.4	10	2.3	12	2.27	6	−0.4	27
C7.53(10:40 UT)	7.53E−6	−4	10	5.43	48	5.1	22	3.9	40
C5.14(12:09 UT)	5.14E−6	−2.6	8	4.17	26	3.36	19	2.67	19

1. On GQD-BEL path amplitude decreases during occurrences of four C class solar flares (Fig. 7a, panel number 2). The size of amplitude perturbations is proportional to the intensity of solar X-ray flux. A phase change on this path is complicated, displaying increase and also decrease during the occurrence of C7.53 ($7.53 \cdot 10^{-6}$ Wm^{-2}) class solar X-ray flare.
2. On DHO-BEL path the amplitude and phase increase and the size of amplitude and phase perturbations are in correlation with the intensity of solar X-ray flux.
3. On ICV-BEL path both amplitude and phase increase with the changes of intensity of X-ray flux. The shape of curves of amplitude variation with time for DHO-BEL and ICV-BEL paths are very similar to each other. The size of amplitude perturbations on DHO-BEL and ICV-BEL paths caused by same solar X-ray flare are similar to each other (Table 5).
4. Phase perturbations on NSC-BEL path display more sensitivity to the changes on intensity of solar X-ray flux than amplitude. During the occurrence of C2.65 ($2.65 \cdot 10^{-6}$ Wm^{-2}) class solar X-ray flare there is no visible development of amplitude perturbation, while the phase increase is significant.

During March 2011 we examined thirty events of solar X-ray flares that occurred in the time sector for solar zenith angle $-60° \leqslant \chi \leqslant 60°$. Intensity of those X-ray flares was in range from C1 to M5.3 ($1 \cdot 10^{-6}$ to 5.3×10^{-5} Wm^{-2}) class. For each flare we measured amplitude and phase perturbations on four VLF/LF paths, except when the transmitter was off-air. In Fig. 8a and 8b there are data points of the observed GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz amplitude and phase perturbations as a function of solar X-ray flare intensity, respectively.

The range of size in amplitude and phase perturbations varies for different paths. Amplitude changes on DHO/23.40 and ICV/20.27 kHz radio signals have strong preferences to increase. In all analyzed events the phase perturbations on DHO/23.40 and ICV/20.27 kHz radio signals show an increase. The amplitude perturbations of GQD/22.10 kHz and NSC/45.90 kHz radio signals are distributed between increase and decrease, or between enhancement and attenuation, which depends on intensity of solar X-ray flux. The obtained results reveal that the phase perturbations on GQD/22.10 kHz show mainly increase and in some events decrease. The phase perturbations on NSC/45.90 kHz have a strong preference for phase increase.

We used the LWPC code for determining electron density enhancements in the D-region which were caused by flares C1 to M5.6 ($1 \cdot 10^{-6}$ to $5.6 \cdot 10^{-5}$ Wm^{-2}) classes that were occurred in March 2011. The unperturbed (averaged) values of $\beta = 0.30$ km^{-1} and $H' = 74$ km are used along four short paths, $D < 2$ Mm and calculated the initial electron density is $Ne(74\text{ km}) = 2.18 \cdot 10^{8}$ m^{-3}.

The basis for modeling altitude profile of electron density during each SID are measured perturbations of amplitude, ΔA and phase, $\Delta\phi$ on four VLF/LF radio signals recorded at Belgrade site. The electron densities (Eq. 1) at height $h = 74$ km for the presently obtained (β_{per}, H'_{per}) as a function of X-ray flare irradiance are shown in Fig. 9. Calculated electron density for each VLF/LF path is given by different symbol and color. For each waveguide resulting data of electron density are performed linear fitting and line is shown on Fig. 9. It is evident that electron density is nearly proportional to the logarithm of the X-ray irradiance maximum. Four sets of electron density display the well known increasing trend with increasing X-ray irradiance (Mitra, 1974).

Our results show good correlation of linear fitting lines calculated for enhancements of electron density induced by different intensities of solar X-ray flares on GQD-BEL, DHO-BEL, ICV-BEL and NSC-BEL short paths during March 2011. These short paths have their own specifications but under major increase in the flux of X-ray, enhancements of the electron density in the D-region over Central Europe are similarly spread inducing close characteristics of the upper boundary of these waveguides.

4.3. Distribution of amplitude perturbations during different solar activity

In this section we will present our results on amplitude and phase perturbations on DHO/23.40 kHz radio signal during different solar activity, at low, medium and high activity of current solar cycle 24. In this period, receiving DHO/23.40 kHz radio signal is stable and sensitive on increase of intensity of solar X-ray flux so recorded data are very useful for further study.

The first analyzed SID effect was induced by B8.8 ($8.8 \cdot 10^{-7}$ Wm^{-2}) class solar flare occurred on 3 November

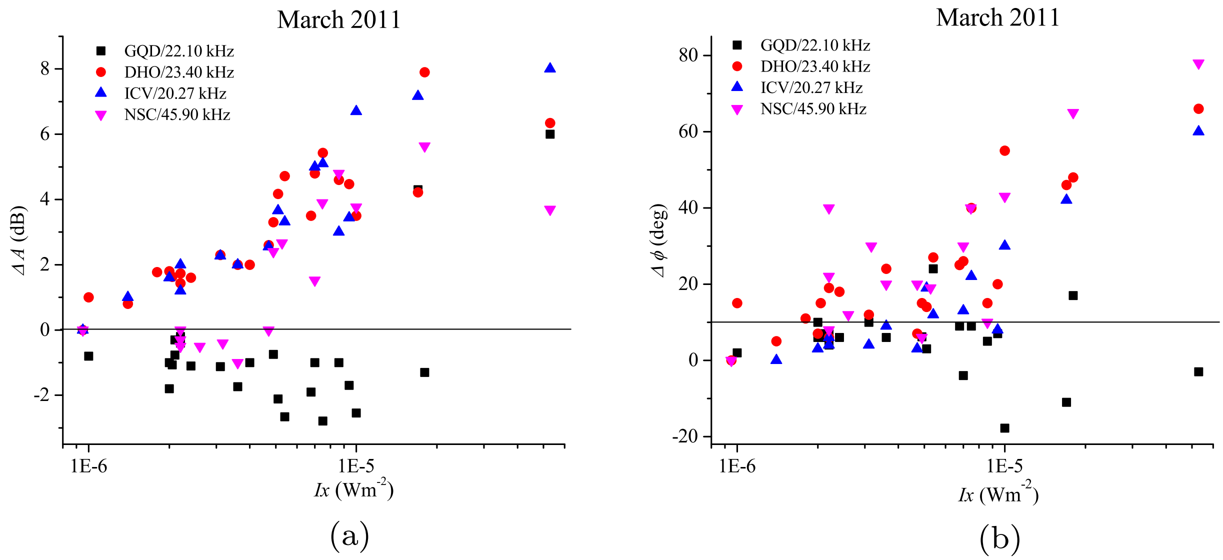

Fig. 8. (a) Observed amplitude perturbations on GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz, and NSC/45.90 kHz radio signals as a function of X-ray flux (b) Observed phase perturbations on the same radio signals as a function of X-ray flux, measured at Belgrade during March 2011.

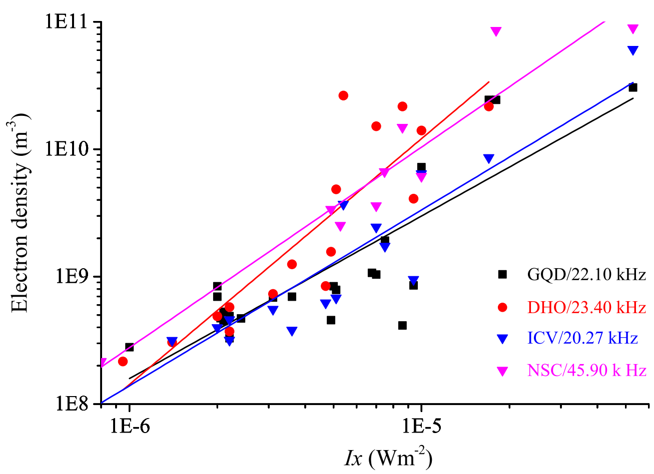

Fig. 9. Values of electron density at height $h = 74$ km during flare occurrences, against maximum intensity of X-ray flux calculated on the basis of VLF/LF propagation data recorded at Belgrade. Initial electron density $Ne(74\text{ km}) = 2.18 \cdot 10^8\ \text{m}^{-3}$.

2008, which induced amplitude and phase perturbations $\Delta A = 1.5$ dB, $\Delta\phi = 7°$, respectively. Electron density at height $h = 74$ km changed from $Ne = 2.18 \cdot 10^8\ \text{m}^{-3}$ to $Ne = 4.56 \cdot 10^8\ \text{m}^{-3}$. From 3 November 2008 to the end of 2014 we selected 251 events of SIDs induced by different classes of solar flares.

Fig. 10a shows the distribution of amplitude perturbations on DHO/23.40 kHz classified in accordance to the months over year. The size of amplitude perturbations is in the range $0.5 < \Delta A < 9$ dB. In Fig. 10a there is a difference in values of amplitude perturbations recorded during winter and summer months.

The observed amplitude and phase perturbations of DHO/23.40 kHz were simulated by the LWPC code. McRae and Thomson (2004) found that the increase of electron density due to a flare of X5 ($5 \cdot 10^{-4}\ \text{Wm}^{-2}$) class lowers H' from mid-day value of ~71 km down to ~58 km and increases β from 0.39 km^{-1} to 0.52 km^{-1}. Grubor et al. (2008) from recorded data of GQD/22.10 kHz radio signal at Belgrade found that a series of flares from C1 to M5 ($1 \cdot 10^{-6}$ to $5 \cdot 10^{-5}\ \text{Wm}^{-2}$) lower H' from 74 km to 63 km and change β in range 0.30–0.49 km^{-1}. On the basis of these results we changed β in steps of 0.01 km^{-1} and H' in steps of 0.1 km as input parameters in RANGE model of the LWPC code. Calculated amplitude perturbations as a function of H' (range 60–74 km) and β (range 0.30–0.60 km^{-1}) are given in the counter plot for the daytime conditions at DHO/23.40 kHz radio signal in Fig. 10b.

Theoretically results show that maximum of amplitude perturbation is $\Delta A \sim 5.5$ dB, which is lower than measured amplitude perturbations up to $\Delta A < 9$ dB. Similar results to ours about measured amplitude perturbations are published by Todoroki et al. (Feb. 2007). Authors successfully used the Finite Difference Frequency Domain (FDFD) model to obtain electron density in the D-region on the basis of propagation VLF radio signals (Japanese transmitters) over short paths.

With the restriction of $\Delta A < 5.5$ dB that were monitored on DHO/23.40 radio signal in period 2011–2014, we selected 201 SIDs for further study. The main aim of our work is to calculate the enhancement of electron densities caused by small and moderate classes of solar X-ray flares.

Fig. 11a shows calculated electron densities at height $h = 74$ km as a function of X-ray flare intensity, obtained on basis of DHO/23.40 kHz data recorded at Belgrade site. Different colors present the calculated electron densities for each year in period 2011–2014. For taking a view of changing electron density as a function of intensity of X-ray flux

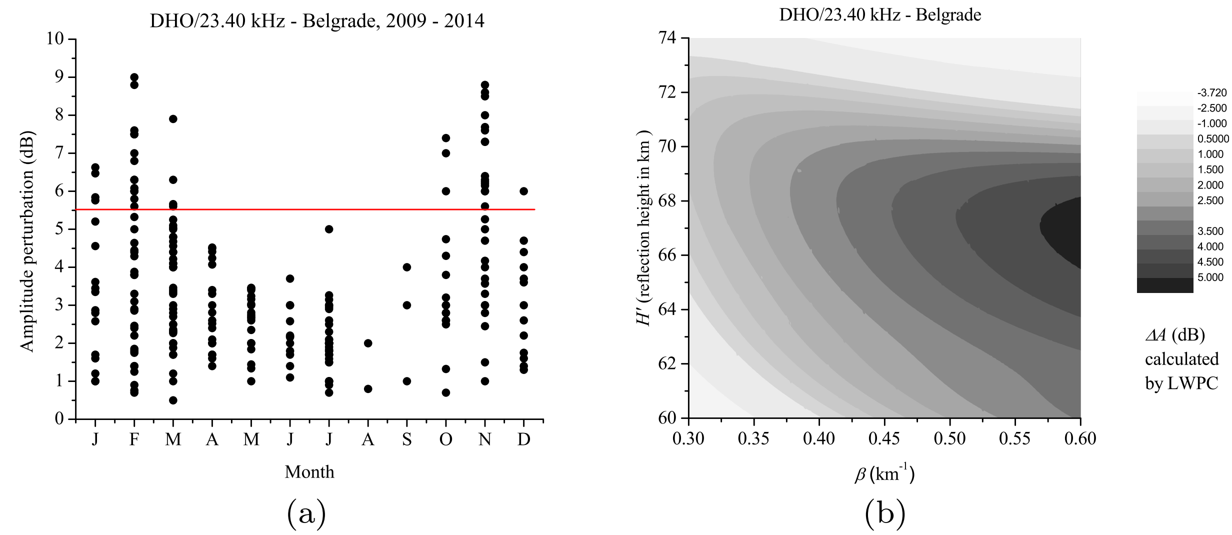

Fig. 10. (a) Distribution of amplitude perturbations classified in accordance to the month, during 2009–2014. There is a red horizontal line that separates SIDs in two groups in accordance of amplitude perturbations. (b) Counter plot of calculated amplitude perturbations as a function of Wait's parameters β and H' by the LWPC code.

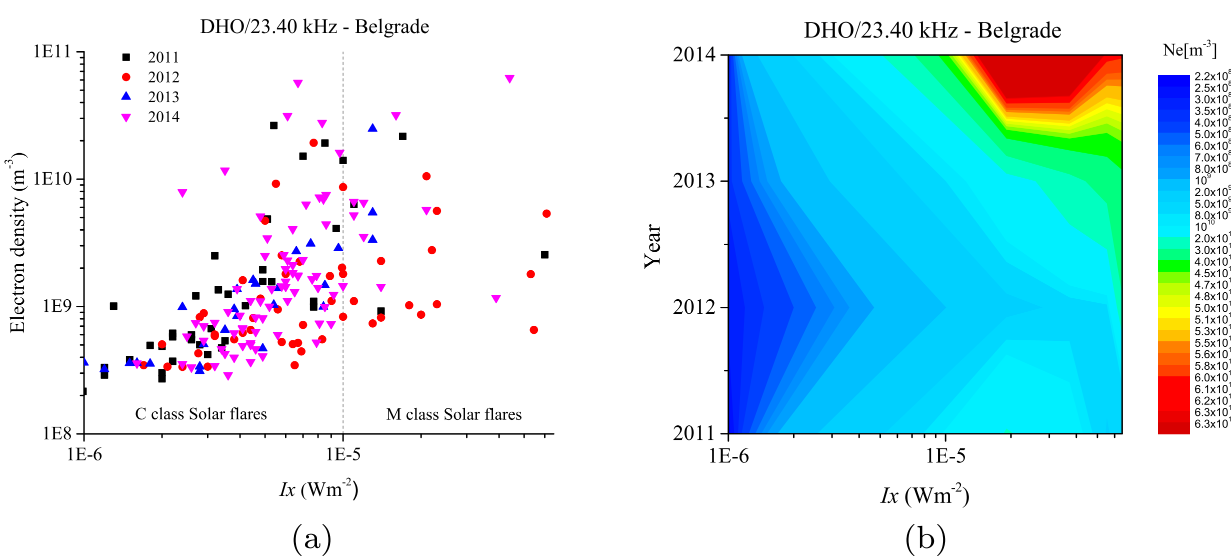

Fig. 11. (a) Electron density at reference height $h = 74$ km as a function of X-ray flux during SIDs in period 2011–2014 (b) surface plot of electron density as a function of X-ray flux during SIDs.

we presented our results as a surface plot, Fig. 11b. Generally, the results show that solar X-ray flares:

1. from C1 to C6 ($1 \cdot 10^{-6}$ Wm^{-2} to $6 \cdot 10^{-6}$ Wm^{-2}), class induced enhancement of electron density is from $Ne \sim 2 \cdot 10^{8}$ m^{-3} to $Ne \sim 2 \cdot 10^{9}$ m^{-3}, respectively
2. from C7 to M1 ($7 \cdot 10^{-6}$ Wm^{-2} to $1 \cdot 10^{-5}$ Wm^{-2}) class induced electron density rises up to values $Ne \sim 10^{10}$ m^{-3},
3. from M1 to M6.1 ($1 \cdot 10^{-5}$ Wm^{-2} to $6.1 \cdot 10^{-5}$ Wm^{-2}) class, the enhancement of electron density is different according to level of solar activity and rises up to values $Ne \sim 6 \cdot 10^{10}$ m^{-3},
4. the greatest enhancement of electron densities (red color) are induced by moderate class solar X-ray flares, which occur more frequently in the year of the maximum of solar cycle 24.

5. Summary and conclusions

The purpose of this work was to analyze the amplitude and phase data acquired by monitoring at Belgrade site VLF/LF radio signals emitted by four European transmitters during a seven-year period (2008–2014). The results of amplitude and phase variations on GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals measurements at short path over Central Europe and their interpretation are summarized here. The most important factors affecting those paths under uniform background conditions are the transmitter frequency, geographical location, the electron density profile, and the ground conductivities encountered.

Our attention is restricted to regular diurnal, seasonal and solar variations including sunrise and sunset effects on propagation characteristics of VLF/LF radio signals. All the paths are similarly illuminated during daytime condition and there are differences in the level of illumination during dawn and dusk in accordance to geographic coordinates of transmitters. We accepted the results obtained by Volland (1964) that VLF radio signals propagating from transmitter to receiver over paths with distance $D < 2$ Mm reflect once on the middle of the paths and propagate as a superposition of discrete modes. In general, for propagation of VLF/LF radio signals over short paths from transmitters to Belgrade site we conclude that:

- The diurnal variation of amplitude is caused by smooth variation of the equivalent reflection height and the reflection characteristics of the D-region during 24 h.
- On the basis of changing reflection characteristics of the D-region our numerical results show that propagation of VLF radio signal is created as a superposition of $n_n \sim 17$ discrete modes during nighttime and $n_d = 7$ during daytime condition. Propagation of LF radio signal is performed with $n_n = 34$ (nighttime) and $n_d = 10$ (daytime) discrete modes. Sunrise effects on VLF/LF propagating over a short path cause a gradual fall of number of discrete modes. This implicates that the number of the discrete modes is induced by the transmitted frequency.
- The process of ionization in the D-region begins when solar zenith angle has value $\chi = -99^0$, and sunrise terminator reaches the height $h = 95$ km. When this process starts in the middle of the propagation path, the consequence is the development of the first amplitude minimum and the transition from phase level during nighttime to phase level during daytime.
- Based on specifications for each path and a function of diurnal-seasonal variation, signal characteristics morphology, i.e. how many amplitude minima and at what time they would be developed is defined. It is characterized by periodic and repeatable variations of amplitude as the dawn-dusk terminator moves along a VLF/LF path.
- On the basis of measured VLF/LF data our conclusion is that the appearances of amplitude minima over short path could be divided in *two types*. The amplitude minima that are appeared in time intervals during transition of nighttime/daytime and daytime/nighttime conditions on the middle of the propagation path belong to the first type. The amplitude minima that occur under daytime condition over all short paths belong to the second type. Usually they are developed as a pair and their timings are symmetrical arrange in a according to a local noon. Timings of their occurrences continuously change from day to day.

Although the solar X-ray flare effects on propagation of VLF/LF radio signals are well recognized on all paths, similarities and differences between them are defined under existing conditions over the paths. Results about propagation characteristics of signal amplitude and phase show that each short path is unique and thus each path reacts differently to the electron density enhancement induced by same solar X-ray flare. As it can be seen from this study the range of size in amplitude and phase perturbations varies for different paths and also statistical results show that the size of amplitude and phase perturbations on VLF/LF radio signal is in correlation with the intensity of X-ray flux. The main results are:

- The DHO/23.40 kHz and the ICV/20.27 kHz radio signals measured at Belgrade site always show amplitude increases and strong preference for phase increases under enhancement of electron density induced by solar X-ray flare.
- Amplitude changes of GQD/22.10 kHz radio signal are evenly distributed between enhancement and attenuation. Phase changes show a different character, displaying increase and also decrease during the occurrence of different solar flare classes.
- The NSC/45.90 kHz radio signal at Belgrade site always shows more sensitivity of phase perturbation to the changes on intensity of solar X-ray irradiance than amplitude.

The model computations applied to the amplitude and phase perturbations on VLF/LF radio signals recorded at Belgrade site are able to reproduce the general features of the electron density enhancement induced by occurrence of solar X-ray flares during the period of ascending phase and maximum of the solar cycle 24.

Acknowledgments

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A STUDY OF HIGH-FREQUENCY PROPERTIES OF PLASMA AND THE INFLUENCE OF ELECTROMAGNETIC RADIATION FROM IR TO XUV

by

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On the basis of calculated values for the conductivity in an external electric field, we determined the high-frequency characteristics of plasmas under extreme conditions (*e. g.* dense plasma focus device). The examined range of frequencies covers the IR, visible, UV, XUV up to X regions and the considered electronic number density and temperature are in the ranges of 10^{21} cm^{-3} *Ne* 5 cm^{-3} and 2 *T* 10^6 K, respectively. The data obtained using this method are important for plasma focus research, laboratory plasma research, investigation of atmosphere plasmas of astrophysical objects like white dwarfs with different atmospheric compositions.

Key word: plasma focus, plasma, dynamic property, electromagnetic radiation

INTRODUCTION

The properties of dense plasmas under extreme conditions are of great interest in various research fields like nuclear physics, astrophysics, terrestrial physics, plasma physics [1-10]. Exploring and improving the new calculation possibilities, simulation techniques and the extension of numerous models in connection with the dynamic properties in the physics of high energy are in the focus of investigators nowadays [11]. Further investigation of strongly correlated plasma and investigations of its electronic properties remain an ongoing problem. For an example theoretical calculations and measurements of reflectivity are important because of its possible use as diagnostic tool in the area of high-density and high-energy physics [9, 12].

Determining high-frequency (HF) plasma properties in the homogeneous electrical field has been a subject of substantial investigation recently and is experiencing a real boom these days. The reason for this is the rapid development of experimental facilities in the field of extreme conditions aimed for demonstrating nuclear fusion in the laboratory [13, 14], for developing intense radiation sources with special properties [11, 15], and to investigate important and fundamental physics processes in astrophysics [16]. Unfortunately, the theoretical work and the explanations of these experimental measurements lag behind experimental research and do not follow it. Therefore, there was a need for more serious and even harder work in the field of theoretical work. There are two basic approaches to those theoretic studies: the generalized Drude-Lorentz model, [17], or the review [18], and the method of moments [19]. In addition, we have been working on the direct extension of the modified random-phase approximation for the calculation of the HF properties [20]. It should also be noted here, that we have to take advantage of growing high performance computing resources in the area of simulations and catch up and reach experimental research.

The aim of this work is determination of HF characteristics of non-ideal plasmas. All the presented values, like the electrical permeability and the coefficients of refractivity and reflectivity, as well as electromagnetic (EM) field penetration depth, are obtained by the help of the numerically calculated values for the dense plasma dynamic conductivity in an external HF electric field. The determination of the dynamic conductivity of a highly ionized plasma in a HF external electric field, as well as obtaining the other plasma pa-

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rameters relies on the method presented in [20]. The method itself is based on the self-consistent field theory developed for the static plasma transport coefficients calculation, such as static plasma electric conductivity, *etc*. After the experimentally proven validity of the presented theory in the investigated domain of the electron densities and temperatures, the method was tested in the domain of more dense, non-ideal plasma *i. e.* was applied for calculation of conductivity of Degenerate B-type (DB) white dwarf atmospheres [21, 22] in wide area of electron densities and temperatures.

This work focuses on the determination of dynamic characteristics of dense plasmas as well as on introducing usable form of the presentation of calculated data (fitting formula) important for laboratory applications, *e. g.* dense plasma focus device (DPF), as well as for astrophysics modeling. All the data presented here will very soon be accessible through http://servo.aob.rs as web service and database.

USED MODEL METHOD

This paper considers a highly ionized plasma in a homogenous and monochromatic external electric field $\vec{E}(t) = \vec{E}_0 \exp(-i\omega t)$. According to [21] and [23], the dynamic electric conductivity of a strongly coupled plasma

$$\sigma(\omega) = \frac{4e^2}{3m}\int_0^{\infty} \tau_\omega(E)\left(-\frac{\mathrm{d}w(E)}{\mathrm{d}E}\right)\rho(E)E\,\mathrm{d}E = \sigma_{\mathrm{Re}}(\omega) + i\sigma_{\mathrm{Im}}(\omega) \quad (1)$$

is presented by the expressions

$$\sigma_{\mathrm{Re}}(\omega) = \frac{4e^2}{3m}\int_0^{\infty} \frac{\tau(E)}{1+[\omega\tau(E)]^2}\left(-\frac{\mathrm{d}w(E)}{\mathrm{d}E}\right)\rho(E)E\,\mathrm{d}E \quad (2)$$

$$\sigma_{\mathrm{Im}}(\omega) = \frac{4e^2}{3m}\int_0^{\infty} \frac{\omega\tau^2(E)}{1+[\omega\tau(\mathrm{E})]^2}\left(-\frac{\mathrm{d}w(E)}{\mathrm{d}E}\right)\rho(E)E\,\mathrm{d}E \quad (3)$$

Here e, m, and E are the charge, mass, and energy of the free electron, $\rho(E)$ is the one-electron states density in the energy space, $w(E) = [\exp(\beta E - \beta\mu) + 1]^{-1}$ – the Fermi-Dirac distribution function, μ – the chemical potential of the ideal gas of the free electrons with the density n_e and the temperature T, $\beta = (k_B T)^{-1}$, and the relaxation time $\tau_\omega(E) = \tau(E)/(1 - i\omega\tau(E))$. In upper expressions $\tau(E)$ is the "static" relaxation time and the method of determination of $\tau(E)$ is described in the previous papers [21, 23, 24] in detail.

Other HF plasma characteristics can be expressed in terms of the quantities $\sigma_{\mathrm{Re}}(\omega)$ and $\sigma_{\mathrm{Im}}(\omega)$. In this way the plasma dielectric permeability is shown as

$$\varepsilon(\omega) = 1 + i\frac{4\pi}{\omega}\sigma(\omega) = \varepsilon_{\mathrm{Re}}(\omega) + i\varepsilon_{\mathrm{Im}}(\omega) \quad (4)$$

where $\varepsilon_{\mathrm{Re}}(\omega) = 1 - (4\pi/\omega)\sigma_{\mathrm{Im}}(\omega)$ and $\varepsilon_{\mathrm{Im}}(\omega) = (4\pi/\omega)\sigma_{\mathrm{Re}}(\omega)$. The coefficients of refraction $n(\omega)$, and reflection $R(\omega)$, are determined as

$$n(\omega) = \sqrt{\varepsilon(\omega)} = n_{\mathrm{Re}}(\omega) + in_{\mathrm{Im}}(\omega), \qquad R(\omega) = \left|\frac{n(\omega)-1}{n(\omega)+1}\right|^2 \quad (5)$$

where, bearing in mind that

$$|\varepsilon(\omega)| = [\varepsilon^2_{\mathrm{Re}}(\omega) + \varepsilon^2_{Im}(\omega)]^{1/2}$$

the real and imaginary part of refractivity are given by

$$n_{\mathrm{Re}}(\omega) = [0.5(|\varepsilon(\omega)| + \varepsilon_{\mathrm{Re}}(\omega))]^{1/2}$$

and

$$n_{\mathrm{Im}}(\omega) = [0.5(|\varepsilon(\omega)| - \varepsilon_{\mathrm{Re}}(\omega))]^{1/2}.$$

From here the equation for the reflectivity could be expressed as

$$R(\omega) = \sqrt{\frac{1 + |\varepsilon(\omega)| - \sqrt{2}\sqrt{|\varepsilon(\omega)| + \varepsilon_{\mathrm{Re}}(\omega)}}{1 + |\varepsilon(\omega)| + \sqrt{2}\sqrt{|\varepsilon(\omega)| + \varepsilon_{\mathrm{Re}}(\omega)}}} \quad (6)$$

In such a way, we determined the other parameter of interest *i. e.* the penetration depth of electromagnetic radiation into plasma, $\Delta(\omega)$. This quantity is the skin-layer width determined as the inverse imaginary part of the electromagnetic field wave number $\Delta(\omega) = (c/\omega)[1/n_{\mathrm{Im}}(\omega)]$ where c is the speed of light and $n_{\mathrm{em}}(\omega)$ is defined above.

Here, it is common to use a dimensionless coupling parameter, the plasma non-ideality coefficient Γ, that characterizes the physical properties of the plasma. It is of especial importance in describing of dense, non-ideal plasmas, as ones considered in this paper. The mentioned parameter $\Gamma = e^2/akT$ as such characterizes the potential energy of interaction at average distance between particles $a = (3/4\pi Ne)^{1/3}$ in comparison with the thermal energy. The well-known Brueckner density parameter $r_s = a/a_B$ is the ratio of Wigner-Seitz and Bohr radius.

RESULTS AND DISCUSSION

As the continuation of previous investigation, that is of interest for DB white dwarf atmospheres [21, 22] and high energy research, the calculations of the HF characteristics of plasma in wide area of electron densities and temperatures were conducted. The investigated areas are of interest for both of the laboratory experiments, *e. g.* DPF, and atmospheres of different stellar types like degenerate a-type (DA), or degenerate c-type (DC) white dwarfs.

The electrical permeability and the coefficients of refractivity and reflectivity of dense non-ideal plasmas are determined on the basis of numerically calculated values for the dense plasma dynamic conductivity in an external HF electric field. Here are considered electronic number density and temperature in the

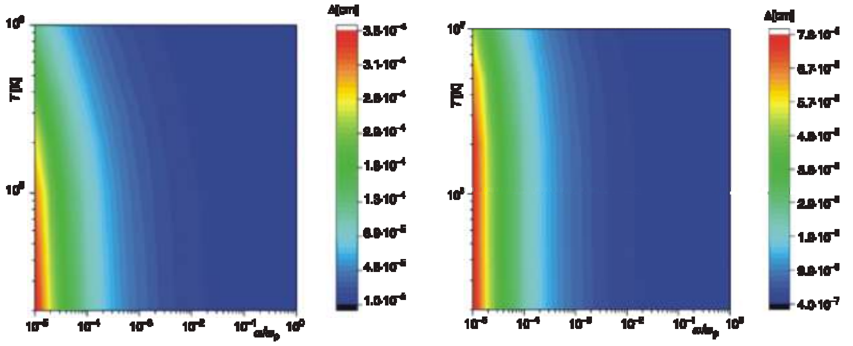

Figure 1. Left: surface plot of the skin layer depth for $Ne = 10^{24}$ cm^{-3} and 2 T 10^6 K; right: same as in left but for Ne = 10^{24} cm^{-3}

ranges of 10^{21} cm^{-3} Ne 10^{24} cm^{-3} and 2 K T 10^6 K, respectively. The examined range of frequencies ω covers the region 0 ω ω_p, where ω_p = $(4\pi Ne e^2/m)^{1/2}$ is the plasma frequency.

Within the considered ranges of variation of electron density and temperature, the behavior of the HF plasma quantities with the increase of the Ne and T is as it is expected. This means that the behavior of those characteristics, with the increasing of Ne and T, remains the same within the whole range of electron number densities and temperatures 10^{21} cm^{-3} Ne cm^{-} . The same conclusion is also related to all yielded parameters, including the penetration depth $\Delta(\omega)$. From the results it could be observed that for the long-wavelength radiation, *i. e.* frequency tends to zero, there is interesting dependence on temperature and frequency of skin-effect Δ at surface plot in fig. 1. Also, the reflectivity coefficient tends to 1, mining the plasma layer acts as a mirror.

Particularly, here we give special attention to analysis of reflectivity data because this quantity is very important in high energy density plasmas (measurements as an important diagnostic tool provide information about the density profile). In fig. 3 we compare the behavior of reflectivity coefficient R, determined in this paper, with the behavior of the corresponding quantities calculated in [25] for $r_s = 5$ and Γ Γ Γ and also for $\Gamma = 0.5$ and $r_s = 0.4$, r_s = 1 and r_s = 2. Here r_s and Γ are previous defined Brueckner density and non-ideality parameters, respectively. The corresponding curves showing theoretical data from [25] are presented by full, dashed, and dotted lines. Figure 3 shows a qualitative agreement (the differences are less or close to 10-25 percents) of our results with the results of [25] in the whole region of ω and for all values of and non-ideality parameters. By analyzing the behavior of corresponding curves in figs. 2 and 3 one can see the tendency that increase in the density and coupling parameters leads to a decrease in the reflection index. Then, in fig. 3 it is seen that at frequencies $\omega < \omega_p$ the reflection occurs most effectively and at ω ω_p the plasma becomes much more transparent.

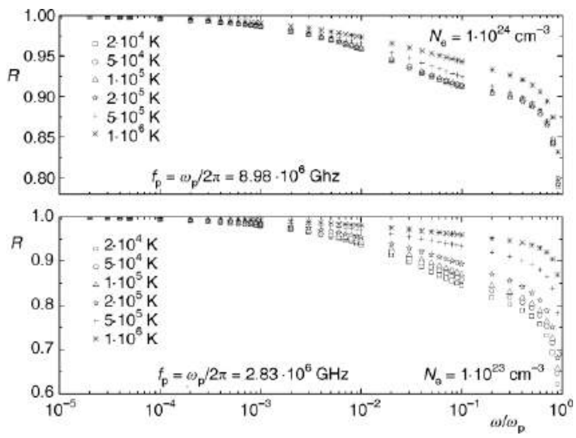

Figure 2. Down: the plasma reflectivity for $Ne = 10^{24}$ cm^{-3} and 2 T 10^6 K; up: same as in lower panel but for $Ne = 10^{23}$ cm^{-3}

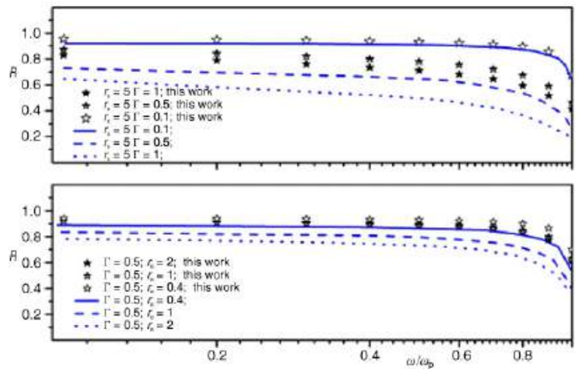

Figure 3. The plasma reflectivity as a function of ω ω_p for various values of quantities r_s and Γ; present results are shown together with results from [25]

In fig. 4 is presented a surface plot of the plasma reflectivity for different values of density as a function of temperature and frequency. With this figure it is possible to map the region of high non-ideality. For a given density the appropriate panel from fig. 4 can be selected and the value of R found for the chosen pair of temperature and frequency.

In order to more simplify the presented results for the further use a fitting procedure is exploited to get the plasma reflectivity from the temperature and frequency for various values of electron density. For all analyzed densities the expression is given by

$$R(x, y) \quad a \quad bx \quad cy \quad dx^2 \quad ey^2 \quad fxy \quad gx^3 \quad hy^3 \quad ixy^2 \quad jx^2y \tag{7}$$

where $x = \omega/\omega_p$ ratio of frequency and plasma frequency (0 ω ω_p), $y = T$, temperature and a-j are calculated parameters. These parameters were computed

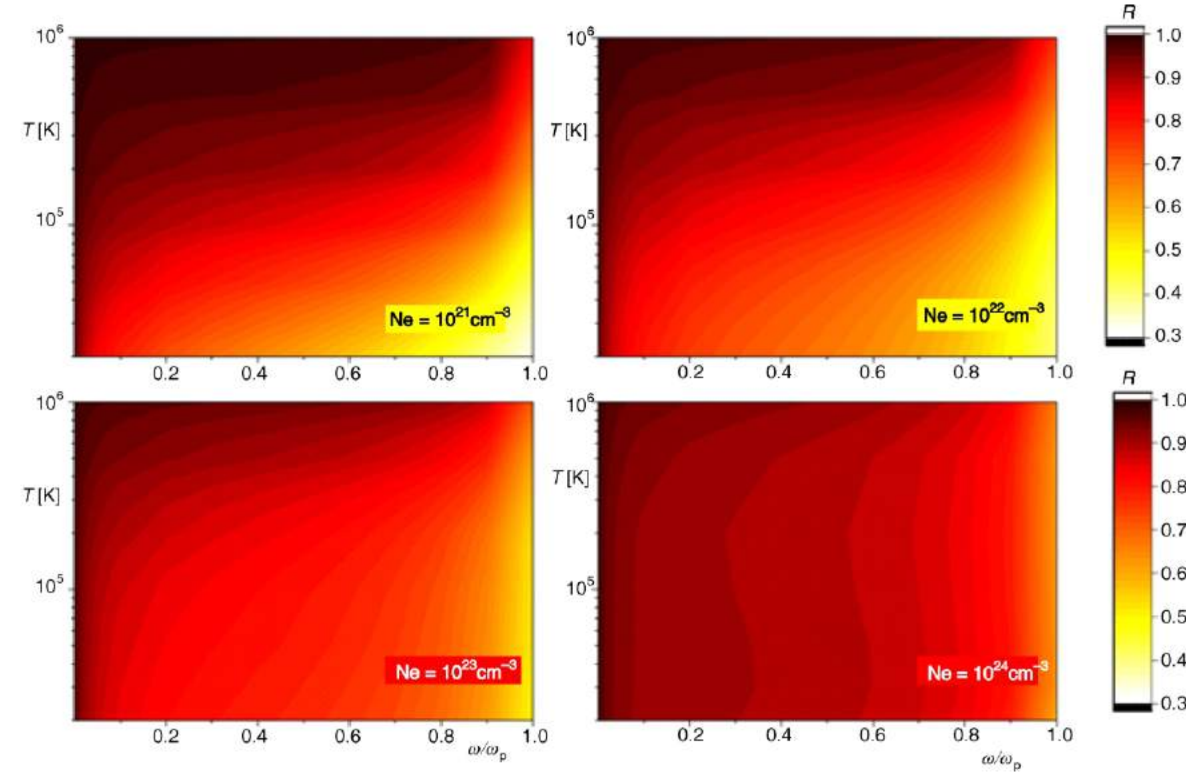

Figure 4. Surface plot of the plasma reflectivity for different values of electron density 10 cm^{-3} *Ne* 10^{24} cm^{-3} as a function of temperature and frequency

Table 1. Parameters (from *a* to *j*) needed for $R(x, y)$ fit given by eq. 7, as a function of electron density where $x = \omega/\omega_p$ and $y = T$

F_p/Ne	10^{21} [cm^{-3}]	10^{22} [cm^{-3}]	10^{23} [cm^{-3}]	10^{24} [cm^{-3}]
a	0.935052097	0.947234943	0.967203184	0.981546732
b	–1.317415548	–1.44143753	–1.253135644	–0.863649267
c	7.29876E-07	4.12914E-07	9.29337E-08	–3.83153E-10
d	2.200777151	2.59112663	2.623576736	2.2174305
e	–1.81598E-12	–9.04495E-13	–1.02346E-13	2.41917E-14
f	1.97343E-06	1.52641E-06	6.20522E-07	1.38124E-08
g	–1.535152818	–1.760714503	–1.851589254	–1.69034055
h	1.15411E-18	5.43242E-19	3.83954E-20	–1.3866E-20
i	–1.17436E-12	–6.97197E-13	–1.04538E-13	6.15697E-14
j	–3.59279E-07	–4.84845E-07	–3.40011E-07	–6.11506E-08

from a standard 3-D fitting procedure, (best-fit value *i. e*. r-Square close to one) and their values as the function of density are shown in tab. 1. We must emphasize that those expressions give good results for values of frequencies in the region $0 < \omega \quad 0.3\,\omega_p$ although they have to be applied with caution beyond this region.

Some HF quantities: The behavior of some HF quantities for various plasma conditions is illustrated here although it is not the main topic of our research. The reason of its representation is that it enables determination of other transport properties. The electrical permeability and the coefficients of refractivity of dense non-ideal plasmas are determined on the basis of numerically calculated values for the dense plasma dynamic conductivity in an external HF electric field. Here we will present the most extreme cases which we think are the most interesting for readers (all other data covering the ranges of 10^{21} cm *Ne* 10^{24} cm^{-3} and 10^4 K < *T* < 10^6 K will be presented in database).

On fig. 5 the real and imaginary part of refraction coefficient for density *Ne* = 10^{24} cm^{-3} in temperature region 2 10^4 K *T* 10^6 K is presented as a function of frequencies ω. From this figure one can see that the behaviour of this HF quantity is similar to the investigated ones in upper material.

Further analysing the presented results it could be observed that for the long-wavelength radiation, *i. e*. frequency tends to zero, even for most extreme cases the imaginary part of the dielectric function diverges, *i. e*., $|\varepsilon(\omega \quad 0)|$ is much greater than real part of the dielectric function (fig. 6).

Astrophysical relevance: As we noted in the above text the investigations of HF characteristics is important for research of atmosphere plasmas of astrophysical objects like white dwarfs with different atmospheric compositions (DA, DC *etc*.), and some other stars (M-type red dwarfs, Sun, *etc*). In order to demonstrate this astrophysical relevance fig.7 is presented

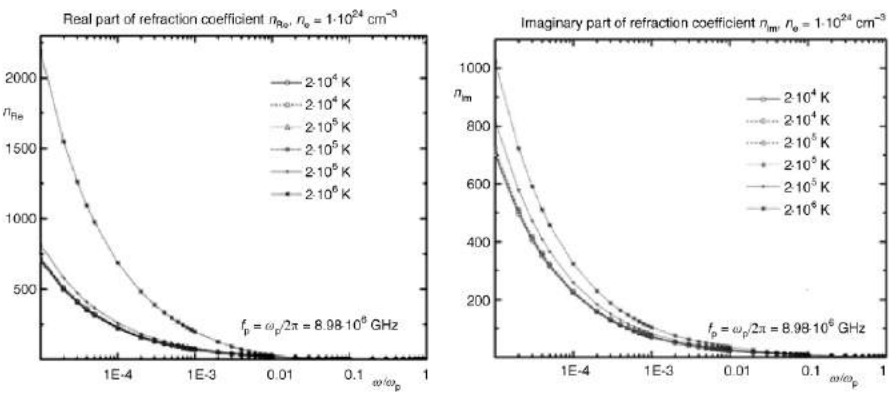

Figure 5. Left: the real part of refraction coefficient for density $Ne = 10^{24}$ cm^{-3}, and 2 10 K T 10^6 K; right: imaginary part of refraction coefficient for the same values of T and Ne as in left

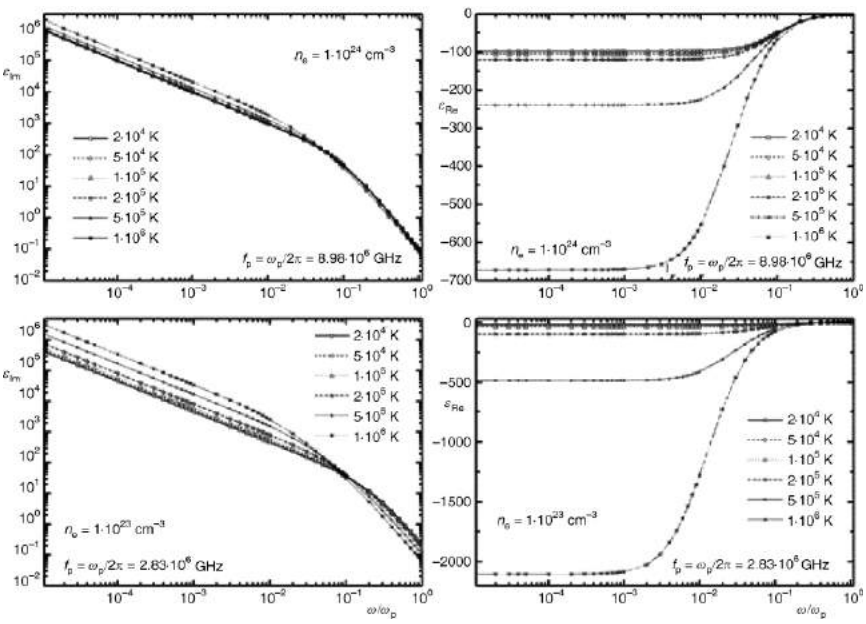

Figure 6. HF dielectric permeability for density $Ne = 10^{23}$ cm^{-3} and 10^{24} cm^{-3} in the temperature region 2 10 K T 10^6 K

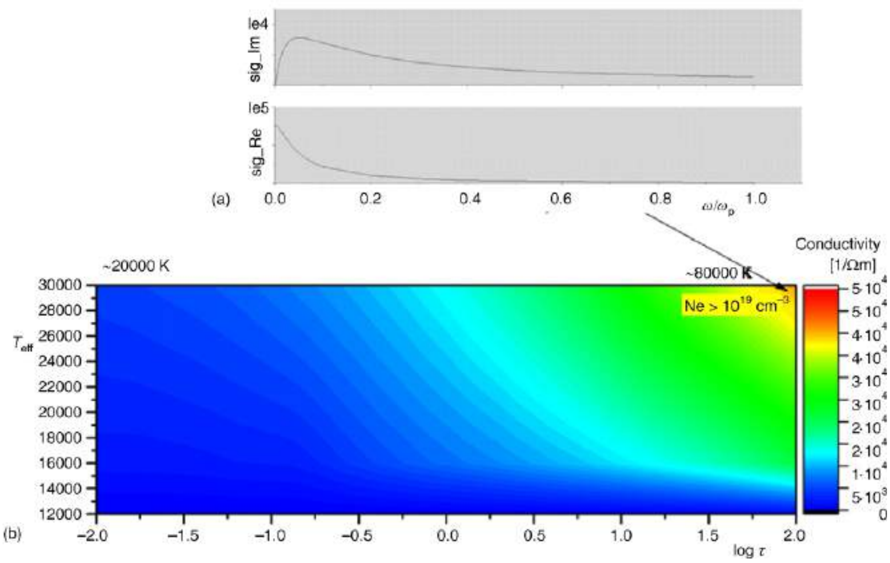

Figure 7(a). Surface plot: onductivity as a function of the logarithm of Rosseland opacity log τ for DB white dwarf atmosphere models with logarithm of surface gravity log g = 8 and various effective temperatures T_{eff} = 1.2 10^4 K, ..., 3 10^4 K; (b) example of HF conductivity for log τ = 2 for DB white dwarf atmosphere models T_{eff} = 3 10^4 K and log g = 8. For the calculations of plasma characteristics of DB white dwarf atmospheres, the data from Koester (private communication) were used

here. In fig. 7(a) is illustrated, by surface plot, the conductivity as a function of the logarithm of Rosseland opacity log τ for DB white dwarf atmosphere models with logarithm of surface gravity log g = 8 and various effective temperatures from T_{eff} = 1.2 K to T_{eff} = = 3 10^4 K. Figure 7(a) shows that increasing the white dwarfs effective temperature, at a fixed value of the logarithm of Rosseland opacity, leads, as a consequence, to an increase of conductivity. Also, it is illustrated here in fig. 7(b) plot of HF conductivity for log $\tau = 2$ for DB white dwarf atmosphere models $T_{\rm eff} = 3\ 10^4\ K$ and log $g = 8$ which corresponds to electron density: 10^{19} cm^{-3} and temperature: $8\ 10^4\ K$. From the presented fig. 7(a,b), it can be observed a regular behaviour of the conductivity considering the characteristics of DB white dwarf atmospheres.

CONCLUSIONS AND PERSPECTIVES

In this paper we calculated the dynamic characteristics of plasmas of increased non-ideality under the influence of IR to XUV, electromagnetic radiation. The presented data covers wide region of electron densities and temperatures. These results, especially fit formula, can be applied in the experiments of DPF, high pressure discharge, shock waves *etc*., where strongly non-ideal plasmas, including extremely dense plasmas, are created. The developed method presents a useful tool for the research of white dwarfs with different atmospheric compositions (DA, DC *etc*.), as well as for some other stars (M-type red dwarfs, Sun *etc*.). In the near future we aim to further improve analysis using GEANT code [26]. Also, our plan is to present the results obtained during this investigation in database which can be accessed directly through http://servo.aob.rs as a web service similarly to the existing MolD and E-MOL databases http://servo.aob.rs/mold, http://servo.aob.rs/emol/ [27, 28].

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AUTHORS' CONTRIBUTIONS

The calculations and simulations were carried out by V. A. Srećković, who wrote the manuscript. M. S. Dimitrijević, D. M. Šulić, and Lj. M. Ignjatović participated in editing and revising of the manuscript. All authors discussed the results and commented on the manuscript.

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ИСПИТИВАЊЕ ВИСОКОФРЕКВЕНЦИЈСКИХ ОСОБИНА ПЛАЗМЕ И УТИЦАЈ ЕЛЕКТРОМАГНЕТНОГ ЗРАЧЕЊА У ДОМЕНУ ОД IR ДО XUV

На основу израчунатих вредности проводности у спољашњем електричном пољу, одређене су високофреквенцијске карактеристике плазми у екстремним условима (на пример, код плазма фокусних уређаја). Испитивани опсег фреквенција покрива IR, видљиву, UV, XUV све до X региона и разматране су електронске густине и температуре у распону 10^{21} cm^{-3} $\leq Ne \leq 5 \cdot 10^{24}$ cm^{-3} и $2\ 10^4$ K T 10^6 K, респективно. Подаци добијени коришћењем ове методе важни су за истраживања плазма фокусних уређаја, за истраживања лабораторијске плазме, а такође и за истраживања плазме астрофизичких објеката, као што су бели патуљци са различитим атмосферским композицијама.

Кључне речи: плазма фокус, плазма, динамичко својство, електромагнетно зрачење

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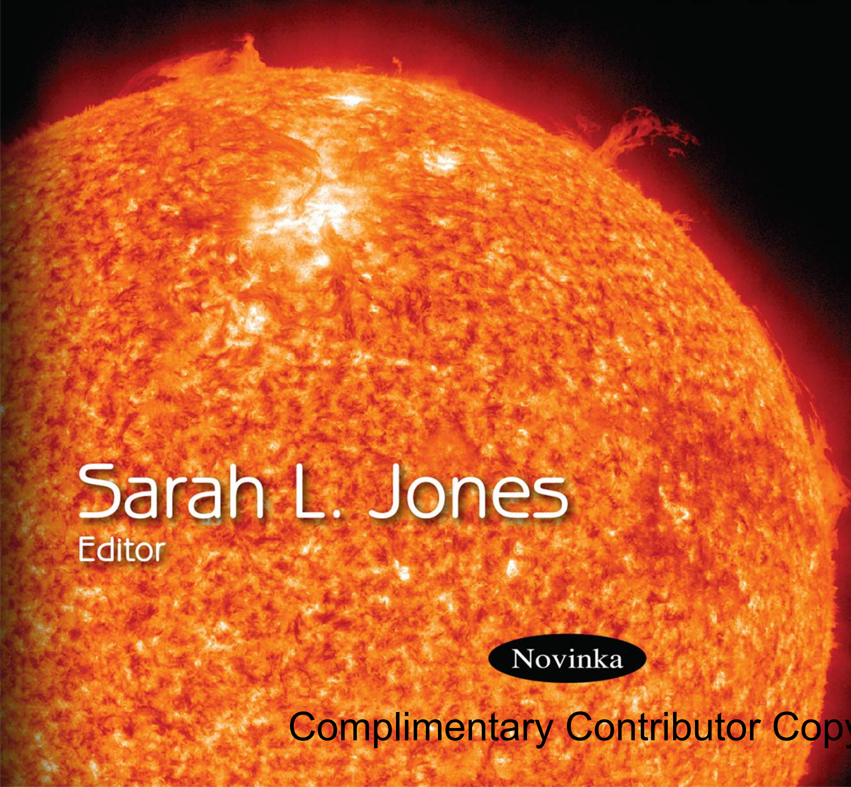

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Chapter 3

ANALYSIS OF THE IONOSPHERIC D-REGION DISTURBANCES IN RESPONSE TO THE EFFECTS OF SOLAR X-RAY FLARES

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ABSTRACT

The sensitivity of Very Low Frequency (VLF, 3-30 kHz) and Low Frequency (LF, 30-300 kHz) propagation in the lower ionosphere makes it an ideal probe for remotely sensing the ambient state and localized perturbations of the lower ionosphere. During occurrence of solar X-ray flare the altitude distribution of the ionospheric electron density is a noticeable and interesting issue and known as Sudden Ionospheric Disturbance (SID). This is an important classical topic event for solar-terrestrial relations. The induced SID in the D-region causes perturbations in the received amplitude and phase on VLF/LF radio signals. The basis of this work is amplitude and phase data acquired by monitoring NAA/24.00 kHz, GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz, radio signals at Belgrade site (44.85^0 N, 20.38^0 E) Serbia

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by AbsPAL and AWESOME receivers since 2003 and 2008 up to 2015, respectively. We expected and estimated differences in amplitude and phase perturbations on VLF/LF radio signals induced by solar X-ray flares which occurrences are under different solar zenith angles over illuminated propagation paths.

Observed VLF perturbations at Belgrade site have sensitive dependence on: *X-ray flare intensity, solar zenith angle, solar flare duration and geophysical characteristics of VLF/LF path.* The model computations applied to the multiple path observations at Belgrade site are able to reproduce a number of the general features of the electron density enhancement induced by occurrence of solar X-ray flares during the period of the ascending phase and the maximum of the Solar Cycle 24.

1. INTRODUCTION

The Earth's atmosphere processes are dependent on the wavelength of solar radiation. The very short wavelengths like X-rays and ultraviolet are completely absorbed by the atmosphere resulting in photoionization and photo dissociation and are responsible for establishment of the ionosphere at heights above ~ 60 km. Also, the longer wavelengths (the visible and infrared light) although partially absorbed by the atmosphere, manage to reach the Earth surface influencing the Earth's climate (Leckner 1978; Bird & Riordan 1986). The observation of solar radiation, and its influence on Earth's ionosphere, especially by the explosive events like solar flares, becomes a requirement and important thing nowadays.

As it is known the ionosphere is the part of the atmosphere that contains ionized gases. The degree of ionization depends on the incident radiation. The primary process is photoionization of thermospheric gases by the Sun's extreme ultraviolet and X-ray radiations. Both these radiations are approximately hundred times stronger at the solar maximum than at solar minimum. Secondary processes include ionization by photoelectrons and scattered or reemitted radiation. The ionosphere, at all latitudes, has a tendency to separate in different regions, despite of the fact that different processes dominate in different latitudinal domains. These regions named D, E, and F are distinct only in the daytime ionosphere at middle latitudes. The different regions are generally characterized by a density maximum at a certain altitude, and density decreases with altitudes on both sides of the maximum. Methods of researching ionosphere are numerous. Depending on the ionospheric composition, preferred techniques and mainly its height (altitude) for investigation are used *rockets, satellites, balloons, digisonde, GPS, different ground based measurements like radars, VLF/LF radio measurements, optical instruments,* and etc. (see e.g., Hargreaves 1992; Prolss 2004). For instance, at ionospheric F-region (150–800 km), it is possible to perform direct satellites and probes measurements. The part of the ionosphere below ~90 km requires special methods for its study, and special theories for its explanation, it is called the D-region.

The parts of the spectrum that penetrate to the D-region have wavelengths less than about 1 nm (X radiation) or greater than 102.7 nm. During quiet solar conditions the D-region is formed primarily by the action of solar Lyman-alpha radiation (121.6 nm) on nitric oxide. Daytime electron density in this region is about or less than Ne ~10^8-10^9 m^{-3}. During the nighttime the ionization rate drops and recombination processes continue duration. Even at night there is a sufficient ionization in the lowest region of ionosphere to affect VLF/LF radio signals. A range of dynamic phenomena occur in the D-region and cause diurnal and seasonal variations in connection with solar activity (Goodman 2005a, b).

VLF and LF bands are below the critical frequencies of the D-region. Most of the energy radiated by the VLF/LF transmitters is trapped between the ground and the D-region, forming the Earth-ionosphere waveguide. Subionospheric VLF/LF signals reflect from the D-region of the ionosphere (during daytime ~70-75 km and during nighttime ~90 km). This propagation is stable both in amplitude and phase and has relatively low attenuation. VLF/LF radio signals propagate over Earth trapped between the imperfect mirrors of the ground and the ionosphere. The effective reflection height depends on the ionization levels of the D-region. The only possible method of probing the D-region is VLF/LF subionospheric radio signals (Budden 1961; Wait 1962; Mitra 1974; Inan et al., 1985; Barr et al., 2000; Thomson et al., 2011).

Any variations on the ionospheric D/E-region lead to changes in the propagation conditions for VLF/LF radio signals propagating subionospherically, and hence changes in the observed amplitude and phase of VLF/LF transmissions are due to different kinds of perturbation sources:(1) solar flares, (2) geomagnetic storms (and the corresponding particle precipitation), (3) the direct effect of lightning and (4) effect of earthquakes (or seismic activity) on to the lower ionosphere (see e.g., Mitra 1974; Carpenter et al., 1984; Bar et al., 2000; Hayakawa 2000, Bothmer & Daglis 2007; Prölss 2004; Thomson et al., 2005).

The phenomenon such as solar X-ray flare illuminating the daytime ionosphere induces unpredictable effects that are associated with space weather. When the solar X-ray flares appear, the X-ray fluxes suddenly increase and the ones with the appreciable wavelength below 1 nm are able to penetrate down to the D-region and increase the ionization rate there (see Mitra 1973; Thomson 2001, 2014 and reference therein).

The purpose of this paper is to study effects of illuminating D-region with *sudden, rapid, and intense variation in X-ray flux* and consequences of this event to propagation characteristics of amplitude and phase on VLF/LF radio signals (SID VLF/LF signatures).

2. Method of Acquirent Data for Analysis SID VLF Signatures

2.1. Observations at VLF and LF Frequencies

All the data were recorded at a Belgrade site by two receiver systems: Absolute Phase and Amplitude Logger (Abs PAL) system and Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME).

In 2003 the Abs PAL system was installed and brought to stable operation. The Abs PAL Belgrade VLF station has been developed by the Radio and Space Physics Group of Otago University, New Zealand (for details see Zigman et al., 2007). The receiver has been in stable operation since 2003, providing simultaneous data (amplitude in dB above 1μV/m, and phase in deg). The Abs PAL was used for receiving, monitoring and for the storage of amplitude and phase delay of VLF data in the regular diurnal and seasonal behavior of the lower ionosphere and also for tracking the signature of solar flares. The Abs PAL VLF receiver can log up to six transmitters at a time, logging phase and amplitude with time resolutions ranging from 50 ms to 60 s.

The second VLF/LF receiver-AWESOME facility is developed by the Stanford University, Stanford USA. The receiver has been in stable operation since 2008, continuously collecting data and providing simultaneous VLF amplitude and phase from worldwide transmitters. The system consists of two loop magnetic antennas, GPS, preamplifier, cables, and equipment connected to the PC (AD card). The software is based on *python* and *mat lab*, which is especially developed for this use by the Stanford University VLF group.

Recorded data are generally saved in two different resolutions - high resolution (50 Hz) and low resolution (1 Hz). Narrowband data can be recorded in a continuous fashion, even in case when as many as 15 transmitters are being monitored (Cohen et al., 2010).

In this chapter we confine our attention to the analysis of amplitude and phase data acquired by monitoring VLF radio signals emitted by five transmitters during a seven-year period (2008-2014). This period covers the ascending phase and the maximum of the Solar Cycle 24. All the data were recorded at a Belgrade site by two receiver systems.

The five transmitter signals in this work are listed in Table 1. Each of these transmitters operates continuously (with the exception of maintenance down time, typically less than several hours per week) and normally transmit data at a bit rate of *Rb* =220 bits/s using minimum-shift keying (MSK) modulation.

Figure 1. Great Circle Paths (GCPs) of subionospherically propagating VLF radio signals recorded at Belgrade site.

VLF radio signals received at Belgrade site include: NAA/24.00 kHz, GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz. The transmitter of NAA/24.00 kHz is located in Maine USA (in Time zone UTC - 5.00). The NAA/24.00 kHz propagates in the Earth-ionosphere waveguide over Atlantic Ocean and Central Europe. The distance of NAA–BEL path is 6540 km and it belongs to the group of *long paths*. The transmitter of GQD/22.10 kHz is located in the UK, but a radio signal propagates over great segment of path in the same time zone where the receiver is. The distance of GQD-BEL path is 1980 km. The three European transmitters of DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signal are located in the same time zone (Time zone UTC +1.00) as a receiver site. The distances of these three paths are in the range 956 < D < 1300 km. Locations of these five transmitters and receivers are shown in Figure 1.

The details of the VLF transmitting and receiving sites and the path geometries are provided in Table 1 and Table 2.

2.2. Acquired Data of X-Ray Flux

The analysis and comparison of VLF data has been carried out together with the examination of the corresponding solar X-ray fluxes.

Table 1. Main characteristics of VLF/LF transmitters

Transmitter	Frequency (kHz)	Site	Geographic coordinates (deg)	GCP (km)	Orientation of propagation path
NAA	24.00	Main, USA	44.63^0 N, 67.28^0 E	6540	west to east
GQD	22.10	Skelton, UK	54.73^0 N, 2.880 W	1980	northwest to southeast
DHO	23.40	Rhauderhent, Germany	53.08^0 N, 7.61^0 E	1300	northwest to east
ICV	20.27	Isola di Tavolara, Italy	40.92^0 N, 9.730 E	976	southwest to northeast
NSC	45.90	Sicily, Italy	38.00^0 N, 13.50^0 E	956	southwest to northeast

Table 2. Main characteristics of VLF/LF receiving systems

Receiver	Class	Start year	Site	Geographic coordinates (deg)
AbsPAL	Electric antenna	2003	Belgrade, Serbia	44.85^0N, 20.38^0E
AWESOME	Loop magnetic antenna	2008	Belgrade, Serbia	44.85^0N, 20.38^0E

Table 3. X-ray peak flux intensities in band 0.1-0.8 nm for different classes of solar flares

Class	Peak flux intensities (W/m^2)
A	$Ix < 10^{-7}$
B	$10^{-7} \leq Ix < 10^{-6}$
C	$10^{-6} \leq I x < 10^{-5}$
M	$10^{-5} \leq I x < 10^{-4}$
X	$10^{-4} \leq Ix$

The intensity of solar X-ray flux is recorded by the GOES satellites (Geostationary Operational Environmental Satellite). The GOES satellites records the X-ray fluxes in two wavelength bands: 0.1-0.8 nm, referred to as "long" or "XL" and 0.05-0.4 nm, referred to as "short" or "XS" (Menzel & Purdom 1994; Hillger & Schmit 2007, 2009, 2011).

The main important data in our work are data of intensity of X-ray flux in the band 0.1-0.8 nm. The satellite data are available from National Oceanic and Atmospheric Administration USA, via the web site: www.swpc.noaa.gov/ftpmenu/lists/xray.html.

Scientists classify solar flares in A, B, C, M, and X classes according to the peak flux in W/m^2 of 0.1-0.8 nm X-rays near Earth. Each category for X-ray flares is also partitioned the different levels and has subdivisions ranging from 1.0 to 9.9, e.g., C1.0 to C9.9, M1.0 to M9.0, and X1.0 to X9.9 (Hillger & Schmit 2011).

The A class and B class solar flares are too weak to make noticeably affect on propagation of VLF/LF radio signals but C class induced changes of amplitude and phase on VLF/LF radio signals. The M class solar flares induce significant disturbances on VLF/LF propagation and beside this can cause some damages (short radio blackouts and minor radiation storms). And then the X class solar flares are more powerful and have the most significant effects on Earth ionosphere (Goodman 2005; Jakowski et al., 2008).

3. Physical Properties of the D-Region

The high atmosphere provides a low pressure laboratory without walls where the reactions occur between electrons, ions and neutral particles. The ionosphere is part of the Earth atmosphere which is mostly ionized by the solar radiation. This region of electroneutral plasma is located in the terrestrial atmosphere at altitudes between around fifty kilometers and several hundreds of kilometers above the Earth's surface. In the ionosphere the presence of charged particles plays a significant role in the propagation of radio waves.

The D-region is located approximately at altitudes ~60-90 km above the Earth's surface. Solar electromagnetic waves propagating below 85 km in the atmosphere are: X-rays of wavelength <1 nm; Lyman-alpha; and wavelengths greater than 180 nm. These radiations can induce ionization of molecular nitrogen and oxygen; nitric oxide; and various atoms such as sodium and calcium. Molecular oxygen and nitrogen are also ionized by cosmic rays. It is possible to explain normal conditions of ionization by cosmic rays and Lyman-alpha. Above 85 km, the behavior of the ionization is related to the formation of the *E-region*. The electron density in the D-region is usually about $\sim 10^8$-10^9 electron/m^3.

During nighttime condition in the D-region occur suddenly changes of electron density altitude profile. The electron density in the D-region drops as a consequence of disappearing solar radiation. Namely, recombination processes overcome the ionization process causing the movement of reflection height at about 90 km, which is at the bottom of the nighttime E-region (Retclife 1972; Mitra 1972; Woods et al., 2009; Prolss 2004; Kelley 2009).

The production of electrons in the D-region is a consequence of space weather conditions. The enhanced X-ray radiation during a solar flare leads to an increased rate of production electrons. The largest difference between quiet and active solar conditions occurs at altitudes between 65 and 75 km. Although the D-region ionization is low compared to the E and F-regions, it does have a huge effect on propagation of radio waves. SIDs, are studding in many scientific institutions and also in our VLF/LF Laboratory, Institute of Physics, Belgrade University, Belgrade.

3.1. Model of Ambient and Disturbed D-Region

In this work, we primarily consider ionospheric disturbances which occur during daytime. We restrict our attention to the study of effects of sudden increase in X-ray irradiance on the lowest altitudes of the ionosphere, specifically the altitude below ~ 70 km in the D-region. A two-parameter analytical expression for the altitude dependence of the D-region electron density was given by Wait and Spies (1964) as:

$$N_e(h,H') = 1.43 \cdot 10^{13} \exp(-0.15 \cdot H') \exp[(\beta - 0,15) \cdot (h - H')] \quad m^{-3}$$
Eq. (1)

where *Ne* is electron density in electrons/m^3, *h* is the height in km and β and *H'* are model parameters having units of km^{-1} and km, respectively. The parameter β (km^{-1}) describes the "sharpness" of the profile. The parameter *H'* (km) was shown to be a good representation of the approximate height at which VLF reflections occur. The Wait and Spies (1964) model has been successfully used in previous comparisons of VLF measurements and theory (e.g., Mitra 1972; Thomson 1993; Cummer et al., 1998; McRae and Thomson 2000) and we also use it in our work.

For propagation of radio waves below the F-region, the effective electron-neutral collision frequency profile, largely determined by the relatively stable neutral density, is important in addition to electron density. In all cases, the exponential altitude profile of collision frequency is given by:

$$\nu(h) = 1.82 \cdot 10^{11} \exp(-0.15 \cdot h) \quad \text{Eq. (2)}$$

where ν is in s^{-1} and *h* in km (Wait and Spies, 1964).

This model has been used to simulate altitude electron density profile in the D-region at regular conditions (Thomson, 1993; McRae and Thomson, 2000), as well as for the perturbed conditions by solar flares (McRae and Thomson 2004; Thomson et al., 2005, Nina et al., 2011, 2012a, b).

3.2. Method of Simulations Propagation of VLF/LF Radio Signals

The radio waves in VLF and LF bands propagate from transmitters through a waveguide bounded by the Earth's surface (ground or sea) and the D-region. The Earth-ionosphere waveguide propagation theory developed by Budden (1962) takes into account: *the Earth's curvature, geomagnetic field, altitude profiles of electron-neutral collision frequency and electron density* and serves as the basis for the numerical modeling codes. A two-dimensional model was devolved at the Naval Research and Development Laboratory (Ferguson et al., 1989 and references therein).

This model, known as the Long Wave Propagation Capability (LWPC) code, is software package of several separate programs, and each of them is designed for execution of specific tasks. The LWPC software package takes as the input path variables: *frequency, transmitter and receiver coordinates, and the orientation of the transmitting and receiving antenna and the boundaries of the operating area.* The program automatically selects paths along geographic bearing angles to ensure that the operating area is fully covered. The diurnal conditions and other relevant parameters are then determined along each path. After the mode parameters along each path are determined, the signal strength along each path is computed.

In this chapter, we used a few step process to estimate the perturbed VLF signal amplitude and phase during a solar flare. Simultaneous observations of amplitude $A_{disturbed}$ and phase $\phi_{disturbed}$ on VLF radio signals during solar X-ray flares could be applied for calculations of electron density profile and ionization rates and effective electron recombination coefficients in the D-region using this method:

1. Using the LWPC code package, we define conditions *in normal ionosphere* over VLF propagation path in order to simulate VLF propagation and to get the best fitting pairs of Wait's parameter β_{nor} and $H'_{nor.}$ Here, *nor* means normal condition.
2. In further investigation (step two) we use the method presented in papers (Mitra 1974; Thomson 1993; Grubor 2008) in order to simulate propagation of VLF radio signal through the waveguide in the *disterbed D-region* induced by additional X-ray radiation during an flare event. The amplitude and phase changes, named as SID VLF signatures are:

$$\Delta A = A_{disturbed} - A_{normal}$$
$$\Delta\phi = \phi_{disturbded} - \phi_{normal}$$

are directly measured using reacorded VLF/LF data during an solar flare event and under normal ionospheric condition (see Figure 5).

3. In the next step we successevely change values of β and H' in LWPC code to obtain: $\Delta A_{culculated}$ and $\Delta\phi_{calculated}$. By a *trial and error* method we have to vary the values of β and H' in LWPC code in order to match as good as posible a pair; $\Delta A_{calculated}$; $\Delta\phi_{calculated}$ with recorded

pair $\Delta A, \Delta\phi$. With the help of this fitting procedure we find the best values of β and H' to simulate disturbed ionospheric density profiles.

4. In fourth step the variation of the D-region electron density height profile $N_e(h)$ is reconstructed, and analyzed throughout different solar flare events.

Moreover, recently is shown in the literature (Thomson 2005; Grubor et al., 2008) that the classification of X-ray solar flares can be performed regarding their effects on the VLF wave propagation along the Earth-ionosphere waveguide, and that is the one of the reason for its modeling.

4. The Ionospheric Effects Induced by Solar Flares on VLF/LF Propagation

4.1. VLF/LF Propagation under Normal Ionospheric Condition in the D-Region

In literature, the first results about diurnal amplitude variations on VLF signals were published in 1933. Yokoyama and Tanimura (1933) studied propagation of 17.7 kHz and 22.9 kHz, over long distances D > 5Mm. They gave explanation for amplitude fading based on single-ray geometrics optics. Budden (1961) and Wait (1985, 1962, 1964) suggested that many rays are needed to explain VLF propagation over long paths. Crombie (1964) and Walker (1965) put forward an explanation based on the use of modes in the earth-ionosphere waveguide. VLF/LF radio signals are reflected from the lowest region in the ionosphere. An apart from sunrise and sunset, exhibit propagation characteristics are very stable in both amplitude and phase. Typically, VLF radio signals propagate with less attenuation during nighttime due to much lower ionization levels in the D-region. The phenomenon of sunrise and sunset development of amplitude minima is characterized by periodic and repeatable variations in amplitude and phase. These variations are a consequence of moving the sunrise/sunset terminator along a VLF propagation path. Daytime propagation is taken to occur when the solar zenith angle at both the transmitter and the receiver is less than 90^0.

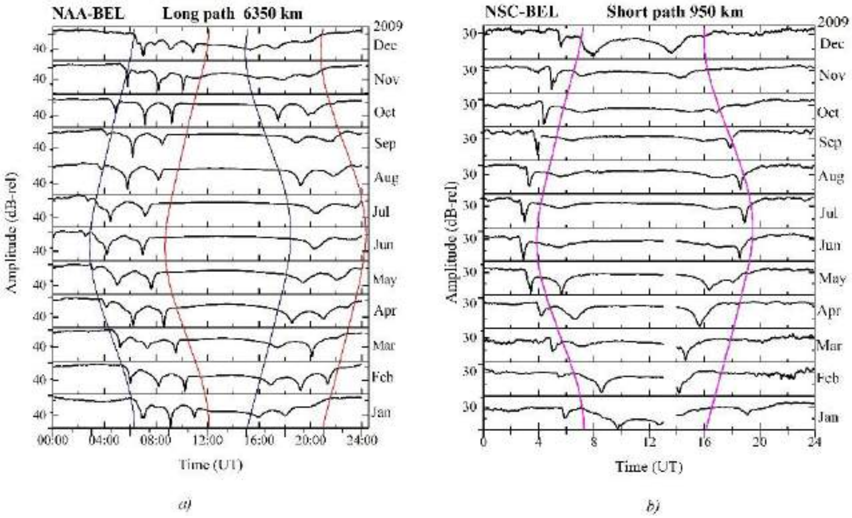

Figure 2. *a)* Typical diurnal amplitude variations on NAA-BEL long path against universal time for each month during 2009, respectively. With blue and red colors are plotted times of sunrise and sunset at Belgrade and Maine, respectively. *b)* Typical diurnal amplitudes variations on NSC-BEL short path for each month during 2009. With magenta color are drown curves of sunrise and sunset during year, respectively for Belgrade.

For studding the phenomenon of sunrise and sunset development of amplitude minima followed by changes in phase we have selected NAA-BEL long path. Observations of the diurnal amplitude and phase variations of the NAA/24.00 kHz have been made at the Belgrade site for many years. The path is sufficiently long and correctly oriented (west-east) to show sunrise and sunset development of amplitude minima. The transmitter is located in Maine, USA in Time zone UTC -5 and the receiver in Time zone UTC +1. Typical diurnal amplitude records for one day in each month for 2009 are shown in Figure 2 a. Continually changes in time of appearing sunrise and sunset at Belgrade (blue color) and Main (red color) for whole year 2009 are also shown in Figure 2a.

The first point is that the recordings of NAA/24.00 kHz radio signal at Belgrade show three amplitude minima during sunrise. Similar but less evident changes occur during sunset. Secondly it is clear that during sunrise on all twelve curves the amplitude minima which occur at the latest times are the deepest. This minimum occurs when the sunrise line is closest to the transmitter (the western end of the path). Figures 2a shows that amplitude minimum occurs while the sunrise or sunset line lies between the transmitter and receiver. Figure 3 (panel 2) shows that at the times of amplitude minima the rate of phase changes becomes noticeable on the NAA-BEL path. Timing of occurrences the amplitude minima shows seasonal variation of appearing sunrise or sunset line over path. Our results are in good correlation with results published by Crumbier (1964) and Walker (1965).

Main characteristics of propagation the NAA/24.00 kHz radio signal over long path to Belgrade are developments of three amplitude minima during time interval between sunrise at Belgrade and Maine (difference in time is ~ 6 h). Similar but less evident changes occur during time interval defined by sunsets at Belgrade and Maine. These amplitude minima are followed with changes of phase values over whole year.

As an example of propagation LF radio signal is shown in Figure 2b. Radio signal with frequency NSC/45.90 kHz (Sicily, Italy) propagetes from South west to Northeast over short path 950 km. Transmitter and recover are in same Time zone.

Typical diurnal amplitude records for one day in each month for 2009 are shown in Figure 2 b. Two curves presenting the appearing of sunrise and sunset at Belgrade (magenta color) for whole year 2009 are shown in Figure 2b. The diurnal variation of amplitude has larger values during nighttime than in daytime condition, because of lower absorption during night. Figure 2b shows well defined amplitude minima on all amplitude registrations against time during year. It is evidently that an amplitude minimum occurs before happening sunrise and one after the sunset at Belgrade. Timings of these developments the amplitude minima are in good correlation with appearing sunrise and sunset at the middle of the propagation path. During daytime there is one pair of amplitude minima whose creation is a consequence of destructive interference of modes. The temporal variability in their creation is correlated with number of light hours for each day during year. The amplitude minima in dawn and morning are sharper than in afternoon and dusk and are the sharpest during summer (Tulip et al., 2016).

Under daytime condition over NSC-BEL path two amplitude minima are observed in morning and afternoon. The lowest values of these amplitude minima are recorded under solar zenith angle in morning $\chi = 74^0$ and in the afternoon $\chi = 71^0$. These amplitude minima are followed with suddenly decreasing of phase values.

4.2. VLF/LF Propagation in Disturbed Ionosphere Conditions

VLF/LF propagation as noted above provides some insight on the way ionization builds up and decays, and provides a routine monitor for the detection and time change of solar-geophysical disturbances. VLF/LF radio signals steeply incident on the ionosphere are reflected from heights within the D-region, and exhibit a cosinusoidal diurnal variation of phase. Such a phase change can be interpreted as giving a measure of the height in the D-region.

Sudden changes in the amplitude and phase of long and short distances subionospheric VLF propagations have been found at daytime in association with events of solar flares. The intensities of VLF and LF radio waves change during an SID in way that it depends on the frequency and on the angle of reflection (Retcliffe, 1972). Behaviors of amplitude and phase perturbations on VLF/LF radio signals induced by different intensity of solar X-ray fluxes, observed on Belgrade site, were examined and these results are presented in recent papers: Grubor et al., 2005, 2008; Zigman et al., 2007; Nina et al., 2012; Šulić and Srećković 2014; Šulić et al., 2016).

4.2.1. SID Effects on VLF Signal Propagation over a Long West-East Path

For example, the diurnal variations of amplitude and phase on NAA/24.00 kHz radio signal against universal time recorded at Belgrade during 05 (normal day) and 08 March 2011 are presented on Figures 3a and 3b.

The first panel of Figure 3a shows the solar X–ray radiation against universal time on 08 March as monitored by GOES-15 satellite. The eruptions of extreme X-ray radiation induce successively four solar flares M class. The solar flares classes: M5.37 ($Ix = 5.37 \cdot 10^{-5}$ Wm^{-2} of X-ray flux in the band 0.1-0.8 nm, peak at 10:44 UT) and M4.46 ($Ix = 4.46 \cdot 10^{-4}$ Wm^{-2}, peak at 18:28 UT) induced phase and amplitude perturbations on NAA/24.00 kHz radio signal which are noticeable in comparing these registrations with NAA/24.00 kHz data recorded 05 March 2011.

As presented in Figure 3a phase (panel 2) and amplitude (panel 3) variations of the NAA/24.00 kHz radio signal track the intensity of X-ray flux quite closely during developments of solar flares.

The solar flare M5.37 class occurred close to local noon at Belgrade and in local morning in Maine, which means illuminations of whole long path NAA-BELL. Very high changes of X-ray radiation induced large huge production of electron in the D-region. The evidence of this SID is measurable with analysis of rising amplitude and phase in according to normal daytime levels. For example, SID VLF signatures are: ΔA ~ 12 dB and $\Delta\phi$ ~ 120^0 at timing the maximum of X-ray radiation.

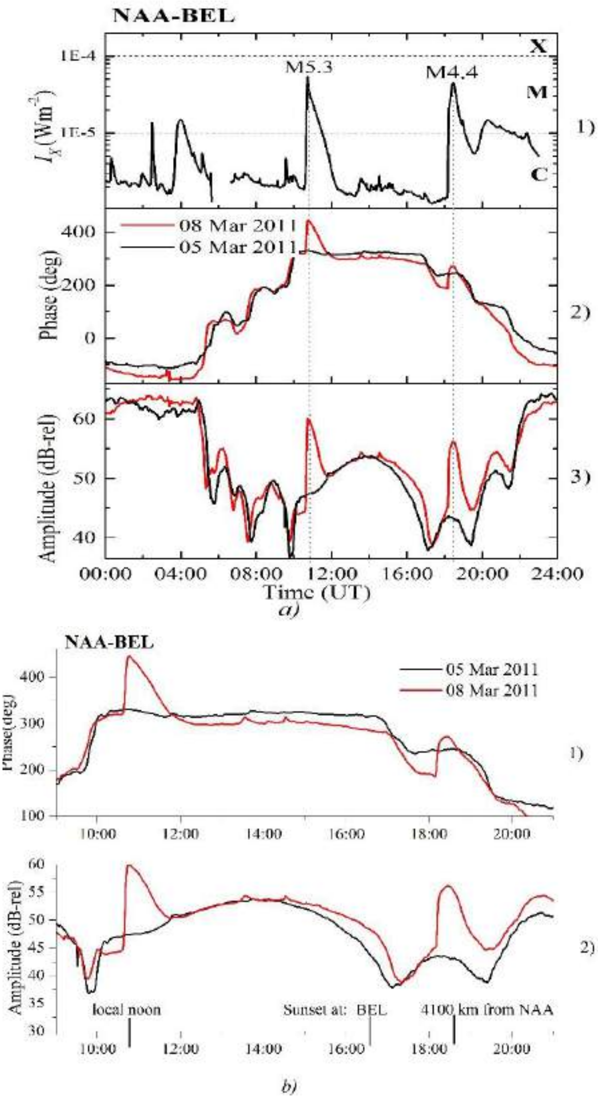

Figure 3. a) Variation of X-ray irradiance (panel 1), phase (panel 2) and amplitude (panel 3) on NAA/24.00 kHz radio signal recorded at Belgrade against universal time on 05 (normal day) and 08 March 2011. The transmitter and receiver are in Time zones UTC-5 and UTC+1, respectively. b) Phase (panel 1) and amplitude (panel (2) on NAA/24.00 kHz radio signal recorded at Belgrade in time interval 10:00-21:00UT.

On 08 March 2011 occurred the solar flare M4.46 ($Ix = 4.46 \cdot 10^{-5}$ Wm^{-2} at 18:28 UT) class and induced significant variations of amplitude and phase on NAA/ kHz radio signal. On the panel 3 of Figure 3a, are noticeable three amplitude minima which occurred during time interval defined by sunsets at Belgrade and Maine. The maximum of X-ray radiation was reached at 18:28 UT, approximately two hours later than sunset occurred at Belgrade on 08 March 2011. Following plotted results on Figure 3b (panel 3) timing of solar flare events is between timings of the first and the second amplitude minima during sunset. Using LWPC code we simulated moving the sunset terminator along NAA-BEL path. The maximum of X-ray flux occurred at18:28 UT and in that moment a sunset terminator was at ~ 4100 km from the NAA transmitter. Propagation of NAA/24.00 kHz radio signal from transmitter to Belgrade has west to east orientation. During this event radio signal propagates under daytime, dusk and nighttime conditions. Changes of amplitude and phase on NAA/24.00 kHz radio signal through the illuminated segment of waveguide were on sufficient levels to be recorded in Belgrade.

On 05 June 2013 southern sunspot AR1762 erupted, producing a long-duration M1.31 ($1.31 \cdot 10^{-5}$ Wm^{-2}) class solar (begin 08:14 UT, peak 08:57 UT, and 09:26 UT). We selected this event to study the influence of isolated solar flare event and their manifestation on NAA-BEL path. The registrations of amplitude and phase on NAA/24.00 kHz radio signal during normal (black color) and disturbed ionospheric (red color) conditions are shown on Figure 4a. Sudden phase increases produced by solar flare indicate changes of reflection height (Figure 4a panel 1). These changes of phase are following with continuously rising of amplitude (Figure 4a panel 3).

Table 4 SID VLF signatures and calculated data by LWPC code in a function of intensity of X-ray flux during solar flare class M1.31

Date: 05 Jun 2013		NAA-BEL path				
Time UT him	I_X (Wm^{-2})	SID VLF signatures		Calculated data by LWPC code		
		ΔA (dB)	$\Delta\phi$ (deg)	β (km^{-1})	H' (km)	$Ne(H')$ (m^{-3})
08:00	3.55E-7	0	0	0.300	74.0	2.18E + 06
08:23	1.24E-6	0.8	10.7	0.315	73.0	2.49E + 06
08:30	2.54E-6	1.57	18	0.330	72.0	2.93E + 08
08:35	4.5E-6	2.3	26.5	0.348	71.0	3.34E + 08
08:38	6.61E-6	2.9	34	0.368	70.0	3.93E + 08
08.43	9.97E-6	3.42	44.4	0.387	69.0	4.63E + 08
08:56	1.31E-5	3.77	54.4	0.392	68.3	5.05E + 08

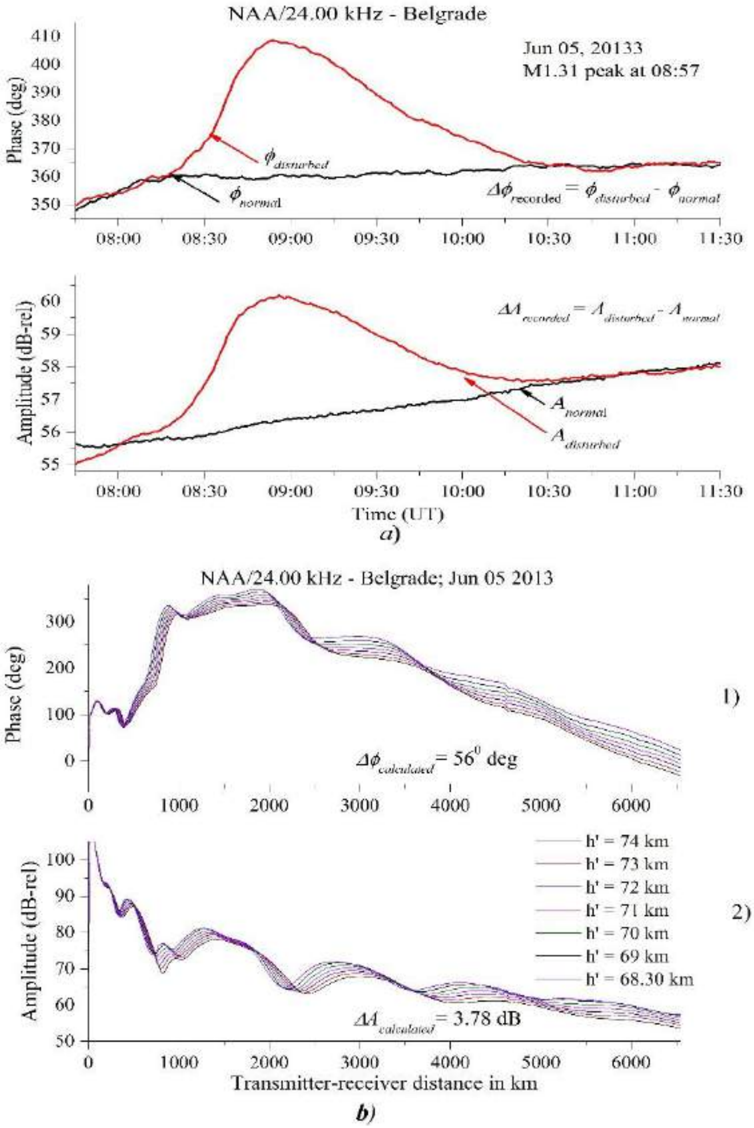

Figure 4. *a)* Diurnal variation of X-ray irradiance (panel 1) and amplitudes (panel 2) on NAA/24.00 kHz radio signal for two days in June 2013. An AbsPAL recording of amplitude during normal day is black line while a recording of amplitude during perturbed day (05 June 2013) is red line; *b)* NAA phase (panel 1) and amplitude (panel 2) signal variations along GCP distance from Maine to Belgrade during M1.31 flare event (05 June 2013).

Using the LWPC code we simulated the propagation of NAA/24.00 kHz radio signal through waveguides where an altitude electron density profile was successively changed. After the mode parameters along each path are determined, the signal strength and phase along each path is computed. In Table 4 are presented calculated results and in this case there is movement of the reflection height *H'* from 74 km to 68.3 km. The parameter β (km^{-1}) the "sharpness" of the electron profile changes from 0.300 to 0.392.

Variation of phase (panel 1) and amplitude (panel 2) of the radio signal along NAA-BEL path are calculated for seven different reflection heights as it successively moving on lower values. Results for event occurred on 05 June 2013 are presented on Figure 4b. The modal interference minima (Wait, 1962) of the amplitude and phase variation along the NAA-BEL path at regular conditions are displayed on the normal day (black color). During occurrence of M1.31 class solar flare, all modal minima are seen to move towards the transmitter (Thomson and Clilverd, 2001). The typical movement of the modal minima is strongly dependent on the lowering of the reflection height, and it is evidently from Figure 4b.

4.2.2. SID Affects on VLF Signal Propagation over a Short Pat

Sudden changes in the amplitude and phase of long and short distances subionospheric VLF propagations have been found at daytime in association with events of solar flares. The intensities of VLF and LF radio waves change during an SID in way that it depends on the frequency and on the angle of reflection (Retcliffe, 1972). Behaviors of amplitude and phase perturbations on VLF/LF radio signals induced by different intensity of solar X-ray fluxes, observed on Belgrade site, were examined and these results are presented in recent papers: Grubor et al., 2005, 2008; Zigman et al., 2007; Nina et al., 2012; Šulić and Srećković 2014; Šulić et al., 2016).

Our statistical results show that both increases and decreases in signal strength have been observed, depending on: *the intensity of solar X-ray radiation, solar zenith angle and frequency*

DHO/23.40 kHz radio signal propagates from Rhauderhent, Germany to the Belgrade receiver site across an all land path (transmitter and receiver are in the same Time zone). VLF radio signal propagates Northwest to Southeast and the distance between transmitter and receiver site is D = 1300 km.

A radio signal with frequency GQD/22.10 kHz (Skelton, UK) propagetes from West to East over short path D = 1980 km. Radio signal propagates over Central Europe. Perturbations of amplitude on GQD/22.10 kHz exhibit rising and decreasing during occurrences of solar flares with different levels of intensity on X-ray flux. A phase change on this path is complicated; displaying rise, decrease and oscillation under the occurrences of different classes solar flares.

Solar flare class C6.8 ($Ix = 6.8 \cdot 10^{-6}$ Wm^{-2}) occurred on 27 February 2014 with intensity maximum at 12:30 UT. Figure 5 gives an instructive example of induced amplitude and phase perturbations on DHO/23.40 kHz and GQD/22.10 kHz, radio signals observed in Belgrade during this event.

On DHO-BEL path the amplitude and phase increase under enhancement of electron density induced by solar flare. Values of SID VLF signatures, ΔA = 4.2 dB; $\Delta\phi = 70^0$ are in correlation with the intensity of solar X-ray irradiance. Amplitude perturbations on GQD/22.10 kHz radio signal show decreasing with time until the intensity of X-ray radiation reaches the maximum. Phase changes show a different character, displaying increase and also decrease during the occurrence of solar flare C6.8 class. T the moment of intensity maximum of X-ray irradiance SID VLF signature are ΔA = -5.4 dB and $\Delta\phi$ = 10^0

The intensities of VLF and LF radio waves change during an SID in way that it depends on the frequency and on the angle of reflection (Retcliffe, 1972).

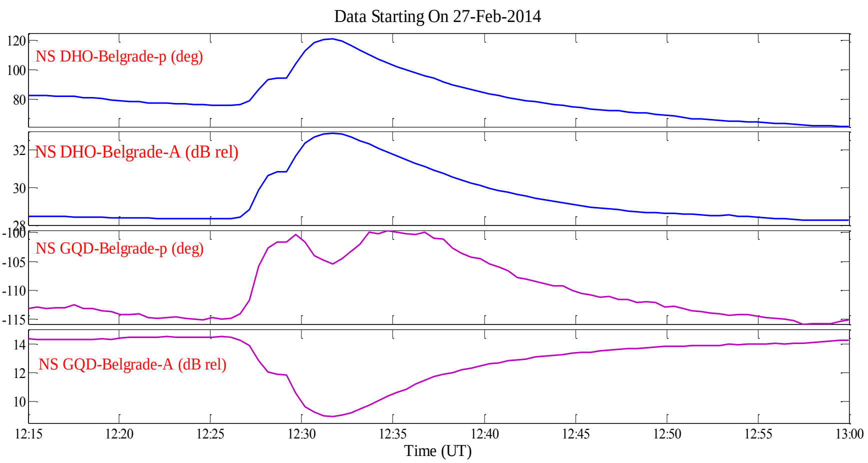

Figure 5. Variation of phase and amplitude on DHO/23.40kHz and GQD/22.10 kHz radio signals recorded at Belgrade against universal time on 27 February 2014.

4.2.3. SID VLF Signatures on a Short Path as a Function of the Intensity Solar X-Ray Radiation

Modified amplitude and phase on GQD/22.10 kHz radio signal by increased X-ray radiation and SID were analyzed during the ascending phase and the maximum of Solar Cycle 24. The monitored amplitude and phase changes on GQD/22.10 kHz radio are results of increased electron density and a decrease in height of the ionosphere boundary. Ionospheric incubation times and duration of perturbations on VLF radio signal are related to intensity of X-ray flare. Characteristics of amplitude and phase on the GQD/22.10 kHz radio signal are presented in papers mentioned earlier. Under normal ionospheric condition stable daytime propagation in waveguide can be characterized by Waits' parameters: β = 0.3 and H' = 74 km. Great segment of GQD-BEL path covers the same time zone where the receiver is, it can be assumed that the whole path is similar illuminated in time sector around local noon in according to the receiver. Amplitude and phase perturbations on GQD/kHz radio signal are strongly dominated by intensity of X-ray radiation and duration of a flare.

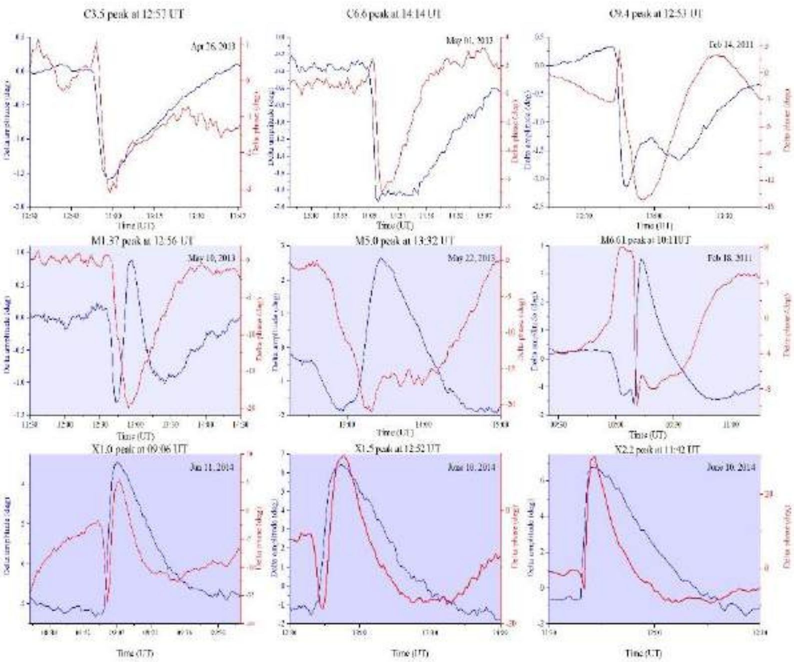

Figure 6. VLF SID signatures of nine solar flare events (ranging from class C3.6 to X2.2) observed on GQD/22.10 kHz radio signal at Belgrade. All events occurred during the ascending phase and the maximum of Solar Cycle 24.

For studding SID VLF signatures on GQD/22.10 kHz we have selected solar flare events whose occurrences where in time intervals of few hours around local noon at Belgrade. All selected nine events (ranging from C3.6 to X2.2 class) were recorded under similar solar zenith angles. Our results are presented on Figure 6 as: *three examples of C class, M class and X class solar flares*. Perturbations of the GQD/22.10 kHz radio signal are presented as temporal changes of ΔA and $\Delta\phi$ during solar flare event.

Table 5. SID VLF signatures and calculated data by LWPC code in a function of intensity of X-ray flux during nine solar flare events (ranging from class C3.6 to X2.2) observed on GQD/22.10 kHz radio signal at Belgrade

GQD-BEL path							
Date	Time UT	I_X Wm^{-2}	SID VLF signatures		Calculated data by LWPC code		
			ΔA dB	$\Delta\varphi$ deg	β km^{-1}	*H'* km	*Ne* m^{-3}
	11:00	$5 \cdot 10^{-7}$	0	0	0.30	74.0	2.18E+8
2013/04/26	12:57	C5.57 $3.57 \cdot 10^{-6}$	-1.85	-3	0.36	70.0	9.12 E+8
2013/05/01	14:15	C6.6 $6.6 \cdot 10^{-6}$	-1.9	-6.9	0.38	69.1	1.39 E+9
2011/02/14	12:54	C9.4 $9.4 \cdot 10^{-6}$	-1.5	-14	0.42	67.5	3.31 E+9
2013/05/10	12:57	M1.3 $1.37 \cdot 10^{-5}$	+0.85	-19.4	0.45	65.4	1.04 E+10
2013/05/22	13:32	M5.0 $5.0 \cdot 10^{-5}$	+2.64	-17	0.46	64.4	1.79E+10
2011/02/18	10:11	M6.61 $6.61 \cdot 10^{-5}$	+3.51	-9	0.44	63.95	1.84E+10
2014/06/10	09:06	X1.1 $1.1 \cdot 10^{-4}$	+5.1	+5.0	0.46	62.3	4.70E+10
2014/06/10	09:59	X1.5 $1.5 \cdot 10^{-4}$	+6.46	+10	0.52	61.1	1.78E+11
2014/06/10	11:43	X2.2 $2.2 \cdot 10^{-4}$	+6.74	+30	0.53	59.5	4.70 E+11

Two examples induced by C3.5 (Ix =3.5·10^{-6} Wm^{-2} at 12:57 UT) and C6.6 (Ix = 6.6·10^{-6} Wm^{-2} at 14:14 UT) class solar flares show decreasing of amplitude and phase to minima of values following the rising of intensity of X-ray radiation. The third example of event induced by C9.4 (Ix = 9.4·10^{-6} Wm^{-2} at 12:57 UT) class solar flare occurred on 14 February 2010. An abrupt decrease of amplitude to minimum precedes the X-ray radiation maximum. Also decrease of phase is noticeable for the plotted results.

Three examples of SID VLF signatures caused by M (Ix = 1.37·10^{-5} Wm^{-2}, Ix = 5.0·10^{-5} Wm^{-2} and Ix =6.1·10^{-5} Wm^{-2}) class solar flares are shown in Figure 6. Amplitude and phase perturbations on GQD/22.10 kHz exhibit *decreasing, oscillating and rising* during the duration of solar flares.

Changes of amplitude on GQD signals during three X class solar flares perform as well defined enhancement that follow the development of the maximum in X-ray radiation. Perturbations of phase are not so clearly in rising, the phase maxima are close to peak of X-ray radiation. We scaled the SID VLF signatures at times when X-ray radiations have peaks. Scaled and calculated data by LWPC code are given in Table 4. It is possible to follow the tendency of transformation from negative into positive growth amplitude and phase during these nine solar flare events. For example, a reflection height is lowered from H' = 74 km to H' = 70 km during C3.5 class solar flare, while during X2.2 class solar flare event a reflection height falls for 14 km. During X2.2 class solar flare event electron density changes for three order of value at reference height h = 74 km in according to ambient value.

4.2.4. Calculation of Altitude Electron Density Profile during SIDs

The amplitude and phase of the VLF/LF radio signal received at any point depend on the electrical conductivity of the lower ionosphere as well as the ground. Under the right circumstances the observed properties of VLF/LF radio signals can be used to determine the spatial and temporal structures of disturbances in the lower ionosphere. Typical daytime ionospheric electron density profile shows an increase with altitude. As input parameters in LWPC code we use β = 0.3 and h' = 74 km and calculated electron density profile is defined with Ne = ~ 10^{7} m^{-3} at h ~ 55 km and Ne ~ 2·10^{9} m^{-3} at h ~ 90 km.

For this paper we selected amplitude and phase perturbations on ICV/20.27 kHz radio signal recorded at Belgrade. Radio signal ICV/20.27 kHz (Isola di Tavolara, Italy) propagates from Southwest to Northeast over short path 980 km.

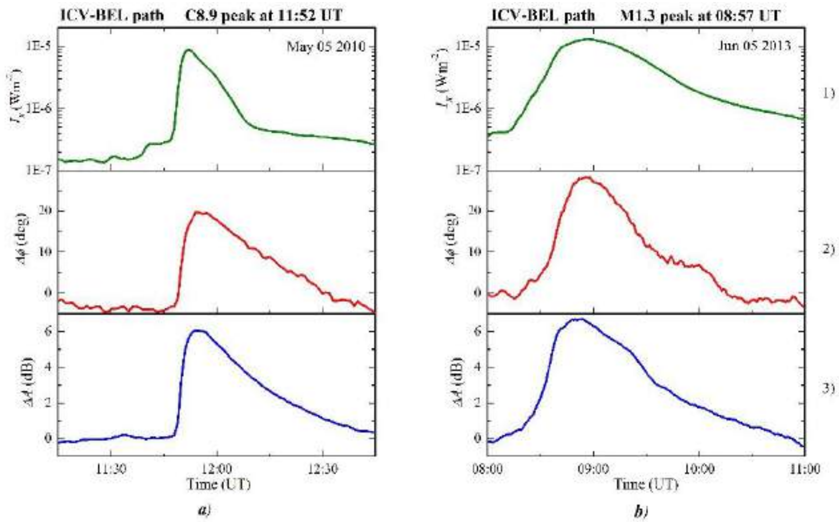

Figure 7. *a)* Variation of X-ray irradiance (panel 1), phase increase (panel 2) and amplitude increase (panel 3) on ICV/20.27 kHz radio signal recorded at Belgrade against universal time on 5 May 2010. *b)* Same as in *a)* but for the 5 Jun 2013.

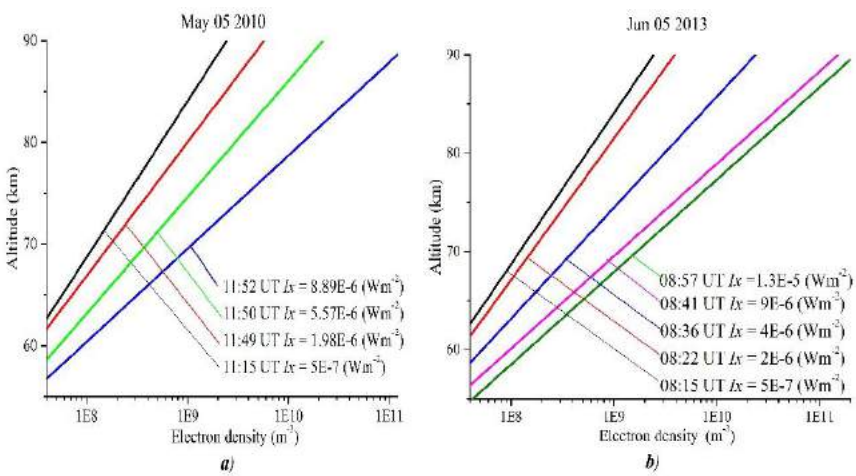

Figure 8. *a)* Electron density height profiles during C8.9 class X-ray solar flare occurred on 5 May 2010. *b)* Same as in *a)* but for the 5 Jun 2013.

On 05 May 2010 occurred suddenly changes in X-ray radiation started at 11:37 UT, reached peak at 11:52 UT and ended at 11:58 UT. The C8.9 (Ix = $8.8 \cdot 10^{-6}$ Wm^{-2}) class solar flare induced significant increasing of amplitude and phase on ICV/20.27 kHz radio signal recorded at Belgrade. The event occurred on 05 June 2013 at 08:14 UT started suddenly changes of X-ray radiation which reached peak at 08:57 UT and ended 09:26 UT. This solar flare M1.31 ($Ix = 1.31 \cdot 10^{-5}$ Wm^{-2}) belongs to long duration flare. The basis for modeling altitude profile of electron density during event of solar flare are measured amplitude and phase increases (ΔA, $\Delta\phi$) on ICV/20.27 kHz radio signal recorded at Belgrade.

Figure 7a shows variation of X-ray radiation (panel 1), phase increase (panel 2) and amplitude increase (panel 3) on ICV/20.27 kHz radio signal recorded at Belgrade during duration of C8.9 class solar flare. Figure 7b shows variations of X-ray radiation, phase increase and amplitude increase over ICV-BEL path during duration of M1.31 class solar flare. The main difference between these two solar flares is not in intensity of them but in their times of duration.

Under the right defining of Waits' parameters β and H' they are used to determine the spatial structures of disturbances in the lower ionosphere. For our calculations we selected times during which intensity of X-ray radiation uniform changes. Results of electron density profiles calculated in times during durations of C8.9 and M1.31 class solar flares are shown on Figure 8a and 8b, respectively.

There are no great differences in enhancements of electron densities during these two solar flares. At reference height h = 74 km:

1. $Ne = 3.05 \cdot 10^9$ m^{-3} on 10 May 2010 at 11:52 UT
2. $Ne = 4.44 \cdot 10^9$ m^{-3} on 05 June 2013at 08:57 UT.

4.2.5. Calculation of Temporal Variation of Electron Density during SID

In this work VLF propagation in the presence of ionospheric disturbances is quantitatively modeled using LWPC code to determine temporal structures of disturbances in the D-region. For this propose we selected solar flare event occurred on 10 May 2013, starting at 12:37 UT Intensity of X-ray radiation reached peak of $Ix = 1.37 \cdot 10^{-5}$ Wm^{-2} at 12:58 UT. Suddenly rising of intensity induced additional ionization in the D-region and has implication on amplitude and phase on GQD/22.10 kHz radio signal recorded at Belgrade. Figure 9a shows recordings of phases and amplitudes on GQD/20.10 kHz radio signal on 09 May 2013 (black color) and 10 May 2013 (red color) Recorded data during 09 May 2013 are used as reference level for normal ionospheric condition. The M1.31 class solar flare induces a phase decrease to minimum value and an oscillation of amplitude. During the duration of the solar flare event amplitude perturbation lays in range -1.34 < ΔA < 0.9 dB.

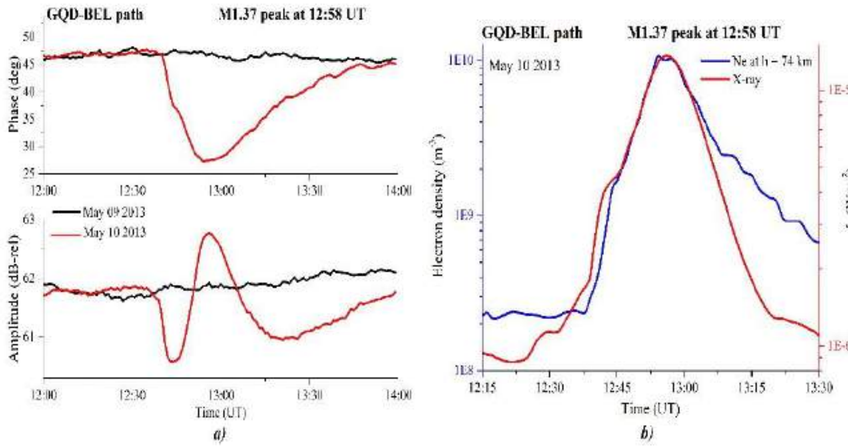

Figure 9. *a)* Variation of phase and amplitude on GQD/22.10 kHz radio signal recorded at Belgrade against universal time on 09 May 2013 and 10 May 2013. *b)* The electron density profile obtained from measured perturbed amplitude and phase of the GQD/22.10 kHz signal at the Belgrade station on 10 May 2013 during M1.37 class solar flare.

In the time interval from 12.00 to 14:00 with step of one minute we calculated Waits parameters' β and H' using observed ΔA and $\Delta\phi$.

Figure 9b shows calculated electron densities and intensity of X-ray irradiance against time. Results show good correlation between intensity of X-ray radiation and electron density variation at reference height h = 74 km during duration of M1.31 class solar flare.

CONCLUSION

In this study the amplitude and phase data acquired by monitoring NAA/24.00 kHz, GQD/22.10 kHz, DHO/23.40 kHz, ICV/20.27 kHz and NSC/45.90 kHz radio signals at Belgrade site by AbsPAL and AWESOME receivers from 2008 have been analyzed. This period covers the ascending phase and the maximum of the Solar Cycle 24.

We studied the effect, during quiet solar conditions as well as during the enhancements of X-ray flux due to the solar flares, on the propagating signal.

The VLF/LF perturbations of the radio signals emitted from the world wide transmitters, received and recorded at Belgrade site, and the solar X-ray fluxes monitored by GOES satellites have been brought into correlation with the flare events occurring in this period. By comparative analyzing SID affects on VLF/LF signal propagation over a different path it can be notice that observed VLF/LF perturbations at Belgrade site, during SID, have sensitive dependence on: *X-ray flare intensity, solar zenith angle, solar flare duration* and *geophysical characteristics of VLF/LF path*.

On the basis of monitored and analyzed VLF data, the model computation (LWPC code) is applied to determine the spatial and temporal structures of disturbances in the D-region, during occurrences of solar C class, M class and X class solar flares. The calculated data are presented in tabulated form as well as in figures. From these results it can be concluded that the explosive X-ray radiation leads to an increased rate of electron production and depending on the flare class the electron density can increase more than few order of magnitudes.

The obtained results confirmed the successful use of applied technique for detecting various explosive space weather phenomena such as solar flares as well for describing and modeling the D-region physical properties during SIDs.

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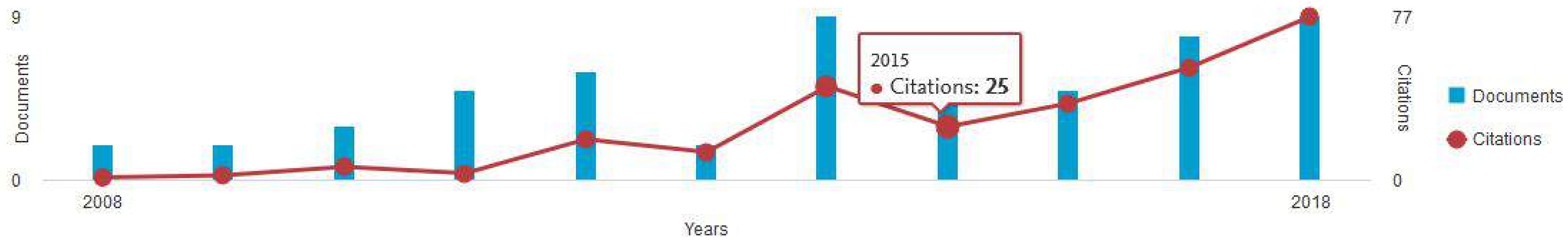

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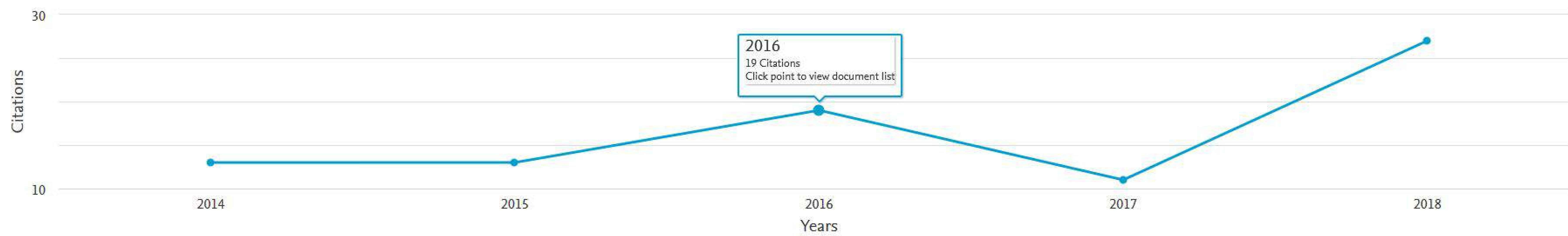

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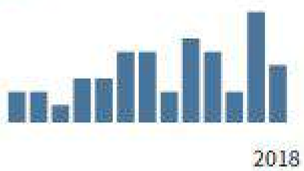

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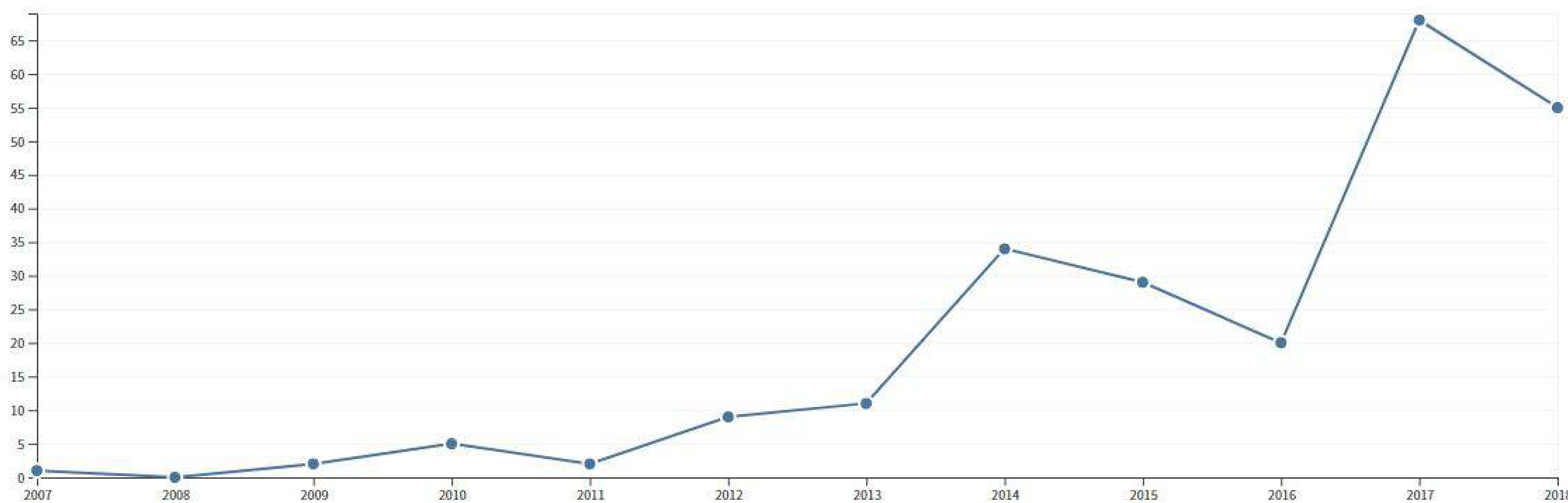

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Education

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The Collisional Atomic Processes of Rydberg Hydrogen and Helium Atoms: Astrophysical Relevance

Galaxies

2018-07 | journal-article

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Sreckovic, Vladimir A — Get A Badge | ResearcherID Labs

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My Institutions (more details)
Primary Institution: Institute of Physics, Belgrade
Sub-org/Dept:
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My Publications (79)
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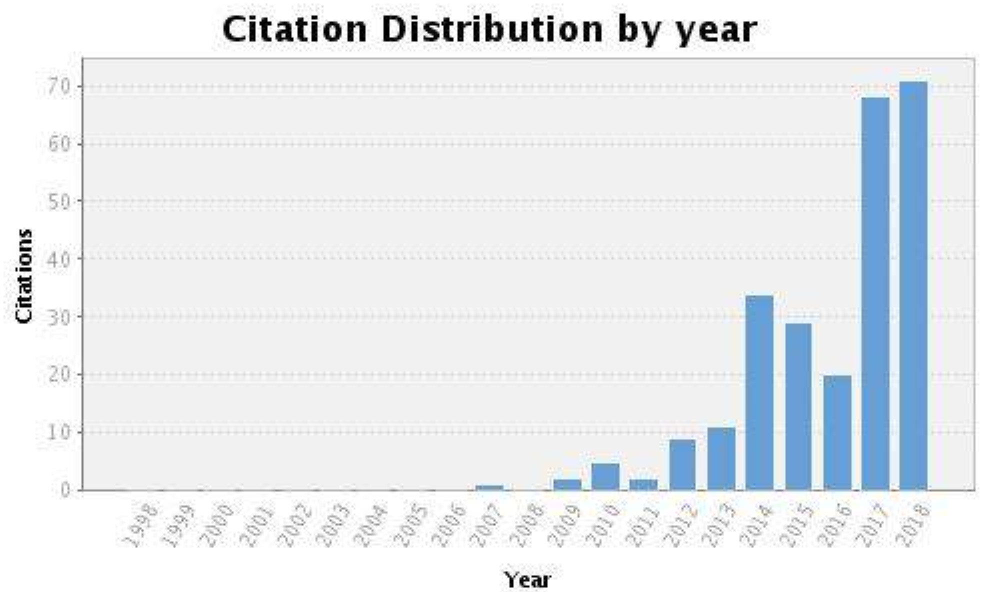
This graph shows the number of times the articles on the publication list have been cited in each of the last 20 years.
Note: Only articles from Web of Science Core Collection with citation data are included in the calculations. More information about these data.



Total Articles in Publication List:	79
Articles With Citation Data:	51
Sum of the Times Cited:	252
Average Citations per Article:	4.94
h-index:	10
Last Updated:	12/01/2018 14:18 GMT

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Vladimir A. Sreckovic

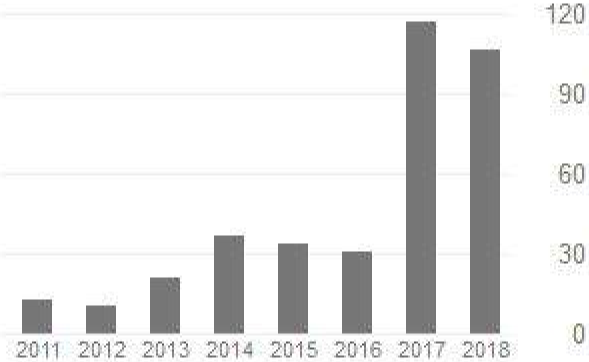
dr., Associate Professor
Верификована је имејл адреса на ipb.ac.rs

Astrophysics Physics Plasma physics Geophysics Atmospheric sciences

ПРАТИ

Навело ПРИКАЖИ СВЕ

	Све	Од 2013
Наводи	401	353
h-индекс	12	11
i10-индекс	15	13



НАСЛОВ	НАВЕЛО	ГОДИНА
Altitude distribution of electron concentration in ionospheric D-region in presence of time-varying solar radiation flux A Nina, V Čadež, V Srećković, D Šulić Nuclear Instruments and Methods in Physics Research Section B: Beam ...	30	2012
Rydberg atoms in astrophysics YN Gnedin, AA Mihajlov, LM Ignjatović, NM Sakan, VA Srećković, ... New astronomy reviews 53 (7-10), 259-265	28	2009
The chemi-ionization processes in slow collisions of Rydberg atoms with ground state atoms: mechanism and applications AA Mihajlov, VA Srećković, LM Ignjatović, AN Klyucharev Journal of Cluster Science 23 (1), 47-75	25	2012
The influence of solar spectral lines on electron concentration in terrestrial ionosphere A Nina, V Cadez, VA Sreckovic, D Sulic Baltic Astronomy, Vol. 20, p. 609-612	24	2012
Effective electron recombination coefficient in ionospheric D-region during the relaxation regime after solar flare from February 18, 2011 A Nina, V Čadež, D Šulić, V Srećković, V Žigman Nuclear Instruments and Methods in Physics Research Section B: Beam ...	23	2012
A comparative study of measured amplitude and phase perturbations on VLF and LF radio signals induced by solar flares DM Sulic, VA Sreckovic Serbian Astronomical Journal 188, 45-54	19	2014
The non-symmetric ion–atom radiative processes in the stellar atmospheres AA Mihajlov, LM Ignjatović, VA Srećković, MS Dimitrijević, A Metropoulos Monthly Notices of the Royal Astronomical Society 431 (1), 589-599	19	2013
Modeling of continuous absorption of electromagnetic radiation in dense partially ionized plasmas	16	2011

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- Aleksandra Nina — Institute of Physics, Univesity of ...
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- V.M. Adamyan — Odessa National I.I. Mechnikov ...
- I.M. Tkachenko — Universidad Politecnica de Valen...
- Paola Bolognesi — CNR-ISM
- Iorenzo Avaldi

3.1.5 Награде и признања за научни рад

УНИВЕРЗИТЕТ У БЕОГРАДУ

ФИЗИЧКИ ФАКУЛТЕТ

ФОНД „Проф. др ЉУБОМИР ЋИРКОВИЋ"

Одлуком Одбора Фонда за најбољу магистарску тезу одбрањену на Физичком факултету у 2005/2006 години, награђује се

Владимир Срећковић

На основу тога издаје се ова

ДИПЛОМА

О ДОДЕЉИВАЊУ НАГРАДЕ

Датум

14.12.2006.год.

Председник одбора

Subject **AGU Research Spotlight: Your GRL Paper Has Been Selected 15-5317**
From Eos_Research_Spotlight <Eos_Research_Spotlight@agu.org>
To sandrast@ipb.ac.rs <sandrast@ipb.ac.rs>
Date 2016-03-04 01:05

- 15-5317_Nina_2015GL065726_ls_ds_ls_ds_lc_.docx (17 KB)

Dear Dr. Nina,

The editors of ***Geophysical Research Letters*** have selected your paper "**Detection of short-term response of the low ionosphere on gamma ray bursts**" (MS# 2015GL065726) to be featured as a Research Spotlight on https://Eos.org and on the journal's website. Congratulations!

As you may know, Research Spotlights summarize the research and findings of the best accepted articles for the broad Earth and space science community. Research Spotlights also may be sent to interested news media and may appear in the semi-monthly *Eos* magazine.

I am sending for your review the attached write-up of your article. Please review the Research Spotlight and respond to us no later than **8 March 2016**, which is 3 working days from now.

If that deadline is too tight, please tell us when you can return it; we do ask, though, for a quick turn-around. If you do not respond we cannot publish this spotlight about your outstanding journal article in our Research Spotlight section.

As you review the Research Spotlight write-up, please remember that it is meant to provide an overview and summary of the research and put it into context for the broad Earth and space science audience as well as for science journalists. It's not meant to be a technical abstract, and it's important to avoid jargon. However, we want the content to be scientifically correct.

If you have edits, please make them to the attached document using tracked changes in Microsoft Word. Do not add more than 30 additional words to the spotlight.

We also need an engaging image to entice readers to your Research Spotlight and learn about your outstanding journal article. The image should be visually appealing rather than strictly technical, and *Eos* needs to be able to secure the copyright permission to use it. If you have one or more images/photographs that you think would do well to accompany the text, please send those to us with captions and credit information; for photographs—the photographer credit line and their permission to crop the image and publish it on Eos.org. Also, the spotlight writer may have included a suggested image for your consideration in the text; please either accept or reject this image suggestion.

Return your edited document and any images to me via reply message. If you have no edits, and no images to offer, please simply reply to this message with your approval.

Thank you very much for your prompt review and response.

Sincerely,

Liz

—

Liz Castenson

Senior Editors' Assistant

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Eos is the leading source for trustworthy news and perspectives about the Earth and space sciences and their impact. Its namesake is Eos, the Greek goddess of the ...

3.2. Ангажованост у развоју услова за научни рад, образовању и формирању научних кадрова

УНИВЕРЗИТЕТ У БЕОГРАДУ ФИЗИЧКИ ФАКУЛТЕТ
UNIVERSITY OF BELGRADE FACULTY OF PHYSICS
Студентски трг 12, 11000 Београд, П.П. 44, Тел: 011-7158-151, Факс: 011-3282-619
Studentski trg 12, 11000 Belgrade, Serbia, POB 44, Tel: +381-11-7158-151, Fax: +381-11-3282-619
www.ff.bg.ac.rs e-mail: *dekanat@ff.bg.ac.rs*

УНИВЕРЗИТЕТ У БЕОГРАДУ
ФИЗИЧКИ ФАКУЛТЕТ
Бр. 617/1
19. 12. 2014. год.
БЕОГРАД, СТУДЕНТСКИ ТРГ 12-16
П. ФАХ 44

ПОТВРДА

Овим се потврђује да је **др ВЛАДИМИР СРЕЋКОВИЋ**, научни сарадник Института за физику био ментор докторске дисертације АЛЕКСАНДРЕ НИНА под називом „ДИЈАГНОСТИКА ПЛАЗМЕ ЈОНОСФЕРСКЕ D ОБЛАСТИ ЕЛЕКТРОМАГНЕТНИМ VLF ТАЛАСИМА".

Др Владимир Срећковић је за ментора докторске дисертације АЛЕКСАНДРЕ НИНА именован на седници Наставно-научног већа Физичког факултета одржаној 21. марта 2012. године.

Докторска дисертација је успешно одбрањена на Физичком факултету 15. априла 2014. године.

Београд, 19.12.2014.

ДЕКАН ФИЗИЧКОГ ФАКУЛТЕТА

Проф. др Јаблан Дојчиловић

3.4. Руковођење пројектима, потпројектима и пројектним задацима

УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ БЕОГРАД
Прегревица 118, 11080 Земун - Београд, Србија
Телефон: +381 11 3713000, Факс: +381 11 3162190, www.ipb.ac.rs
ПИБ: 100105980, Матични број: 07018029, Текући рачун: 205-66984-23

РЕПУБЛИКА СРБИЈА
УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ
0801 Бр. 1728/1
19-10-2016 20___ год.

Београд, 19.10.2016.

На основу члана 27. Статута Института за физику 0801 бр. 285/4 од 30. маја 2011. године (измене и допуне на седницама 17.06.2013. год. и 23.12.2014. год.) и важећег Правилника о организацији и систематизацији рада (радних места) на Институтут за физику, а у циљу испуњавања законских обавеза Института везаних за рад и безбедност на раду, директор Института за физику доноси следећу

О Д Л У К У

Сви запослени научни радници на Институту за физику се једнозначно распоређују у следеће лабораторије (истраживачке групе):

1. Лабораторија за нелинеарну фотонику
2. Лабораторија за спектроскопију плазме и ласере
3. Лабораторија за холографију, оптичке материјале и фотоничке кристале
4. Лабораторија за квантну и нелинеарну оптику
5. Лабораторија за ласерску интеракцију са материјалима и ласере
6. Лабораторија за биофизику
7. Лабораторија за метаматеријале
8. Лабораторија за фотоакустику
9. Лабораторија за примену рачунара у науци
10. Лабораторија за грануларне материјале
11. Лабораторија за биомиметику
12. Лабораторија за физику материјала под екстремним условима
13. Лабораторија за гасну електронику
14. Лабораторија за нелинеарну физику
15. Лабораторија за истраживања у области електронских материјала
16. Лабораторија за физику нано-композитних структура и био-вибрационих спектара
17. Лабораторија за чврсто стање
18. Лабораторија за графен, друге 2Д материјале и уређене наноструктуре
19. Лабораторија за мезоскопску физику
20. Лабораторја за физику високих енергија
21. Група за гравитацију, честице и поља
22. Лабораторија за физику атомских сударних процеса
23. Лабораторија за физику животне средине
24. Нискофонска лабораторија за нуклеарну физику
25. Лабораторија за астрофизику и физику јоносфере

За сваку од наведених лабораторија се доноси посебна одлука којом се утврђује списак истраживача чланова, даје кратак опис области деловања, и поставља руководилац лабораторије у наредном једногодишњем периоду.

Ова одлука ступа на снагу даном доношења.

ДИРЕКТОР ИНСТИТУТА ЗА ФИЗИКУ

др Александар Богојевић

РЕПУБЛИКА СРБИЈА УНИВЕРЗИТЕТ У БЕОГРАДУ ИНСТИТУТ ЗА ФИЗИКУ

УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ БЕОГРАД
Прегревица 118, 11080 Земун - Београд, Србија
Телефон: +381 11 3713000, Факс: +381 11 3162190, www.ipb.ac.rs
ПИБ: 100105980, Матични број: 07018029, Текући рачун: 205-66984-23

РЕПУБЛИКА СРБИЈА УНИВЕРЗИТЕТ У БЕОГРАДУ ИНСТИТУТ ЗА ФИЗИКУ
0801 Бр. 1753/1
20-10-2016 20___ год.

Београд, 20.10.2016.

На основу члана 27. Статута Института за физику 0801 бр. 285/4 од 30. маја 2011. године (измене и допуне на седницама 17.06.2013.год. и 23.12.2014.год.), директор Института за физику доноси

О Д Л У К У

У Лабораторију за астро физику и физику јоносфере Института за физику се распоређују следећи истраживачи:

1. др Владимир Срећковић, виши научни сарадник
2. др Љубинко Игњатовић, научни саветник
3. др Александра Нина, научни сарадник

Област деловања лабораторије:

Соларна и звездана астрофизика, истраживања горњих слојева атмосфере.

За руководиоца лабораторије се именује др Владимир Срећковић, виши научни сарадник.

Одлука ступа на снагу даном доношења.

ДИРЕКТОР ИНСТИТУТА ЗА ФИЗИКУ

др Александар Богојевић

Лабораторија за астрофизику и физику јоносфере

ОБЛАСТ ДЕЛОВАЊА

Соларна и звездана астрофизика, истраживања горњих слојева атмосфере.

Руководилац лабораторије је др Владимир Срећковић, виши научни сарадник.

СВЕ ЛАБОРАТОРИЈЕ
ИНСТИТУТА ЗА ФИЗИКУ >>

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др Љубинко Игњатовић

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United Kingdom	■ Mr Nick FRASER

COST Association COST Action CA17106

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Science officer of the Action:
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Administrative officer of the Action:
Ms Tania GONZALEZ OVIN

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CA COST Action CA16214

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MC Vice Chair	Dr Brynmor HASKELL (PL)

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WG Leader	Dr Patrick WELTEVREDE
WG Leader	Dr Sebastiano BERNUZZI
WG Leader	Dr Pablo CERDA-DURAN
WG Leader	Dr Roberta ZANIN

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Greece	Prof Vasiliki PAVLIDOU
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Turkey	Prof Solen BALMAN
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United Kingdom	Dr Patrick WELTEVREDE

Country	**MC Substitute**
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Netherlands	Dr Anna WATTS
Netherlands	Dr Jason HESSELS
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Poland	Dr Morgane FORTIN
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Slovenia	Prof Gabrijela ZAHARIJAS
Spain	Dr Laura TOLOS
Spain	Dr Cristina MANUEL
Spain	Dr Gloria SALA
Spain	Dr Pablo CERDA-DURAN
Turkey	Dr Onur AKBAL
United Kingdom	Dr David Ian JONES
United Kingdom	Dr Alberto SESANA

COST Near Neighbour Countries

Institution Name	**MC Observer**
Ioffe Physical Technical Institute	Prof Dmitry Yakovlev
Zewail City of Science and Technology	Dr Alaa Ibrahim
Lomonosov Moscow State University	Prof Sergey Popov
Institute of Radio Astronomy	■ Dr Svetlana Petrova

COST International Partner Countries

Institution Name	**MC Observer**
Monash University	Dr Duncan Galloway
Monash University	Prof Yuri Levin
McGill University	■ Prof Vicky Kaspi
McGill University	Dr Vanessa Graber
University of British Columbia	Prof Ingrid Stairs
Pontificia Universidad Catolica de Chile	Prof Andreas Reisenegger
University of Manitoba	Prof Samar Safi-Harb
Universidad Nacional Autonoma de Mexico	Dr Dany Page
West Virginia University	■ Prof Duncan Lorimer
West Virginia University	Dr Maura McLaughlin
Stony Brook University	Prof Rosalba Perna
The Institute of Mathematical Sciences	Dr Manjari Bagchi
Institute for Cosmic Ray Research	■ Dr Daniela Hadasch
Pennsylvania State University	■ Prof George Pavlov
Pennsylvania State University	Dr Bettina Posselt

Specific Organisations

Organisation Name	MC Observer
European Space Agency	■ Dr Celia Sanchez Fernandez

COST Association COST Action CA16214

Description

Parties

Management Committee

General Information*

Chair of the Action:
Dr Nanda REA (ES)

Vice Chair of the Action:
Dr Brynmor HASKELL (PL)

Science officer of the Action:
Dr Fatima BOUCHAMA

Administrative officer of the Action:
Ms Milena STOYANOVA

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Deadline for manuscript submissions:
31 March 2019

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Dear Colleagues,

Many fields in physics and astronomy, depend on data for ionic, atomic and molecular collision processes. Nowadays, in the field of astrophysics modeling of these data is especially important and needed for simulations/calculations. Additionally, these processes are important for diagnostics, analysis and modeling of fusion plasma, laser produced plasma, lasers design and development and various plasmas in industry and technology. Among these amounts of data collection, there are collisional and radiative processes that even today are poorly represented. Therefore, there is an urgent need to collect these data, as well as to develop methods for improving the existing ones.

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A special issue of *Data* (ISSN 2306-5729).

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Guest Editor
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The Astrophysics and Ionospheric Laboratory, Institute of Physics, Pregrevica 118, 11080 Zemun, Belgrade, Serbia
E-Mail

Special Issue Information

Dear Colleagues,

The space and Earth's layers are mediums permanently exposed to influences of numerous perturbations characterized with time- and space-dependent intensity. For this reason, detection of the astrophysical and terrestrial events and their influences, as well as the development and application of various models, must be based on observation data.

The challenges related to data volume, variety and data flow are similar in astro- and geo-observations. This Special Issue aims to encourage the communication among the disciplines by identifying and grouping relevant research solutions. Its goals are to engage a broad community of researchers, both users and contributors, to make new discoveries enabled by the growth of data and technology and to continue interdisciplinary exchanges of ideas and methodologies with other fields.

We would like to invite you to submit articles addressing the data collection in astrophysics and geophysics, its acquisition, processing, and management, so that these results will be used by other scientists and that the compilation of such data sets will be useful to data producers as well. Potential topics include, but are not limited to:

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The space and Earth's layers are mediums permanently exposed to influences of numerous perturbations characterized with time- and space-dependent intensity. For this reason, detection of the astrophysical and terrestrial events and their influences, as well as the development and application of various models, must be based on observation data. The challenges related to data volume, variety and data flow are similar in astro- and geo-observations. This Special Issue aims to encourage the communication among the disciplines by identifying and grouping relevant research solutions. Its goals are to engage a broad community of researchers to make new discoveries enabled by the growth of data and technology and to continue interdisciplinary exchanges of ideas and methodologies with other fields.

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Miodrag Dačić: *The Rising and Setting of the Sun and Moon for Belgrade and Lunar Phases – 2018* 53

ВАСИОНА, часопис за астрономију, излази у четири броја годишње. Издаје Астрономско друштво „Руђер Бошковић". Адреса уредништва и администрације: Народна опсерваторија, Калемегдан, Горњи град 16, 11 000 Београд; телефон: 011/3032133; e-mail: adrb@adrb.org; URL: http://www.adrb.org. Чланарина-претплата за 2018. годину износи 1200 динара, за иностранство 20 евра. Чланарину-претплату слати у корист текућег рачуна број 205-29948-66.

ВАСИОНА, бр. 2018/1–2, година LX, књига XV, стр. 1–64, штампано јануара 2018.

штампа: „Скрипта интернационал", Београд

Subject **Fwd: [Data] Manuscript ID: data-279156 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-10 17:40

```
-------- Original Message --------
Subject: [Data] Manuscript ID: data-279156 - Editor Decision
Date: 2018-05-04 09:47
From: data@mdpi.com
To: June Xiong <june.xiong@mdpi.com>
Cc: data@mdpi.com, Aleksandra  Nina <sandrast@ipb.ac.rs>, Vladimir Sreckovic <vlada@ipb.ac.rs>
Reply-To: Vladimir Sreckovic <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-279156
Type of manuscript: Article
Title: S[redacted]
Astronomical Objects
Authors: A[redacted]
Received: 19 February 2018
E-mails:[redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Vladimir Sreckovic, Aleksandra Nina:
Decision: Reject and encourage resubmission
Notes: The referees are in principal right.  Obviously, the
authors tried to correct the manuscript, but not enough for
acceptance in this stage.

We encourage a new submission of the manuscript. But this time with the
possible changes
in accordance with the referees and to moderate some strong
statements and conclusion that exist in the work.
article is not so bad and has potential.
Decision Date: 4 May 2018
http://susy.mdpi.com/user/assigned/process_form/436b49cc302e9346558f4ec11c4b541a

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/539994/xYIZT5gR

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Dr Sreckovic Vladimir
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Head of The Astrophysics and Ionospheric Laboratory,
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Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
```

http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: [Data] Manuscript ID: data-300795 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-10 17:36

-------- Original Message --------
Subject: [Data] Manuscript ID: data-300795 - Editor Decision
Date: 2018-05-28 14:42
From: data@mdpi.com
To: June Xiong <june.xiong@mdpi.com>
Cc: data@mdpi.com, Aleksandra Nina <sandrast@ipb.ac.rs>, Vladimir Sreckovic <vlada@ipb.ac.rs>
Reply-To: Vladimir Sreckovic <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-300795
Type of manuscript: Article
Title: [redacted]
Authors: [redacted]
Received: 20 April 2018
E-mails: [redacted],
[redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Sreckovic Vladimir, Aleksandra Nina:
Decision: Accept in current form
Notes:
Decision Date: 28 May 2018
http://susy.mdpi.com/user/assigned/process_form/a99e92b6768d20427f9e3af7802eca14

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/572677/v1XBYt9n

Ms. June Xiong
Assistant Editor
E-Mail: june.xiong@mdpi.com

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fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
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www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: [Data] Manuscript ID: data-309533 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-10 17:35

-------- Original Message --------
Subject: [Data] Manuscript ID: data-309533 - Editor Decision
Date: 2018-06-20 11:29
From: data@mdpi.com
To: June Xiong <june.xiong@mdpi.com>
Cc: data@mdpi.com, Aleksandra Nina <sandrast@ipb.ac.rs>, Vladimir Sreckovic <vlada@ipb.ac.rs>
Reply-To: Vladimir Sreckovic <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-309533
Type of manuscript: Article
Title: [redacted]
Authors: [redacted]
Received: 13 May 2018
E-mails: [redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Sreckovic Vladimir, Nina Aleksandra:
Decision: Accept in current form
Notes: Since the Reviewer 2 do not have any direct and constructive remarks on the work but general, we think that his opinion should be omitted. The only direct critique of this Reviewer 2 is that the software does not work on his Ubuntu up-to-date machine. We considered his remark here too. We checked, and the software is pretty easy to install and run on Linux machines (on Ubuntu up-to-date and Suse distribution) as well as on Windows machines. In the attachment is a snapshot of installed software on Ubuntu. Of course, like any experienced Linux user, it's a good idea to install the necessary Python libraries, etc.
For these reasons we think that his opinion should be omitted and that positive opinions of the Reviewer 1 and Reviewer 3 must be accepted.
Decision Date: 20 June 2018
http://susy.mdpi.com/user/assigned/process_form/7f0663a2d92d9e49a23b250707273e5d

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/596947/WGI8vxTa

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fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: [Data] Manuscript ID: data-365785 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-10 17:37

-------- Original Message --------
Subject: [Data] Manuscript ID: data-365785 - Editor Decision
Date: 2018-09-28 09:43
From: data@mdpi.com
To: Jingjing Lu <jingjing.lu@mdpi.com>
Cc: data@mdpi.com, Aleksandra Nina <sandrast@ipb.ac.rs>, "Vladimir A. Sreckovic" <vlada@ipb.ac.rs>
Reply-To: "Vladimir A. Sreckovic" <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-365785
Type of manuscript: Article
Title: [redacted]
Authors: [redacted]
Received: 16 September 2018
E-mails: [redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Aleksandra Nina, Vladimir Sreckovic:
Decision: Accept after minor revision
Notes: We analyzed the text and comments of the referees. We concluded that the existing version is correctly written and that it should be accepted for publication after some minor corrections which are suggested by reviewers.
Decision Date: 28 September 2018
http://susy.mdpi.com/user/assigned/process_form/1db8c944102200c97c802761ea33cb6d

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/728558/JyDQhgI4

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www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: [Data] Manuscript ID: data-379348 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-24 09:00

-------- Original Message --------
Subject: [Data] Manuscript ID: data-379348 - Editor Decision
Date: 2018-11-23 10:54
From: data@mdpi.com
To: Cody Peng <cody.peng@mdpi.com>
Cc: data@mdpi.com, Aleksandra Nina <sandrast@ipb.ac.rs>, "Vladimir A. Sreckovic"
<vlada@ipb.ac.rs>
Reply-To: "Vladimir A. Sreckovic" <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-379348
Type of manuscript: Article
Title: [redacted]
Authors: [redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Aleksandra Nina, Vladimir Sreckovic:
Decision: Accept in current form
Notes: The authors positively responded to all reviewers' comments. Note to authors for submissions of future manuscripts: in addition to answers to reviewers, it is necessary to clearly indicate changes (highlight, bold) in the text when replying.
Decision Date: 23 November 2018
http://susy.mdpi.com/user/assigned/process_form/a17286df169320854f7ff36bd46dbf90

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/814140/lehfvW2R

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Subject **Fwd: [Data] Manuscript ID: data-398980 - Editor Decision**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <edits@publons.com>
Date 2018-11-24 09:06

-------- Original Message --------
Subject: [Data] Manuscript ID: data-398980 - Editor Decision
Date: 2018-11-24 09:05
From: data@mdpi.com
To: Victoria Shi <victoria.shi@mdpi.com>
Cc: data@mdpi.com, Aleksandra Nina <sandrast@ipb.ac.rs>, "Vladimir A. Sreckovic" <vlada@ipb.ac.rs>
Reply-To: "Vladimir A. Sreckovic" <vlada@ipb.ac.rs>

Dear Editor,

A decision has been made regarding the following manuscript:

Manuscript ID: data-398980
Type of manuscript: Data Descriptor
Title: [redacted]
Authors: [redacted]
Received: 15 November 2018
E-mails: [redacted]
Data in Astrophysics & Geophysics: Research and Applications
http://www.mdpi.com/journal/data/special_issues/Astro_Geophy

Decision done by Sreckovic Vladimir, Aleksandra Nina:
Decision: Accept in current form
Notes:
Decision Date: 24 November 2018
http://susy.mdpi.com/user/assigned/process_form/32d16f4c595b48ad7d29f2a688e404ed

You can find the editor's decision at the following link:

http://susy.mdpi.com/user/decision/process_form/816912/IU0jn6W9

Ms. Victoria Shi
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E-Mail: victoria.shi@mdpi.com

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www.researchgate.net/profile/V_Sreckovic

3.5.1. Рецензије научних радова

https://orcid.org/0000-0001-7938-5748

https://researcherid.com/rid/S-5724-...

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- (3) Journal of Atmospheric and Solar-Te...
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- (2) Journal of Physics B: Atomic, Molec...
- (1) Atmospheric Research
- (1) Data
- (1) Environmental Sciences Group
- (1) Measurement Science and Technolo...
- (1) Remote Sensing

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- Advances in Space Research
- Data
- Atoms

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2018	✓ Reviewed for Atoms
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2018	✓ Reviewed for Remote Sensing
2018	✓ Reviewed for Atoms
2018	✓ Reviewed for Atoms
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2018	✓ Reviewed for Atoms
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2018	✓ Reviewed for Atoms
2018	✓ Reviewed for Atoms
2018	✓ Reviewed for Journal of Atmospheric and Solar-Terrestrial Physi...
2018	✓ Reviewed for IEEE Transactions on Plasma Science
2018	✓ Reviewed for Atoms
2018	✓ Reviewed for Atmospheric Research
2018	✓ Reviewed for IEEE Transactions on Plasma Science
2017	✓ Reviewed for Atoms

#	RESEARCHER	INSTITUTION	# VERIFIED REVIEWS	# REVIEWS LAST 12 MONTHS ▼	# VERIFIED EDITORIAL RECORDS
19	Boris Furtula	University of Kragujevac	91	25	4
20	BA Biljana Arsic	University of Manchester	46	24	-
21	AT Aleksandra Torbica	University of Novi Sad	39	24	-
22	Dragan Lambić	University of Novi Sad	91	23	-
23	Milan S. Dimitrijević	Astronomical Observatory	116	23	15
24	Biljana P. Stošić	University of Nis, Faculty of Electronic Engineering	42	21	3
25	Branko Brkljač	BioSense Institute	43	21	-
26	Slavko Pokorni	Information Technology School, Belgrade	77	21	-
27	KM Komljenovic Miroslav	Institute for Multidisciplinary Research, University of ...	66	21	-
28	MB Milan Bjelica	University of Belgrade	141	20	-
29	P Petar Čolović	University of Novi Sad	66	20	1
30	BG Bogdanovic Gordana	-	82	19	-
31	Ivan Jaric	Biology Centre of the Czech Academy of Sciences, Ins...	91	18	23
32	Vladimir Sreckovic	Institute of Physics Belgrade	29	18	6
33	Mladen Terzic	Rheinmetall Automotive	25	18	-
34	SS Snezana Stankovic	University of Belgrade	85	18	-
35	ZB Zorica Bogdanović	University of Belgrade, Faculty of Organizational Scie...	35	18	-
36	Boris Delibašić	University of Belgrade	102	18	-
37	Ilija Djekic	University of Belgrade	94	18	-
38	EM Emina Sudar Milovanovic	University of Belgrade, Institute Vinca	21	17	-

Subject **[Atoms] Manuscript ID: atoms-225166 - Thank you for reviewing: paper rejected**
From Lauren Liu <lauren.liu@mdpi.com>
Sender <lauren.liu@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc <atoms@mdpi.com>
Reply-To <atoms@mdpi.com>
Date 2017-11-01 06:54

Dear Dr. Sreckovic,

Thank you for kindly helping reviewing the following paper for Atoms (ISSN 2218-2004, http://www.mdpi.com/journal/atoms):

Manuscript ID: atoms-225166
Type of manuscript: Article
Title: [redacted]
Authors: [redacted]

The paper has been rejected by the academic editor after peer review. You can see the comments of other reviewers by creating an account on our submission system at http://susy.mdpi.com and visiting the reviews section.

We would like to invite you once again to contribute papers for peer-review and rapid publication in any MDPI open access journal. We are also keen to hear what you think about MDPI: to participate in a quick survey, click here: https://www.surveymonkey.com/r/mdpiReviewerFeedback.

Kind regards,

Lauren Liu
Assistant Editor
E-Mail:lauren.liu@mdpi.com
--
Ms. Lauren Liu
MDPI Tongzhou Office, Beijing
Room 2207, Jincheng Center,No.21 Cuijingbeili. Tongzhou District, Beijing, 101101, China
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Tel. +41 61 683 77 34; Fax: +41 61 302 89 18
E-Mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

Subject [Atoms] Manuscript ID: atoms-296853 - Review Received - Thanks

From <atoms@mdpi.com>

Sender <susy@mdpi.com>

To Vladimir Sreckovic <vlada@ipb.ac.rs>

Cc Lauren Liu <lauren.liu@mdpi.com>, <atoms@mdpi.com>

Date 2018-04-18 12:42

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-296853
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
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Kind regards,

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E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Subject **[Atoms] Manuscript ID: atoms-303759 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Lauren Liu <lauren.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-05-19 22:37

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-303759
Title: [redacted]
Authors: [redacted]

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Subject **[Atoms] Manuscript ID: atoms-327536 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Lauren Liu <lauren.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-07-05 12:02

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-327536
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
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Kind regards,

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E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Subject **[Atoms] Manuscript ID: atoms-337491 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Macy Liu <macy.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-08-17 19:12

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-337491
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
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Kind regards,

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Subject	**[Atoms] Manuscript ID: atoms-356328 - Review Received - Thanks**
From	<atoms@mdpi.com>
Sender	<susy@mdpi.com>
To	Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc	Macy Liu <macy.liu@mdpi.com>, <atoms@mdpi.com>
Date	2018-09-26 15:00

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-356328
Title: [redacted]
Authors[redacted]
Ahmed, [redacted]
Madison[redacted]
Cardena[redacted]
Kline, [redacted]
Eric Hu[redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
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http://www.mdpi.com/journal/atoms/

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Subject **[Remote Sensing] Manuscript ID: remotesensing-369078 - Review Received - Thanks**
From <remotesensing@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Zlatan Bisercic <bisercic@mdpi.com>, <remotesensing@mdpi.com>
Date 2018-10-04 17:00

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: remotesensing-369078
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
https://www.surveymonkey.com/r/remotesensingreviewer

Kind regards,

Remote Sensing Editorial Office
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E-mail: remotesensing@mdpi.com
http://www.mdpi.com/journal/remotesensing/

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Subject **[Atoms] Manuscript ID: atoms-320206 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Lauren Liu <lauren.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-07-07 17:46

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-320206
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
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Kind regards,

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E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Subject **[Atoms] Manuscript ID: atoms-335327 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Macy Liu <macy.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-07-20 15:17

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-335327
Title: [redacted]
Authors: [redacted]

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Tel. +41 61 683 77 34 (office)
Fax +41 61 302 89 18 (office)
E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

*** This is an automatically generated email ***

Subject **Fwd: Thank you for reviewing manuscript [redacted]**

From Vladimir Sreckovic <vlada@ipb.ac.rs>

To <reviews@publons.com>

Date 2018-04-04 21:31

-------- Original Message --------
Subject: Thank you for reviewing manuscript D region ionospheric response to solar flares revealed from MF radar measurements
Date: 2018-04-04 21:26
From: Journal of Atmospheric and Solar-Terrestrial Physics <EviseSupport@elsevier.com>
To: vlada@ipb.ac.rs
Reply-To: atp-eo@elsevier.com

This message was sent automatically. Please do not reply.

Ref: ATP_2018_54
Title: [redacted]
Journal: Journal of Atmospheric and Solar-Terrestrial Physics
Dear Sreckovic,

Thank you for your review for the above-referenced manuscript. I greatly appreciate the commitment of your time and expertise. Without the dedication of reviewers like you, it would be impossible to manage an efficient peer review process and maintain the high standards necessary for a successful journal.

When a final decision has been reached regarding this manuscript you will be able to view this decision, as well as reviews submitted by any other reviewers, at:
http://www.evise.com/evise/faces/pages/navigation/NavController.jspx?JRNL_ACR=ATP.
You can also access your review comments here, at any time.

I hope that you will consider Journal of Atmospheric and Solar-Terrestrial Physics as a potential journal for your own publications in the future.

Kind regards,

Robert Strangeway
Editor
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[1] http://help.elsevier.com/app/answers/list/p/9435/
[2] https://www.elsevier.com/legal/privacy-policy

--
Dr Sreckovic Vladimir

Associate Professor
Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **[Atoms] Manuscript ID: atoms-388809 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir A. Sreckovic <vlada@ipb.ac.rs>
Cc Atoms Editorial Office <atoms@mdpi.com>, Macy Liu <macy.liu@mdpi.com>
Date 2018-11-06 12:50

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-388809
Title: [redacted]
Authors: [redacted]

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Kind regards,

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E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Subject	**[Data] Manuscript ID: data-379348 - Review Received - Thanks**
From	<data@mdpi.com>
Sender	<susy@mdpi.com>
To	Vladimir A. Sreckovic <vlada@ipb.ac.rs>
Cc	Data Editorial Office <data@mdpi.com>, Cody Peng <cody.peng@mdpi.com>
Date	2018-10-29 15:26

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: data-379348
Title: [redacted]
Authors: [redacted]
Andreas [redacted]
Kostunin [redacted]
Polyakov [redacted]
Viktoria [redacted]

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Kind regards,

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Office: St. Alban-Anlage 66, CH-4052 Basel
Tel. +41 61 683 77 34 (office)
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E-mail: data@mdpi.com
http://www.mdpi.com/journal/data/

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Subject **Fwd: [Atoms] Manuscript ID: atoms-284825 - Review Received - Thanks**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <reviews@publons.com>
Date 2018-03-14 18:06

-------- Original Message --------
Subject: [Atoms] Manuscript ID: atoms-284825 - Review Received - Thanks
Date: 2018-03-13 21:03
From: atoms@mdpi.com
To: Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc: Lauren Liu <lauren.liu@mdpi.com>, atoms@mdpi.com

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-284825
Title: [redacted]
Authors: [redacted]

To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at
https://www.surveymonkey.com/r/mdpiReviewerFeedback

Kind regards,

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E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Dr Sreckovic Vladimir
Associate Professor
Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: TPS11029.R1 - Review Submitted Successfully**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <reviews@publons.com>
Date 2018-03-14 18:06

-------- Original Message --------
Subject: TPS11029.R1 - Review Submitted Successfully
Date: 2018-03-14 10:32
From: IEEE Transactions on Plasma Science <onbehalfof@manuscriptcentral.com>
To: vladimir.sreckovic@ipb.ac.rs
Reply-To: hartmann.peter@wigner.mta.hu

14-Mar-2018

Dear Prof. Sreckovic:

Thank you for reviewing manuscript # TPS11029.R1 entitled "[redacted]" for the IEEE Transactions on Plasma Science.

On behalf of the Editors of the IEEE Transactions on Plasma Science, we appreciate the voluntary contribution that each reviewer gives to the Journal. We thank you for your participation in the online review process and hope that we may call upon you again to review future manuscripts.

Sincerely,
Dr. Peter Hartmann
Editor, IEEE Transactions on Plasma Science

--
Dr Sreckovic Vladimir
Associate Professor
Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Thank you for reviewing for Meas. Sci. Technol. - MST-107883.R1**
From Measurement Science and Technology <onbehalfof@manuscriptcentral.com>
To <vladimir.sreckovic@ipb.ac.rs>
Reply-To <mst@iop.org>
Date 2018-11-30 21:53

Dear Dr Sreckovic,

Re: "[redacted]
Article reference: MST-107883.R1

Thank you for your report on this Paper, which is being considered by Measurement Science and Technology.

We appreciate the time and effort that you have spent reviewing this manuscript and we are very grateful for your assistance.

We hope that we will be able to call upon you again to review future manuscripts.

Yours sincerely

Sarah Poulter, Emma Wright and Beth Hammond

On behalf of the IOP peer-review team:
Charlotte O'Neale - Editor
Sam Blomfield and Maddy Cumbes - Associate Editors
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www.iopscience.org/mst

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Letter reference: ERWPSNFR05

Subject **Thank you for reviewing for Meas. Sci. Technol. - MST-107883**
From Measurement Science and Technology <onbehalfof@manuscriptcentral.com>
To <vladimir.sreckovic@ipb.ac.rs>
Reply-To <mst@iop.org>
Date 2018-11-12 22:09

Dear Dr Sreckovic,

Re: [redacted]
Article reference: MST-107883

Thank you for your report on this Paper, which is being considered by Measurement Science and Technology.

We appreciate the time and effort that you have spent reviewing this manuscript and we are very grateful for your assistance.

We hope that we will be able to call upon you again to review future manuscripts.

Yours sincerely

Sarah Poulter, Emma Wright and Beth Hammond

On behalf of the IOP peer-review team:
Charlotte O'Neale - Editor
Sam Blomfield and Maddy Cumbes - Associate Editors
Sarah Poulter, Emma Wright and Beth Hammond - Editorial Assistants

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Letter reference: ESPSNS05

Subject **TPS11029 - Review Submitted Successfully**
From IEEE Transactions on Plasma Science <onbehalfof@manuscriptcentral.com>
To <vladimir.sreckovic@ipb.ac.rs>
Reply-To <hartmann.peter@wigner.mta.hu>
Date 2018-01-31 13:11

31-Jan-2018

Dear Prof. Sreckovic:

Thank you for reviewing manuscript # TPS11029 entitled "[redacted]" for the IEEE Transactions on Plasma Science.

On behalf of the Editors of the IEEE Transactions on Plasma Science, we appreciate the voluntary contribution that each reviewer gives to the Journal. We thank you for your participation in the online review process and hope that we may call upon you again to review future manuscripts.

Sincerely,
Dr. Peter Hartmann
Editor, IEEE Transactions on Plasma Science

Subject **[Atoms] Manuscript ID: atoms-320206 - Review Received - Thanks**
From <atoms@mdpi.com>
Sender <susy@mdpi.com>
To Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc Lauren Liu <lauren.liu@mdpi.com>, <atoms@mdpi.com>
Date 2018-06-12 10:53

Dear Dr. Sreckovic,

A short note to thank you very much for your review of the following manuscript:

Manuscript ID: atoms-320206
Title: I[redacted]
Authors: V[redacted]

If we decide to ask the authors for revisions, we will send you the revised version soon. To help us improve our services, we kindly ask you to fill in our online survey on the peer-review process at https://www.surveymonkey.com/r/mdpiReviewerFeedback

Kind regards,

Atoms Editorial Office
Postfach, CH-4020 Basel, Switzerland
Office: St. Alban-Anlage 66, CH-4052 Basel
Tel. +41 61 683 77 34 (office)
Fax +41 61 302 89 18 (office)
E-mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

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Subject	**Thank you for reviewing manuscript** [redacted]
From	Journal of Atmospheric and Solar-Terrestrial Physics <EviseSupport@elsevier.com>
To	<vlada@ipb.ac.rs>
Reply-To	<atp-eo@elsevier.com>
Date	2018-04-04 21:26

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Ref: ATP_2018_54
Title: D region ionospheric response to solar flares revealed from MF radar measurements
Journal: Journal of Atmospheric and Solar-Terrestrial Physics

Dear Sreckovic,

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I hope that you will consider Journal of Atmospheric and Solar-Terrestrial Physics as a potential journal for your own publications in the future.

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Robert Strangeway
Editor
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Subject	**Thank you for reviewing manuscript [redacted]**
From	Journal of Atmospheric and Solar-Terrestrial Physics <EviseSupport@elsevier.com>
To	<vlada@ipb.ac.rs>
Reply-To	<atp-eo@elsevier.com>
Date	2018-07-19 12:43

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Ref: ATP_2018_54_R1
Title: [redacted]
Journal: Journal of Atmospheric and Solar-Terrestrial Physics

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Subject **Thank you for reviewing manuscript [redacted]**

From Journal of Atmospheric and Solar-Terrestrial Physics <EviseSupport@elsevier.com>

To <vlada@ipb.ac.rs>

Reply-To <atp-eo@elsevier.com>

Date 2018-10-22 11:43

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Ref: ATP_2018_54_R2
Title: [redacted]
Journal: Journal of Atmospheric and Solar-Terrestrial Physics

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Subject **Fwd: [Atoms] Manuscript ID: atoms-225166 - Thank you for reviewing: paper rejected**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <reviews@publons.com>
Date 2018-02-02 10:24

-------- Original Message --------
Subject: [Atoms] Manuscript ID: atoms-225166 - Thank you for reviewing: paper rejected
Date: 2017-11-01 06:54
From: Lauren Liu <lauren.liu@mdpi.com>
To: Vladimir Sreckovic <vlada@ipb.ac.rs>
Cc: atoms@mdpi.com
Reply-To: atoms@mdpi.com

Dear Dr. Sreckovic,

Thank you for kindly helping reviewing the following paper for Atoms (ISSN 2218-2004, http://www.mdpi.com/journal/atoms):

Manuscript ID: atoms-225166
Type of manuscript: Article
Title: [redacted]
Authors: Al[redacted]

The paper has been rejected by the academic editor after peer review. You can see the comments of other reviewers by creating an account on our submission system at http://susy.mdpi.com and visiting the reviews section.

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Kind regards,

Lauren Liu
Assistant Editor
E-Mail:lauren.liu@mdpi.com
--
Ms. Lauren Liu
MDPI Tongzhou Office, Beijing
Room 2207, Jincheng Center,No.21 Cuijingbeili. Tongzhou District, Beijing, 101101, China
E-Mail: atoms@mdpi.com
Tel./Fax: +86 10 8152 1170
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Tel. +41 61 683 77 34; Fax: +41 61 302 89 18
E-Mail: atoms@mdpi.com
http://www.mdpi.com/journal/atoms/

--
Dr Sreckovic Vladimir
Associate Professor
Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: TPS11029 - Review Submitted Successfully**
From Vladimir Sreckovic <vlada@ipb.ac.rs>
To <reviews@publons.com>
Date 2018-02-02 10:24

-------- Original Message --------
Subject: TPS11029 - Review Submitted Successfully
Date: 2018-01-31 13:11
From: IEEE Transactions on Plasma Science <onbehalfof@manuscriptcentral.com>
To: vladimir.sreckovic@ipb.ac.rs
Reply-To: hartmann.peter@wigner.mta.hu

31-Jan-2018

Dear Prof. Sreckovic:

Thank you for reviewing manuscript # TPS11029 entitled "[redacted]" for the IEEE Transactions on Plasma Science.

On behalf of the Editors of the IEEE Transactions on Plasma Science, we appreciate the voluntary contribution that each reviewer gives to the Journal. We thank you for your participation in the online review process and hope that we may call upon you again to review future manuscripts.

Sincerely,
Dr. Peter Hartmann
Editor, IEEE Transactions on Plasma Science

--
Dr Sreckovic Vladimir
Associate Professor
Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

Subject **Fwd: Thank you for reviewing manuscript [redacted]**

From Vladimir Sreckovic <vlada@ipb.ac.rs>

To <reviews@publons.com>

Date 2018-03-10 20:18

-------- Original Message --------
Subject: Thank you for reviewing manuscript Atmospheric Response to the 20 March 2015 Solar Eclipse by Lidar Measurements
Date: 2018-03-02 10:57
From: Atmospheric Research <EviseSupport@elsevier.com>
To: vlada@ipb.ac.rs
Reply-To: atmos@elsevier.com

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Ref: ATMOSRES_2018_114
Title: [redacted]
Journal: Atmospheric Research
Dear Sreckovic,

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http://www.evise.com/evise/faces/pages/navigation/NavController.jspx?JRNL_ACR=ATMOSRES.
You can also access your review comments here, at any time.

I hope that you will consider Atmospheric Research as a potential journal for your own publications in the future.

Kind regards,

Olivier Dessens
Assistant Editor
Atmospheric Research

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[2] https://www.elsevier.com/legal/privacy-policy

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Dr Sreckovic Vladimir
Associate Professor

Head of The Astrophysics and Ionospheric Laboratory,
Institute of Physics,
Pregrevica 118, 11080 Zemun,
Belgrade, Serbia
phone: +381 11 3160 260 ext. 205,
fax: +381 11 3162 190,
email: vlada@ipb.ac.rs
http://www.ipb.ac.rs/
www.researchgate.net/profile/V_Sreckovic

3.5.2. Организација научних скупова

11th Serbian Conference on Spectral Line Shapes in Astrophysics
Šabac, Serbia, August 20-25, 2017

- Home
- Programme
- Registration & fees
- Participants
- Travel
- Accomodation
- Proceedings

Previous 10th SCSLSA
(Srebrno Jezero, 15 - 19 June, 2015)

Selected papers which have been presented at 10th SCSLSA are published in the special issue Journal of Astrophysics and Astronomy
Abstracts, Presentation and Photos

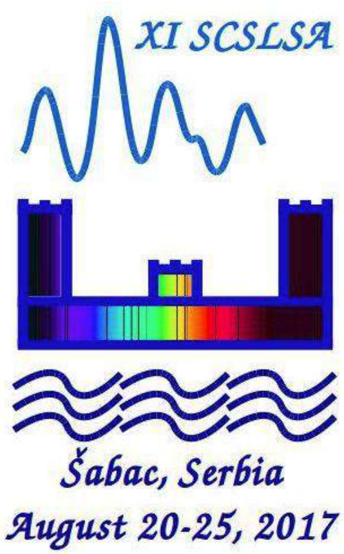
Previous 9th SCSLSA
(Banja Koviljača, 13 - 17 May, 2013)

Selected papers which have been presented at 9th SCSLSA are published in the special issue Advances in Space Research: "SpectralLine Shapes in Astrophysics and Related Phenomena."
Abstracts, Presentation and Photos

Previous 8th SCSLSA
(Divčibare, 6 - 10, June, 2011)

Procceedings of the 8th SCSLSA are published in **Baltic Astronomy** vol. 20, no.3-4, 2011 [contents]

Procceedings of the special session "Spectral Lines and Black Holes" are published in New Astronomy



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Scientific Rationale

The spectral lines, their widths, and shapes, are powerful tools for emitting/absorbing gas diagnostics in different astrophysical objects (from the Solar system to the most distant objects in the Universe - quasars). The emission/absorption lines of astrophysical objects are produced over a wide range of distances from an observer and under a wide range of physical and kinematical conditions. Therefore in astrophysical objects the lines from X-ray (Fe K) to the radio (radio recombination line) have been observed. On the other hand, the experimental and theoretical investigations of laboratory plasma have been applied in spectroscopic astrophysical research, especially atomic data needed for line shape calculations. This conference will bring together astronomers (observers and theoreticians) and physicists to review the present stage of investigation (Serbia and elsewhere), with the aim of improving our knowledge in this field, and to better understand the significance of emission/absorption lines for future astrophysical investigations.

The program will focus on:
- Stellar and interstellar spectral lines
- Spectral line phenomena in extragalactic objects
- Spectral lines in laboratory plasma

This is the 11th conference in the series. All materials (programme, talk presentations, photos, etc.) from the previous meetings are avalaible at the following link through Serbian Virtual Observatory.

During the Conference on August 24th, special session on 'Collisions and spectral line shapes' will be held in honor of Milan S. Dimitrijevic 70th birthday.

Scientific Organizing Committe

Luka Č. Popović (Astronomical Observatory, Belgrade, Serbia)
- Chairman (lpopovic@aob.rs)

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Emanuel Danezis (University of Athens, Greece)
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Veljko Vujčić (Astronomical Observatory, Belgrade)

Reviews, 2012
Abstracts, Presentation and Photos

Previous 7th SCSLSA

(Zrenjanin, 15 - 19, June, 2009)

Procceedings of the 7th SCSLSA can be found in New Astronomy Reviews, 2009
Abstracts, Program and Photos

Previous 6th SCSLSA

(Sremski Karlovci, 11 - 15, June, 2007)

Procceedings of the 6th SCSLSA can be found in AIP Conference Proceedings
Abstracts, Presentation, Program and Videos

Previous 5th SCSLSA

(Vršac, 6 - 10, June, 2005)

Procceedings of the 5th SCSLSA can be found in Mem.S.A.It
Program, Abstract and Photos

Previous 4th SCSLS

(Aranđelovac, 10 - 15, October, 2003)

Procceedings of the 4th SCSLS can be found in Publ. Astron. Obs. Belgrade No. 76.
Program, Papers and Photos

Previous 3rd YuCSLS

(Brankovac, Fruška Gora, 4 - 6, October, 1999)

Procceedings of the 3rd YuCSLS can be found in Journal of Research in Physics,
SPECIAL ISSUE Contributed Papers of III YuCSLS, Volume 28, Number

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Organized by: Astronomical Observatory Belgrade

Co-organizers:
Faculty of Mathematics, University of Belgrade
Astronomical Society of Serbia

Venue

The conference will be held in a city of Šabac Šabac. The venue is the hotel Sloboda

Renovated hotel Sloboda – superior, luxurious 12.625 m2 edifice in Šabac city center has undoubtedly once again become the symbol of this town by the Sava river. City pedestrian zone is positioned right next to the hotel and one can step to the central city square right from the hotel.

Hotel offers 95 accommodation units, with capacity of 285 guests (180 beds). It includes three multifunctional halls from 30-750 seats, the largest one offering 900 m2 and possibility of partition.

Guests will be able to enjoy half-board and À la carte restaurant "A", lobby bar and cafe-patisserie "Vremeplov" ("Time machine"), offering view on the town square and pedestrian zone. Interior of this patisserie is retro-inspired and all "Vremeplov" guests have a privilege to walk through the history of "little Paris" and enjoy traditional delicacies, served in a modern way.

One of the most attractive parts of this hotel is two level SPA and Wellness centre. This modern centre is available to guests who can relax in pool, jacuzzi, Finnish sauna, salt relaxation room, steambath, tepidariums and enjoy large offer of different massages and treatments. There is also a small fitness centre available inside wellness area, equipped with cardio machines.

For more details visit the following links:
Accomodation
SPA and Wellness

3, 1999. Proceedings and Photos

Previous 2nd YuCSLS
(Bela Crkva, 29. September - 2. October, 1997)

Procceedings of the 2nd YuCSLS can be found in Publ. Astron. Obs. Belgrade No. 57.
Proceedings and Photos

Previous 1st YuCSLS
(Krivaja, 11 - 14, September, 1995)

Procceedings of the 1st YuCSLS can be found in Publ. Astron. Obs. Belgrade No. 50.
Papers, Program and Conference Photo

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II Workshop on Astrophysical Spectroscopy

October 9 - 13, 2013, Vrujci, Serbia

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Zoran Simić, Astronomical Observatory, Belgrade, Co-Chairman

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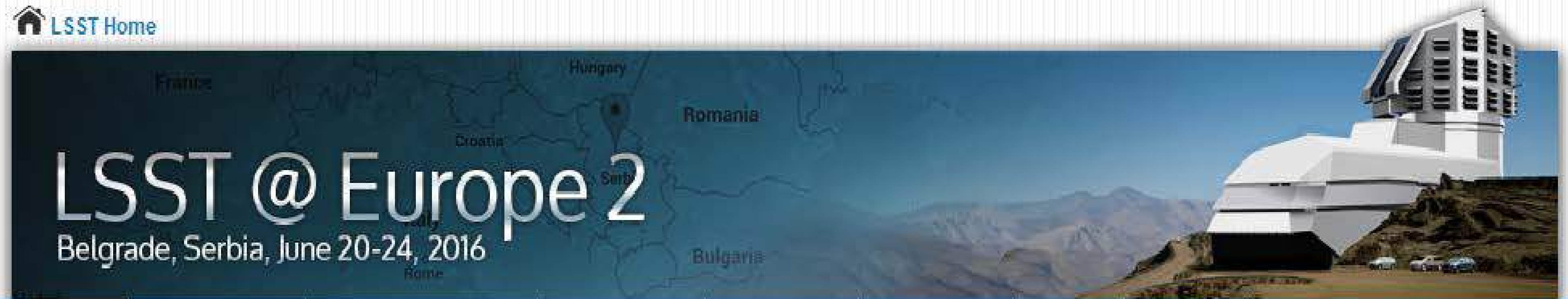
LSST Home



Latest News

Conference online

Conference started on Monday and before the rainstorm conference photo was taken. Lot of other photos can be found at facebook page

Note that there is a live stream of the talks at this link

Final Announcement distributed

See the announcement (plain

Meeting Summary

This is the second conference in the series. The first, very successful, LSST@Europe conference was held in Cambridge, UK in September 2013. This meeting enabled close interaction between the LSST personnel and European scientists interested in LSST.

Since that meeting, many countries and institutions in Europe have formalised their involvement in LSST. We aim to bring together European scientists with an interest in LSST and to provide to them an opportunity to interact with leaders of LSST Project and LSST Science Collaborations, and among themselves.

The main objectives of the 2016 meeting are to:

- discuss and further develop LSST science cases
- discuss various modifications of LSST baseline observing strategy
- provide an update on the status of the LSST Project and LSST Science Collaborations
- further develop the network of European scientists involved in various aspects of LSST
- provide an update on LSST Data Management Level 1 and Level 2 data products
- discuss the European potential for the development of LSST Level 3 data products and tools
- develop concepts to allow funding of European LSST activities via responses to EU H2020 and other European calls.
- via LSST Science Collaboration parallel sessions, promote increased European scientist engagement in LSST

First announcement (plain text or pdf)

Final announcement (plain text or pdf)

LSST@Europe2

Belgrade, June 20-24, 2016

First Announcement

Dear colleagues,

We are pleased to inform you that the LSST@Europe2 conference will be held in Belgrade, Serbia, June 20-24, 2016. We look forward to welcoming you to Belgrade to what will be a key event in developing European participation in the LSST project; see
https://project.lsst.org/meetings/lsst-europe-2016

Scientific Rationale

This is the second conference in the series. The first, very successful, LSST@Europe conference was held in Cambridge, UK in September 2013. This meeting enabled close interaction between the LSST personnel and European scientists interested in LSST.

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- discuss the European potential for the development of LSST Level 3 data products and tools
- develop concepts to allow funding of European LSST activities via responses to EU H2020 and other European calls.
- via LSST Science Collaboration parallel sessions, promote increased European scientist engagement in LSST

IMPORTANT DATES:
2015 Dec 1: Registration and abstract submission opens
2016 Mar 20: End of 'early bird' registration
2016 Mar 20: Close of contributed abstract submission
2016 Apr 20: Science programme available
2016 May 31: Close of late registration period and close of poster abstracts
Meeting dates: June 20-24, 2016

Meeting website:
https://project.lsst.org/meetings/lsst-europe-2016

Meeting Location:

Hotel Zira, Ruzveltova 35, 11000 Belgrade

We have block booked accommodation at the conference venue, details on the conference website.

Nearest airport: Belgrade, Serbia (BEG)

Registration and conference fees:

The registration for the meeting will open in December 1, 2015.
The conference fee will be €300 (€200 for students) if paid before March 20, 2016 and €400 Euros (€300 for students) thereafter.

We anticipate that there will be some travel support available for students and/or early stage researchers. Details will be made available on the conference website.

Scientific Organizing Committee members for LSST@Europe2 conference include:

Željko Ivezić (University of Washington, USA) (co-Chair: SOC)
Nicholas Walton (University of Cambridge, UK) (co-Chair: SOC)
Darko Jevremović (AOB, Belgrade, RS) (Chair: LOC)
Pierre Antilogus (IN2P3, Paris, FR)
Sarah Bridle (University of Manchester, UK)
Andy Connolly (University of Washington, USA)
Bozena Czerny (Nicolaus Copernicus Astronomical Center, Warsaw, PL)
Eva Grebel (University of Heidelberg, DE)
Isobel Hook (Lancaster University, UK)
Laszlo Kiss (Konkoly Observatory, Budapest, HU)
Reynald Pain (Universite Pierre et Marie Curie, Paris, FR)
Luka Popović (AOB, Belgrade, RS)
Timo Prusti (ESTEC, ESA, NL)
Matthias Steinmetz (AIP, Potsdam, DE)
Lucianne Walkowicz (Adler Planetarium, Chicago, US)

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Dragana Ilić, University of Belgrade (Secretary)
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Jovan Aleksić, AOB, Belgrade
Luka Popović, AOB Belgrade
Aleksandra Nina, Institute of Physics, Belgrade
Veljko Vujčić, AOB, Belgrade
Vladimir Srećković, Institute of Physics, Belgrade
Zoran Simić, AOB, Belgrade

12th Serbian Conference on Spectral Line Shapes in Astrophysics
Vrdnik, Serbia, Jun 3-7, 2019

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- Participants
- Transportation
- Accomodation
- Proceedings

Previous 11th SCSLSA
(Sabac, 21 - 25 August, 2017)

Selected papers which have been presented at 11th SCSLSA are published in the special issue Atoms
Abstracts, Presentation and Photos

Previous 10th SCSLSA
(Srebrno Jezero, 15 - 19 June, 2015)

Selected papers which have been presented at 10th SCSLSA are published in the special issue Journal of Astrophysics and Astronomy
Abstracts, Presentation and Photos

Previous 9th SCSLSA
(Banja Koviljača, 13 - 17 May, 2013)

Selected papers which have been presented at 9th SCSLSA are published in the special issue Advances in Space Research: "SpectralLine Shapes in Astrophysics and Related Phenomena."
Abstracts, Presentation and Photos

Previous 8th SCSLSA
(Divčibare, 6 - 10, June, 2011)

Procceedings of the 8th SCSLSA are published in **Baltic Astronomy** vol. 20, no.3-4, 2011 [contents]

Procceedings of the special session "Spectral Lines and Black Holes" are published in New Astronomy Reviews, 2012
Abstracts, Presentation and Photos

Previous 7th SCSLSA
(Zrenjanin, 15 - 19, June, 2009)

Procceedings of the 7th SCSLSA can be found in New Astronomy Reviews, 2009
Abstracts, Program and Photos

Previous 6th SCSLSA
(Sremski Karlovci, 11 - 15, June, 2007)

Scientific Rationale

The spectral lines, their widths, and, more generally, the shapes, are powerful tools for emitting/absorbing gas diagnostics in different astrophysical objects, (from the Solar system to the most distant objects in the Universe - quasars. The emission/absorption lines of astrophysical objects are produced over a wide range of distances from an observer and under a wide range of physical and kinematic conditions. Therefore, in astrophysical objects the lines from X-ray (e.g. Fe Ka) to the radio (e.g., the radio recombination lines) wavelength range have been observed. On the other hand, the experimental and theoretical investigations of laboratory plasma have been used in spectroscopic astrophysical research; in particular, the same atomic data are needed for line-shape calculations. This conference will bring together astronomers (observers and theoreticians) and physicists from Serbia and elsewhere to review the present stage of research, with the aim of improving our knowledge in this field, and to better understand the significance of emission/absorption lines for future astrophysical investigations.

The program will focus on:

- Stellar and interstellar spectral lines
- Spectral line phenomena in extragalactic objects
- Spectral lines in laboratory and general plasma

This is the 12th conference in the series. The official website of the conference is http://servo.aob.rs/scslsa12/ or http://www.scslsa.matf.bg.ac.rs. All materials (programme, talks, presentations, photos, etc.) from the previous meetings are available at http://servo.aob.rs/eeditions/SCSLSA.php through Serbian Virtual Observatory (http://servo.aob.rs).

****

Scientific Organizing Committee

Chairs:
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Evgeny Stambulchik (Weizmann Institute of Science, Israel)

Victor Afanasiev (Special Astrophysical Observatory, Russian Academy of Science, Russia)
Evaggelia Lyrazi (University of Athens, Greece)
Milan S. Dimitrijević (Astronomical Observatory, Belgrade, Serbia)
Darko Jevremović (Astronomical Observatory, Belgrade, Serbia)
Wolfram Kollatschny (Institute of Astrophysics, University of Goettingen, Germany)
Evencio Mediavilla (Instituto de Astrofísica de Canarias, Spain)
Gillian Peach (University College, London, United Kingdom)
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Jagoš Purić (Faculty of Physics, University of Belgrade, Serbia)
Sylvie Sahal-Bréchot (Observatoire de Paris-Meudon, France)
Vladimir Srećković (Institute of physics, Serbia)
Jack Sulentic (Instituto de Astrofísica de Andalucia, Spain)
Roland Stamm (Aix-Marseille Universit'e, France)

Local Organizing Committee

Chair:
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Maša Lakičević (Faculty of Mathematics, University of Belgrade)
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Saša Simić (Faculty of Sciences, Department of Physics, University of Kragujevac)

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email subject: SCSLSA12

Organized by: Faculty of Mathematics, University of Belgrade

Co-organizer: Astronomical Observatory Belgrade

Venue

To be anounced.

Procceedings of the 6th SCSLSA can be found in
AIP Conference Proceedings
Abstracts, Presentation, Program and Videos

Previous 5th SCSLSA
(Vršac, 6 - 10, June, 2005)

Procceedings of the 5th SCSLSA can be found in
Mem.S.A.It
Program, Abstract and Photos

Previous 4th SCSLS
(Aranđelovac, 10 - 15, October, 2003)

Procceedings of the 4th SCSLS can be found in
Publ. Astron. Obs. Belgrade No. 76.
Program, Papers and Photos

Previous 3rd YuCSLS
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Journal of Research in Physics,
SPECIAL ISSUE Contributed Papers of III YuCSLS,
Volume 28, Number 3, 1999. Proceedings and Photos

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Procceedings of the 2nd YuCSLS can be found in
Publ. Astron. Obs. Belgrade No. 57.
Proceedings and Photos

Previous 1st YuCSLS
(Krivaja, 11 - 14, September, 1995)

Procceedings of the 1st YuCSLS can be found in
Publ. Astron. Obs. Belgrade No. 50.
Papers, Program and Conference Photo

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7. Одсек за физику плазме и јонизованих гасова (9)

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Weather in Belgrade

23°
10°

Monday	26° 10°
Tuesday	30° 13°
Wednesday	25° 13°

theweather.com +info

Latest News

Group photo uploaded

March 30th, 2015

Local information and program updated

March 27th, 2015

If needed contact Darko @ +381628373385

List of participants updated

March 26th, 2015

Invitations to attend the meeting sent by e-cost

March 25th, 2015

Preregistration Closed

March 25th, 2015

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Tentative list of participants

March 10th, 2015

This is the list of people who expressed wish to attend the meetings. No approval of any

cost has been made yet.
Updated March 17th

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March 5th, 2015

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March 5th, 2015

If you are interested to participate in this meeting please preregister here. Details about the actual registration will be communicated soon.

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XI BULGARIAN-SERBIAN ASTRONOMICAL CONFERENCE 14 - 18 MAY, 2018, BELOGRADCHIK, BULGARIA

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XI BULGARIAN-SERBIAN ASTRONOMICAL CONFERENCE

14 - 18 MAY, 2018, BELOGRADCHIK, BULGARIA

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d book of abstracts, the welcome cocktail and coffee breaks. The payment is due upon registration at the Conference and

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The deadline for REGISTRATION
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X SERBIAN-BULGARIAN ASTRONOMICAL CONFERENCE

May 30 - June 3, 2016, Belgrade, Serbia

BOOK OF ABSTRACTS

Eds. Milan S. Dimitrijević and Milcho K. Tsvetkov

BELGRADE, 2016

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On the back cover: Moon landscape, Ivanka Ivanova Nikolova.
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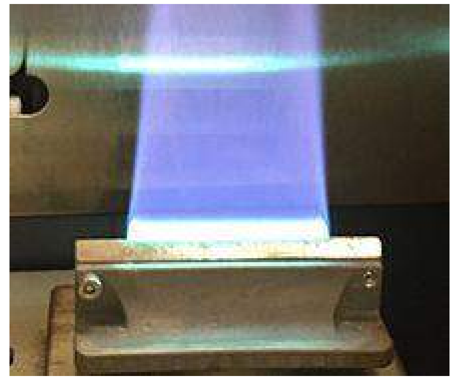
3.6. Утицајност научних резултата

WIKIPEDIA

Chemi-ionization

Chemi-ionization is the formation of an ion through the reaction of a gas phase atom or molecule with an atom or molecule in an excited state while also creating new bonds.[1][2] This process is helpful in mass spectrometry because it creates unique bands that can be used to identify molecules.[3] This process is extremely common in nature as it is considered the primary initial reaction in flames.



The majority of chemi-ionization occurs in the base of the flame.

Contents

History
Reactions
Astrophysical implications
See also
References

History

The term chemi-ionization was coined by Hartwell F. Calcote in 1948 in the Third Symposium on Combustion and Flame, and Explosion Phenomena.[4] The Symposium performed much of the early investigation into this phenomenon in the 1950s. The majority of the research on this topic was performed in the 1960s and '70s. It is currently seen in many different ionization techniques used for mass spectrometry.[5][6]

Reactions

Chemi-ionization can be represented by

$$G^* + M \longrightarrow M^{+\bullet} + e^- + G$$

where G is the excited state species (indicated by the super-scripted asterisk), and M is the species that is ionized by the loss of an electron to form the radical cation (indicated by the super-scripted "plus-dot").

The most common example of A-type chemi-ionization occurs in hydrocarbon flame. The reaction can be represented as

$$O + CH \longrightarrow HCO^+ + e^-$$ [7]

This reaction is present in any hydrocarbon flame and can account for deviation in the amount of expected ions from thermodynamic equilibrium.[8] This can then lead to B-type chemi-ionization which can be represented as

$$\mathrm{HCO^+ + e^- \longrightarrow \begin{pmatrix} H_3O^+ \\ C_3H_3 \end{pmatrix} + M \longrightarrow M^+ + products}$$

As well as

$$\mathrm{CH + O + M \longrightarrow CHO + M^* \longrightarrow M + } hv$$

Where M* represents an excited state metal. This reaction illustrates the light generated by the chemi-ionization reaction resulting in the light we know from flames.[9]

Astrophysical implications

Chemi-ionization has been postulated to occur in the hydrogen rich atmospheres surrounding stars. This type of reaction would lead to many more excited hydrogen atoms than some models account for. This affects our ability to determine the proper optical qualities of solar atmospheres with modeling.[10]

See also

- Penning ionization
- Associative ionization
- Charge-exchange ionization

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WIKIPEDIA

Rydberg atom

A **Rydberg atom** is an excited atom with one or more electrons that have a very high principal quantum number.[1][2] These atoms have a number of peculiar properties including an exaggerated response to electric and magnetic fields,[3] long decay periods and electron wavefunctions that approximate, under some conditions, classical orbits of electrons about the nuclei.[4] The core electrons shield the outer electron from the electric field of the nucleus such that, from a distance, the electric potential looks identical to that experienced by the electron in a hydrogen atom.[5]

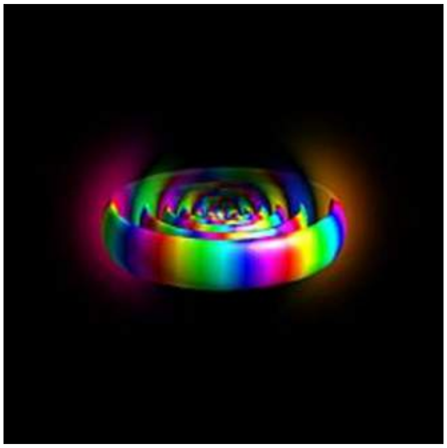

Figure 1: Electron orbital of a Rydberg atom with n=12. Colors show the quantum phase of the highly excited electron.

In spite of its shortcomings, the Bohr model of the atom is useful in explaining these properties. Classically, an electron in a circular orbit of radius r, about a hydrogen nucleus of charge $+e$, obeys Newton's second law:

$$\mathbf{F} = m\mathbf{a} \Rightarrow \frac{ke^2}{r^2} = \frac{mv^2}{r}$$

where $k = 1/(4\pi\varepsilon_0)$.

Orbital momentum is quantized in units of $\hbar$:

$$mvr = n\hbar.$$

Combining these two equations leads to Bohr's expression for the orbital radius in terms of the principal quantum number, n:

$$r = \frac{n^2\hbar^2}{ke^2m}.$$

It is now apparent why Rydberg atoms have such peculiar properties: the radius of the orbit scales as n^2 (the n = 137 state of hydrogen has an atomic radius ~1 µm) and the geometric cross-section as n^4. Thus Rydberg atoms are extremely large with loosely bound valence electrons, easily perturbed or ionized by collisions or external fields.

Because the binding energy of a Rydberg electron is proportional to $1/r$ and hence falls off like $1/n^2$, the energy level spacing falls off like $1/n^3$ leading to ever more closely spaced levels converging on the first ionization energy. These closely spaced Rydberg states form what is commonly referred to as the *Rydberg series*. **Figure 2** shows some of the energy levels of the lowest three values of orbital angular momentum in lithium.

Contents

History

In the hydrogen atom, the pure $1/r$ Coulomb potential does not couple Stark states from adjacent n-manifolds resulting in real crossings as shown in **figure 5**. The presence of additional terms in the potential energy can lead to coupling resulting in avoided crossings as shown for lithium in **figure 6**.

Applications and further research

Precision measurements of trapped Rydberg atoms

The radiative decay lifetimes of atoms in metastable states to the ground state are important to understanding astrophysics observations and tests of the standard model.[18]

Investigating diamagnetic effects

The large sizes and low binding energies of Rydberg atoms lead to a high magnetic susceptibility, χ. As diamagnetic effects scale with the area of the orbit and the area is proportional to the radius squared ($A \propto n^4$), effects impossible to detect in ground state atoms become obvious in Rydberg atoms, which demonstrate very large diamagnetic shifts.[19]

Rydberg atoms exhibit strong electric-dipole coupling of the atoms to electromagnetic fields and has been used to detect radio communications.[20][21]

In plasmas

Rydberg atoms form commonly in plasmas due to the recombination of electrons and positive ions; low energy recombination results in fairly stable Rydberg atoms, while recombination of electrons and positive ions with high kinetic energy often form autoionising Rydberg states. Rydberg atoms' large sizes and susceptibility to perturbation and ionisation by electric and magnetic fields, are an important factor determining the properties of plasmas.[22]

Condensation of Rydberg atoms forms Rydberg matter, most often observed in form of long-lived clusters. The de-excitation is significantly impeded in Rydberg matter by exchange-correlation effects in the non-uniform electron liquid formed on condensation by the collective valence electrons, which causes extended lifetime of clusters.[23]

In astrophysics

It has been suggested[24] that Rydberg atoms are common in interstellar space and could be observed from earth. Since the density within interstellar gas clouds is many orders of magnitude lower than the best laboratory vacuums attainable on Earth, Rydberg states could persist for long periods of time without being destroyed by collisions.

Strongly interacting systems

Due to their large size, Rydberg atoms can exhibit very large electric dipole moments. Calculations using perturbation theory show that this results in strong interactions between two close Rydberg atoms. Coherent control of these interactions combined with their relatively long lifetime makes them a suitable candidate to realize a quantum computer.[25] In 2010 two-qubit gates were achieved experimentally.[26][27] Strongly interacting Rydberg atoms also feature quantum critical behavior, which makes them interesting to study on their own.[28]

Current research directions

Since 2000's Rydberg atoms research is encompasses broadly three directions: sensing, quantum optics and quantum simulation [2]. High electric dipole moments between Rydberg atomic states are used for radiofrequency and teraherz sensing and imaging[29][30], including non-demolition measurements of individual microwave photons[31]. Electromagnetically induced transparency was used in combination with energy level shifts due to interactions between two atoms excited in Rydberg state to provide medium that exhibits strongly nonlinear behavior for at the level of individual optical photons[32][33]. The tuneable interaction between Rydberg states, enabled also first quantum simulation experiments[34][35].

Classical simulation

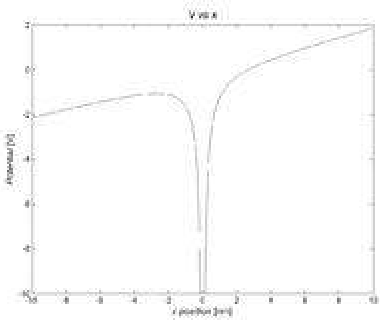

Figure 7. Stark - Coulomb potential for a Rydberg atom in a static electric field. An electron in such a potential feels a torque that can change its angular momentum.

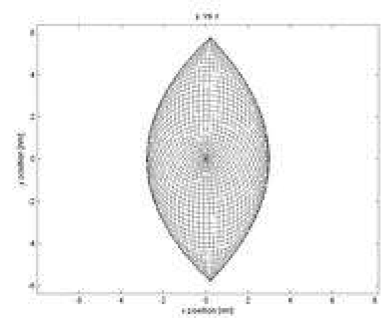

Figure 8. Trajectory of the electron in a hydrogen atom in an electric field E = -3 x 10^6 V/m in the *x*-direction. Note that classically all values of angular momentum are allowed; **figure 4** shows the particular orbits associated with quantum mechanically allowed values. See the animation.

A simple $1/r$ potential results in a closed Keplerian elliptical orbit. In the presence of an external electric field Rydberg atoms can obtain very large electric dipole moments making them extremely susceptible to perturbation by the field. **Figure 7** shows how application of an external electric field (known in atomic physics as a Stark field) changes the geometry of the potential, dramatically changing the behaviour of the electron. A Coulombic potential does not apply any torque as the force is always antiparallel to the position vector (always pointing along a line running between the electron and the nucleus):

$$|\tau| = |\mathbf{r} \times \mathbf{F}| = |\mathbf{r}||\mathbf{F}|\sin\theta,$$

$$\theta = \pi \Rightarrow \tau = 0.$$

With the application of a static electric field, the electron feels a continuously changing torque. The resulting trajectory becomes progressively more distorted over time, eventually going through the full range of angular momentum from $L = L_{\mathrm{MAX}}$, to a straight line L=0, to the initial orbit in the opposite sense $L = -L_{\mathrm{MAX}}$.[36]

The time period of the oscillation in angular momentum (the time to complete the trajectory in **figure 8**), almost exactly matches the quantum mechanically predicted period for the wavefunction to return to its initial state, demonstrating the classical nature of the Rydberg atom.

See also

- Heavy Rydberg system
- Old quantum theory

- Quantum chaos
- Rydberg molecule
- Rydberg polaron

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3.8. Уводна предавања на конференцијама и друга предавања

11th Serbian Conference on Spectral Line Shapes in Astrophysics
Šabac, Serbia, August 21-25, 2017

Belgrade, 14th September, 2017

We certify that Vladimir Srećković has presented the work ***Atom-Atom and Ion-Atom collisional processes: Modeling of stellar atmospheres*** as an Invited Lecture in the **11th Serbian Conference on Spectral Line Shapes in Astrophysics** International Conference held in Šabac, Serbia, August 21-25, 2017 (http://servo.aob.rs/scslsa11/).

Prof. dr Luka Č. Popović

Chairman of the Scientific Organizing Commettee
Astronomical observatory Belgrade,
Department of astronomy
Faculty of Mathematics
University of Belgrade

11th Serbian Conference on Spectral Line Shapes in Astrophysics

Šabac, Serbia, August 21-25, 2017

- Home
- Programme
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- Accomodation
- Proceedings
- Photos

Previous 10th SCSLSA
(Srebrno Jezero, 15 - 19 June, 2015)

Selected papers which have been presented at 10th SCSLSA are published in the special issue Journal of Astrophysics and Astronomy
Abstracts, Presentation and Photos

Previous 9th SCSLSA
(Banja Koviljača, 13 - 17 May, 2013)

Selected papers which have been presented at 9th SCSLSA are published in the

Programme of 11th SCSLSA

Monday, August 21, 2017

16:00 - 17:00 ***Arrival and registration of participants***

17:00 - 19:00 ***Poster presentation***

19:00 - 21:00 ***Welcome Cocktail***

Tuesday, August 22, 2017

Opening and plenary talks
Chair: L. C. Popovic

8:50 - 9:00	***Opening ceremony***	
9:00 - 9:30	***Evgeny Stambulchik***	*A study of supersonic turbulence in stagnating plasmas*
9:30 - 10:00	***Maja Vuckovic***	*Irradiation effects in spectra of close binary systems*
10:00 - 10:30	***Jian-Min Wang***	*Super-Eddington accreting massive black holes in active galactic nuclei*
10:30 - 11:00	***Coffee break***	

Spectral line phenomena in extragalactic objects
Chair: M.S. Dimitrijevic

11:00 - 11:30	***Wolfram Kollatschny***	*Optical spectroscopy of the changing look AGN HE1136-2304*
11:30 - 12:00	***Alberto Rodriguez-Ardila***	*Feedback in the central parsec of active galactic nuclei mapped from high-ionisation line*

special issue Advances in Space Research: "SpectralLine Shapes in Astrophysics and Related Phenomena." Abstracts, Presentation and Photos

Previous 8th SCSLSA (Divčibare, 6 - 10, June, 2011)

Procceedings of the 8th SCSLSA are published in **Baltic Astronomy** vol. 20, no.3-4, 2011 [contents]

Procceedings of the special session "Spectral Lines and Black Holes" are published in New Astronomy Reviews, 2012 Abstracts, Presentation and Photos

Previous 7th SCSLSA (Zrenjanin, 15 - 19, June, 2009)

Procceedings of the 7th SCSLSA can be found in New Astronomy Reviews, 2009 Abstracts, Program and Photos

12:00 - 12:20	***Sergei Kotov***	*Active galactic nuclei search*
12:20 - 12:40	***Dmitry Oparin***	*Kinematics of ionized gas outflows caused by star formation*
12:40 - 13:00	***Marko Stalevski***	*Revealing the structure of AGN in Circinus*
13:00 - 15:00	***Working lunch***	

Spectral line shapes phenomena in plasma
Chair: J. Rosato

15:00 - 15:30	***Aleksandar Milosavljevic***	*High resolution soft X-ray spectroscopy of dilute species (same for astrophysics) at the Pleiades beam line*
15:30 - 15:45	***Cristina Yubero***	*On the gas temperature determination in Ar plasma at atmospheric pressure from broadenings of atomic emission lines*
15:45 - 16:00	***Jose Munoz***	*Determination of gas temperature in microwave discharges sustained in Argon-Neon mixtures by using pressure broadening spectral lines*
16:00 - 16:30	***Coffee break***	

Spectral line shapes phenomena in plasma
Chair: V.L. Afanasiev

16:30 - 17:00	***Paola Marziani***	*Black hole mass estimates from high-ionisation lines: Breaking a taboo?*
17:00 - 17:20	***Masa Lakicevic***	*The connections between the mid-infrared and optical spectral line and continuum characteristics of AGNs: AGN vs. starburst emission*
17:20 - 17:40	***Giovanni LaMura***	*Models of emission line profiles and spectral energy distributions to characterize the multiple frequency properties of active galactic nuclei*
17:40 - 18:00	***Dimitris Stathopoulos***	*Long term variability of Si IV and C IV broad absorption troughs of 10 BALQSOs*

Wednesday, August 23, 2017

Special session: Line shapes in astrophysics and fusion plasma research: Common challenges
Chair: R. Stamm

9:30 - 10:00	***Joel Rosato***	*Line shape modeling for magnetic white dwarf and tokamak edge plasmas: Common chalenges*
10:00 - 10:20	***Ibtissem Hannachi***	*Effects of turbulence on line shapes in astrophysical and fusion plasmas*

Spectral line phenomena in extragalactic objects (line variability)
Chair: J.M. Wang

11:10 - 11:30	***Patricia Rojas Lobos***	*Reverberation of optical polarisation in AGN*
11:30 - 11:50	***Sasa Simic***	*Long-term monitoring super-massive binary candidates: variability in the broad line and continuum*
11:50 - 12:10	***Edi Bon***	*Testing a binary black hole hypothesis for the case of NGC 5548*
12:10 - 13:30	***Working Lunch***	
13:35 -	***Excursion***	*Visiting 'Sirmium'*

Thursday, August 24, 2017

Collisions and spectral line shapes (in honour of Milan S. Dimitrijevic's 70th birthday)
Chair: G. Peach

9:30 - 10:00	***Sylvie Sahal-Brechot, Nikola Konjevic, Gillian Peach, Luka Popovic***	*Scientific contribution of M.S. Dimitrijevic and scientific collaboration*
10:00 - 10:30	***Roland Stamm***	*Stark broadening from impact theory to simulations*
10:30 - 11:00	***Coffee break***	

Collisions and spectral line shapes (in honour of Milan S. Dimitrijevic's 70th birthday)
Chair: E. Stambulchik

11:00 - 11:30	***Vladimir Sreckovic***	*Atom-Atom and Ion-Atom collisional processes: Modeling of stellar atmospheres*
11:30 - 11:50	***Antonios Antoniou***	*Time-scale variation of the components that form the CIV and SiIV DACs in the UV spectrum of the O-star HD93521*

Previous 6th SCSLSA
(Sremski Karlovci, 11 - 15, June, 2007)

Procceedings of the 6th SCSLSA can be found in AIP Conference Proceedings
Abstracts, Presentation, Program and Videos

Previous 5th SCSLSA
(Vršac, 6 - 10, June, 2005)

Procceedings of the 5th SCSLSA can be found in Mem.S.A.It
Program, Abstract and Photos

Previous 4th SCSLS
(Aranđelovac, 10 - 15, October, 2003)

Procceedings of the 4th SCSLS can be found in Publ. Astron. Obs. Belgrade No. 76.
Program, Papers and Photos

Previous 3rd YuCSLS
(Brankovac, Fruška Gora, 4 - 6, October, 1999)

Procceedings of

the 3rd YuCSLS can be found in Journal of Research in Physics, SPECIAL ISSUE Contributed Papers of III YuCSLS, Volume 28, Number 3, 1999.
Proceedings and Photos

Previous 2nd YuCSLS
(Bela Crkva, 29. September - 2. October, 1997)

Procceedings of the 2nd YuCSLS can be found in Publ. Astron. Obs. Belgrade No. 57.
Proceedings and Photos

Previous 1st YuCSLS
(Krivaja, 11 - 14, September, 1995)

Procceedings of the 1st YuCSLS can be found in Publ. Astron. Obs. Belgrade No. 50.
Papers, Program and Conference Photo

Sponsors

1. *Ministry of Education, Science and Technological Development*

11:50 - 12:10	***Zlatko Majlinger***	*Regularities and systematic trends on ZrIV Stark widths*
12:10 - 12:30	***Nenad Milovanovic***	*Calculation of Stark broadening parameters of SII multiplets and stellar models analysis*
12:30 - 13:00	***Milan Dimitrijevic and Norbert Przybilla***	*On the Stark broadening of Si III spectral lines in B type stars*
13:00 - 15:00	***Working lunch***	

Spectral line shapes in astrophysics: databases
Chair: E. Danesis

15:00 - 15:30	***Bratislav Marinkovic***	*Electron scattering data and collisional databases needed for understanding processes in comas*
15:30 - 16:00	***Robert Beuc***	*Spectra of diatomic molecules: From cold to hot*
16:00 - 16:20	***Dimitrios Tzimeas***	*ASTA software: An advanced spectral analysis algorithmic environment for emission and absorption line spectra*
16:20 - 16:40	***Aleksandra Nina***	*Spatial behaviour of D-region plasma parameters during the dominant influence of Lyα line after a Solar X-ray flare*
16:40 - 17:10	***Coffee break***	

Collisions and spectral line shapes
Chair: V. Sreckovic

17:10 - 17:30	***Milos Skocic***	*Uncommon line shapes of CuI lines in laser induced plasma*
17:30 - 17:50	***Kamel Ahmed-Touati***	*Doppler broadening of spectral line shapes in relativistic plasmas*
17:50 - 18:10	***Sonja Vidojevic***	*Automatic shape recognition of type III radio bursts in Solar wind dynamical radio spectra*
18:10 - 18:30	***Med Tayeb Meftah***	*Contribution of Lienard-Wiechert potential to the electron broadening of spectral line shapes in plasmas*

18:30 - 18:50	***Joris Scheers***	*Charge-state-resolved studies of Sn plasma using laser induced breakdown spectroscopy*

19:30 - 24:00	***CONFERENCE DINNER***

Friday, August 25, 2017

Line shapes in astrophysics (surveys and variability)
Chair: W. Kollatschny

10:00 - 10:30	***Serguei Dodonov***	*1-m Schmidt telescope reconstruction: Scientific goals and first results*
10:30 - 11:00	***Marko Krco***	*Fast telescope capabilities and the upcoming multi-beam survey*
11:00 - 11:30	***Coffee break***	

Spectral line phenomena in extragalactic objects
Chair: P. Jovanovic

11:30 - 11:50	***Alla Shapovalova & Victor Afanasiev***	*Progress report on the SAO optical monitoring of type 1 AGNs*
11:50 - 12:10	***Nemanja Rakic***	*Spectral line characteristics of AGNs in the frame of the intrinsic Baldwin effect*
12:10 - 12:30	***Elena Shablovinskaya***	*Photometric and polarimetric interpretation of blazar AO0235+164 behaviour*
12:30 - 12:50	***Djordje Savic***	*Super massive binary black hole and polarisation in the broad lines*
12:50 - 13:00	***Closing ceremony***	
13:00 - 14:00	***Working lunch***	
14:00 -	***Departure to Belgrade***	

***** List of posters *****

P01:	R. Aloui, H. Elabidi, S. Sahal-Brechot and M. S. Dimitrijevic	*QUANTUM AND SEMICLASSICAL STARK WIDTHS OF Ar VII SPECTRAL LINES*

P02	A. Avci, M. Tanriver and F. F. Ozeren	*THE SPECTRAL ANALYSIS OF CW Cep FOR SURROUNDING STRUCTURE*
P03:	S. Banerjee, M. Nrisimhamurty, G. Aravind, P. C. Deshmukh,V. Radojevic, S. T. Manson	*SPECTRAL WIDTHS AND LINESHAPES OF AUTOIONIZATION RESONANCES IN THE NEON ISOELECTRONIC SEQUENCE*
P04:	V. Borka Jovanovic, P. Jovanovic, D. Borka and S. Capozziello	*SOLVING THE MISSING MATTER PROBLEM AT GALACTIC SCALES THROUGH A NEW FUNDAMENTAL GRAVITATIONAL RADIUS*
P05:	E. Caux, J.M. Glorian, M. Boiziot, S. Bottinelli and C. Vastel	*CASSIS, a VO-TOOL SOFTWARE PACKAGE TO ANALZYE HIGH SPECTRAL RESOLUTION OBSERVATIONS*
P06:	M. S. Dimitrijevic, A. Valjarevic and S. Sahal-Brechot	*SEMICLASSICAL STARK BROADENING PARAMETERS OF Ar VII SPECTRAL LINES*
P07:	M. S. Dimitrijevic, Z. Simic, A. Valjarevic, C. Yubero	*STARK WIDTHS OF Na IV SPECTRAL LINES*
P08:	D. K. Efimov, N. N. Bezuglov, M. S. Dimitrijevic, A. N. Klyucharev, V. A. Sreckovic and F. Fuso	*NONLINEAR SPECTROSCOPY OF ALKALI ATOMS IN COLD MEDIA*
P09:	H. Feng and Jianjun Chen	*THE PROFILES OF LAMOST ARC LINES*
P10:	A. Garcia Lopez, P. Marziani, M. D'Onofrio, A. Del Olmo	*THE Hβ LINE PROFILE ALONG THE QUASAR MAIN SEQUENCE*
P11:	R. Hamdi, N. Ben Nessib, S. Sahal-Brechot and M.S. Dimitrijevic	*STARK WIDTHS OF Ar II SPECTRAL LINES IN THE ATMOSPHERES OF SUBDWARF B STARS*
P12:	Lj. M. Ignjatovic and V. A. Sreckovic	*THE SCREENING CHARACTERISTICS OF THE ASTROPHYSICAL PLASMAS: THREE-COMPONENT SYSTEMS*
P13:	N. Kieu, J. Rosato, R. Stamm, J. Kovacevic-Dojcinovic , M. S. Dimitrijevic , L. C. Popovic and Z. Simic	*A NEW ANALYSIS OF STARK AND ZEEMAN EFFECTS ON HYDROGEN LINES IN MAGNETIZED DA WHITE DWARFS*
P14:	S. Marceta Mandic , M. Lakicevic , S. Bianchi , A. De Rosa , J. Kovacevic-Dojcinovic and L. C. Popovic	*CONNECTION BETWEEN X-RAY, OPTICAL AND IR SPECTRAL CHARACTERISTIC FOR A SAMPLE OF AGNs*

P15:	M. M. Martinovic	*ESTIMATION OF THE QUASI THERMAL NOISE SPECTRUM AROUND THE PLASMA FREQUENCY*
P16:	A. Nina, V. M. Cadez, J. Bajcetic, S. T. Mitrovic and L. C. Popovic	*TIME EVOLUTION OF X RADIATION SPECTRUM DURING A SOLAR X-RAY FLARE*
P17:	E. Perez-Hernandez, A. Kovacevic, L. C. Popovic, A. I. Shapovalova, W. Kollatschny and D. Ilic	*TIME DELAYS EVOLUTION AND PERIODICITIES OF THE CONTINUUM AND EMISSION LINES OF 4 TYPE 1 AGN*
P18:	M. A. Pursiainen, P. Jovanovic, and L. C. Popovic	*THE RELATIVISTIC Fe Kα LINE IN TYPE 1 AGN: REASONS FOR THE LACK OF DETECTION*
P19:	J. Rosato, N. Bonifaci and R. Stamm	*SPECTROSCOPIC DIAGNOSTICS OF THE ELECTRON DENSITY IN CORONA DISCHARGES*
P20:	N. M. Sakan, V. A. Sreckovic, Z. Simic and M. S. Dimitrijevic	*THE APPLICATION OF THE CUT-OFF COULOMB MODEL POTENTIAL FOR THE CALCULATION OF BOUND - BOUND STATE TRANSITIONS*
P21:	V. A. Sreckovic, M. S. Dimitrijevic, Z. Simic and N. M. Sakan	*THE CROSS SECTIONS AND THE RATE COEFFICIENTS OF THE FREE-FREE ABSORPTION PROCESSES IN STELLAR ATMOSPHERES*
P22:	V. A. Sreckovic and D. M. Sulic	*SOLAR X RAY FLARES AND THEIR IMPACT ON THE IONOSPHERE*
P23:	V. A. Sreckovic, Lj. M. Ignjatovic, D. Jevremovic, V. Vujcic and M. S. Dimitrijevic	*RADIATIVE AND COLLISIONAL MOLECULAR DATA AND VIRTUAL LABORATORY ASTROPHYSICS: STATE OF ADVANCEMENT AND PERSPECTIVES*
P24:	R. Venger, T. Tmenova, F. Valensi, A. Veklich, Y. Cressault, V. Boretskij	*DETAILED INVESTIGATION OF THE ELECTRIC DISCHARGE PLASMA BETWEEN COPPER ELECTRODES IMMERSED INTO WATER*

Conference Program

The program is available for download.

Monday, October 16

16:00	*The 130th anniversary of the Astronomical Observatory of Belgrade (Solemn Academy)* *Place: Serbian Academy of Sciences and Arts - SASA Main Hall (2nd floor)*
17:00 19:00	*Welcome cocktail - SASA (1st floor - cafeteria)*

Tuesday, October 17

Chair: L. Č. Popović - Opening and talks devoted to anniversaries place: Main Hall (2nd floor)	
08:00	Registration
09:00	Opening ceremony
09:30	**Gojko Djurašević**: Foundation of Astronomical Observatory in 1887 and role of Milan Nedeljković
10:00	**Zoran Knežević**: 125 Years from the Birth of Academician V. Mišković
10:30	*Coffee break*
Chair: D. Urošević - Extragalactic astronomy and cosmology place: Main Hall (2nd floor)	
11:00	**Stefano Bianchi**: Challenges to the AGN Unified Model
11:30	**Dragana Ilić**: Spectroscopy and Spectropolarimetry of AGNA: from Observations to Modelling
12:00	**Srdjan Samurović**: Visible and Invisible Matter in Nearby Galaxies: Theory and Observations
12:30	**Marko Stalevski**: Peculiar Mid-Infrared Morphology of Active Galactic Nucleus in Circinus
13:00	*Lunch time*
Chair: Z. Knežević - 125th anniversary of the birth of V. Mišković place: Hall 2, 1st floor	
15:00	**Vojislava Protić - Benišek**: Academician Vojislav V. Mišković (1892 -1976): Life and Work of the Great Serbian Astronomer
15:30	**Natalija Janc**: Correspondence of Vojislav V. Mišković about his Doctorate with Milutin Milanković, Miodrag Ibrovac and Oton Kučera
15:50	**Slobodan Ninković**: Etudes de statistique stellaire - Mišković's thesis
16:10	**Milica Čolaković & Sanja Petrović**: Vojislav Mišković's traces in the Library of the Serbian Academy of Sciences and Arts
16:30	*Coffee break*

Chair: G. Djurašević - History, philosophy and teaching of astronomy
place: Hall 2, 1st floor

17:00	**Veselka Trajkovska**: Milan G. Nedeljković - the Founder and First Director of Astronomical Observatory in Belgrade
17:20	**Milan S. Dimitrijević**: Astronomical Work of Anatoly Anatolyevich Mihajlov (1941-2016)
17:40	**Olga Atanacković**: Astronomy Education in Serbia 2014-2017
18:00	**Dušan Vukadinović**: Department of Astronomy at Petnica Science Center: 2013-2017
18:15	**Zoran Tomić**: Project of Promotion of Astronomy Sky is the Limit

Wednesday, October 18

Chair: S. Samurović - Stellar physics and physics of the interstellar medium
place: Hall 2, first floor

09:30	**John Raymond**: Collisionless Shock Waves in the Solar Corona and Supernova Remnants
10:00	**Dušan Onić**: Emission nebulae: structure and evolution
10:30	**Olivera Latković**: Observational studies of close binary stars
11:00	**Aleksandra Ćiprijanović**: Contribution of Galaxies and Galaxy Clusters to the Diffuse Gamma-Ray Background
11:20	*Coffee break*

Chair: O. Atanacković - Extragalactic astronomy and cosmology
place: Hall 2, first floor

11:50	**Debora Šijački**: Cosmological simulations of structure formation: a critical view
12:20	**Nemanja Martinović**: Reconstructing Formation and Evolution of Compact Dwarf Candidates in Clusters of Galaxies
12:40	**Majda Smole**: Early Growth of Supermassive Black Holes and Gravitational Wave Recoil
13:00	**Jelena Stanković**: New cosmological solutions in Nonlocal Modified Gravity
13:20	*Lunch time*

Chair: M.S. Dimitrijević - Astrophysical spectroscopy and instruments
place: Hall 2, first floor

15:00	**Slobodan Jankov**: Regulus observed with VLTI/AMBER
15:20	**Ana Vudragović**: Spectroscopical and Photometrical Analysis of Nearby Galaxies of Different Morphological Types
15:40	**Vladimir Srećković**: Radiative and Collisional Atomic/Molecular Data for Astrophysics
16:00	**Oliver Vince**: The First Year of the Milankovic telescope
16:20	*Coffee break*

Chair: N. Pejović - History, philosophy and teaching of astronomy
place: Hall 2, first floor

16:50	**Nataša Stanić**: The Nature of Educational Activities in Planetarium and its Contribution to the Advancement of Astronomical Education
17:10	**Sonja Vidojević**: Astronomy Competitions and their Role in Astronomy Education in Serbia
17:30	**Dragoslav Stoiljković**: Boscovich's Comprehesion of Absolute and Relative Movement

Thursday, October 19

Chair: Z. Cvetković - Astrometry, dynamical astronomy, and planetology
place: Hall 2, 1st floor

09:30	**Dmitry Bisikalo**: Gaseous envelopes of hot Jupiter
10:00	**Rade Pavlović**: Dynamics and Kinematics of Celestial Bodies and Systems

10:30	**Viktor Radović**: Excluding Interlopers from Asteroid Families
10:50	**Ivana Milić-Žitnik**: Impact of Yarkovsky Effect and Mean-Motion Resonances on Main Belt Asteroid's Transport
11:10	*Coffee break*
Chair: I. Vince - Stellar physics and physics of the interstellar medium place: Hall 2, 1st floor	
11:30	**Omar Tibolla**: Cosmic Ray Origin: Beyond the Standard Model(s). The Case of Pulsar Wind Nebulae and Unidentified Very High Energy Gamma-Ray Sources
12:00	**Tijana Prodanović**: Cosmic-Ray Acceleration in Galactic and its Implications
12:20	**Sladjana Knežević**: Revealing Shock and Cosmic-Ray Properties from Balmer Emission in Supernova Remnants: the Case of Tycho
12:40	**Milica Vučetić**: Optical Supernova Remnants and their Influence on Star Formation Rates Derived from Hα Emission
13:00	**Jovana Petrović**: Dissecting the Galactic TeV Excess
13:20	*Lunch time*
Chair: R. Pavlović - Astrometry, dynamical astronomy, and planetology place: Hall 2, 1st floor	
15:00	**Dušan Marčeta**: Possibilities and Optimization of Landing on the Southern Hemisphere of Mars
15:20	**Mihailo Martinović**: A study of quasi-thermal noise and shot noise in space plasmas
15:40	**Dejan Vujičić**: The Application of Nine Degrees of Freedom Sensor in Determination of Telescope Position
16:00	**Ištvan Vince**: Illuminance and Visibility at Twilights
16:20	*Coffee break*
Chair: S. Jankov - Stellar and galactic systems place: Hall 2, 1st floor	
17:00	**Vesna Borka Jovanović**: Tests of gravity at galactic and extragalactic scales: theory vs observations
17:30	**Lazar Živadinović**: Density Profile of the Milky Way: Comparison of Dynamical Model and Monte Carlo Method for Determining Stellar Space Densities
17:50	**Stefania Gravina**: Stellar kinematics around Galactic Center
18:10	**Anna D'Addio**: Testing extended theory of gravity by SgrA*
19:30	*CONFERENCE DINNER*

Friday, October 20

Chair: A. Kovačević - Interdisciplinary studies (astrobiology, astrochemistry, geophysics, atmospheric physics, and space astronomy) and simulations place: Hall 2, 1st floor	
10:00	**Zuzana Kanuchova**: Laboratory simulations of space weathering effects. Some applications
10:30	**Vladimir Djošović**: Probing the Galactic Habitability Time Scales
10:50	**Stanislav Milošević**: Influence of the Softening Length on Stability of Spiral Galaxies in N-Body Simulations
11:10	**Ana Mitrašinović**: Bar Detection in N-Body Simulations Using Fourier Analysis
11:30	*Coffe Break*
Chair: P. Jovanović - Gravitation and cosmology place: Hall 2, 1st floor	
12:00	**Žarko Mijajlović**: Is Cosmological Constant Transient Phenomena?
12:20	**Milan Milošević**: Braneworld Cosmology and Tachyon Inflation - RSII Numerical Models
12:40	**Ivan Dimitrijević**: Cosmological Perturbations in Nonlocal Gravity
13:00	*Assembly of the Serbian Astronomical Society*

14:30	*Excursion*

Saturday, October 21

Contact person: Milan Stojanović place: Astronomical Observatory, Volgina 7	
11:00 13:00	**Guided tour at Astronomical Observatory**

Poster presentation will be during the whole Conference (poster panels are in the front of the Conference Hall 2)

List of Posters:

1. A. B. Nedeljković
   NECESSITY OF RE-DEFINITION OF PLANET, AS PROPOSED BY ALAN STERN ET AL

2. A. Ćiprijanović, T. Prodanović and M. Z. Pavlović
   CONSTRAINING THE COLLECTIVE RADIO EMISSION OF LARGE SCALE ACCRETION SHOCKS

3. A. Nina, V.M. Čadež, L.Č. Popović, V. A. Srećković, J. Bajčetić, S.T. Mitrović, M. Radovanović, M. Todorović Drakul, A. Kolarski and S. Simić
   LOW IONOSPHERIC RESPONSE TO ASTRO-GEO-PHENOMENA

4. A. Vudragović, O. Vince, S. Samurović and M. Jovanović
   NEAR-INFRARED PHOTOMETRY OF THE NEARBY SPIRAL GALAXY NGC 2841

5. A.I. Klyuyeva, A.V. Belov and E.A. Eroshenko
   RIGIDITY SPECTRUM OF GALACTIC COSMIC RAYS VARIATIONS DURING THE FORBUSH EFFECTS

6. B. Krstin
   KORELACIJA ASTRONOMIJE I GEOGRAFIJE

7. B. Novaković, V. Radović and V. Đošović
   ASTEROID FAMILIES PORTAL: An online platform to study asteroid families

8. D.V. Lukić
   PROTOCOL FOR ACTIVE SETI IN SOL NEIGHBORHOOD

9. D.V. Lukić
   SEARCH FOR POSSIBLE EXOMOONS WITH FAST TELESCOPE

10. D.V. Lukić
    CAN WE AFFORD AN INTERSTELLAR FLIGHT?

11. G. Damljanović, S. Boeva, O. Vince, G. Latev, R. Bachev, M.D. Jovanović, Z. Cvetković and R. Pavlović
    OBSERVATIONS OF GAIA-FUN-TO FROM 2014 USING SERBIAN AND BULGARIAN TELESCOPES

12. Ž. Disterlo
    RADIO ODJEK DELTA AURIGIDS U PERIODU 2006-2016 GODINE

13. M. Stalevski
    The dust covering factor in active galactic nuclei

14. M.S. Dimitrijević, S. Sahal-Bréchot, N. Moreau
    THE STARK-B DATABASE, A NODE OF VIRTUAL ATOMIC AND MOLECULAR DATA CENTER (VAMDC)

15. A. Bajić and M.S. Dimitrijević
    OVID, FASTI, SUN AND STARS

16. M.S. Dimitrijević
    ON THE ASTRONOMICAL SYMBOLS ON ROMAN REPUBLICAN AND IMPERIAL COINS

17. M.D. Jovanović, G. Damljanović and O. Vince
    R AND V BAND MONITORING OF QUASARS THAT ARE IMPORTANT FOR THE LINK BETWEEN

ICRF AND THE FUTURE GAIA CELESTIAL REFERENCE FRAME

18. N. Todorović
THE FINE STRUCTURE OF CHAOS IN THE SOLAR SYSTEM

19. N. Martinović, M. Micic, A. Mitrašinović, M. Smole, S. Milošević
WHAT CAN ECCENTRICITIES OF MEMBERS OF CLUSTERS OF GALAXIES TELL US ABOUT CLUSTER EVOLUTION?

20. N. Martinović, M. Micic, A. Mitrašinović, S. Milošević, M. Smole
DWARF GALAXY DEMOGRAPHY IN CLUSTERS OF GALAXIES FROM COSMOLOGICAL SIMULATIONS

21. N.M. Sakan, V.A. Srećković, Z.Simić and M.S. Dimitrijević
THE SPECTRAL COEFFICIENTS OF ABSORPTION PROCESSES IN DENSE STRONGLY IONIZED ASTROPHYSICAL PLASMAS

22. N.M. Sakan, V.A. Srećković, Z. Simić and M.S. Dimitrijević
THE OPTICAL CHARACTERISTICS OF DENSE, STRONGLY IONIZED HYDROGENE PLASMA, APPLICABLE IN ASTROPHYSICAL OBJECTS

23. O. Vince, M. D. Jovanović, I. Vince and A. Janješ
FIRST SPECTRA FROM THE TELESCOPE MILANKOVIĆ

24. S. Samurović
DYNAMICAL MODELS OF THREE LENTICULAR GALAXIES: NGC 1023, NGC 3115 and NGC 4526

25. S. Samurović, G. Djurašević, Z. Cvetković, R. Pavlović and O. Vince
TELESCOPE "MILANKOVIĆ": MOUNTING, PRESENT AND FUTURE WORK

26. M. Bílek and S. Samurović
TWO TYPES OF DARK MATTER DISTRIBUTION IN EARLY-TYPE GALAXIES

27. S. Boeva, G. Latev, G. Nikolov, R. Zamanov, B. Spassov and M. Belcheva
FAST VARIABILITY OF GK PERSEI

28. V. Čadež
ANALYSIS OF ELECTROMAGNETIC WAVES IN IONOSPHERIC PLASMA MODELS

29. V. A. Srećković, Lj.M. Ignjatović, A. Nina and M. S. Dimitrijević
THE NEW MODEL METHOD OF THE ELECTROSTATIC SCREENING OF THE ASTROPHYSICAL PLASMAS: MULTI-COMPONENT SYSTEMS

30. V. A. Srećković and D. M. Šulić
STRONG SOLAR X RAY FLARES: INFLUENCE ON THE IONOSPHERE

31. V. Zeković
RESONANT MICROINSTABILITY AS A TRIGGER OF COLLISIONLESS SHOCK FORMATION

32. R. Pavlović, Z. Cvetković, G. Damljanović, O. Vince and M. D. Jovanović
THE FIRST TEST OF NEW ANDOR IXON 897 EMCCD CAMERA

33. Z. Prnjat
MILUTIN'S SUNDIAL IN KRALJEVO

34. S. Ninković
ON A NEW FORMULA FOR THE VELOCITY-DISPERSION RATIO

35. S. Ninković
ON A SIPMLE FORMULA FOR CALENDARS

36. S. Čolaković and V. Protić-Benišek
STAR HERITAGE : PRESERVATION THE PARK AND VEGETATION WITHIN THE COMPLEX OF THE BELGRADE ASTRONOMICAL OBSERVATORY

29th Summer School and International Symposium on the Physics of Ionized Gases

Dr. Vladimir Srećković

Institute of Physics,
Belgrade, Serbia

Belgrade, 9th February 2018.

Dear Dr. Srećković,

on behalf of the Scientific and Organizing Committees, we have a pleasure to invite you to attend the *29th Summer School and International Symposium on the Physics of Ionized Gases* (SPIG 2018) and present a **Progress Report** (20 min, including questions and discussions).

The SPIG 2018 will be held from 28th August to 1st September in Belgrade, Serbia. The details of the conference are available at http://www.spig2018.ipb.ac.rs/
Unfortunately, due to the limited conference budget, the organizers cannot commit to any financial support.
We look forward to welcoming you to Belgrade.

Yours sincerely,

Goran Poparić
(Co-Chair of the Scientific Committee)

Duško Borka
(Co-Chair of the Loc. Org. Committee)

Bratislav Obradović
(Co-Chair of the Scientific Committee)

Milan Rajković
(Co-Chair of the Loc. Org. Committee)

Local organizing Committee:

Vinča Institute of Nuclear Sciences, PO Box 522, 11001 Belgrade, Serbia
http://www.spig2018.ipb.ac.rs/
Tel: +381 11 6455451
+381 11 6308 425
Fax: +381 11 6308 425

10th Serbian Conference on Spectral Line Shapes in Astrophysics
(10th SCSLSA) Srebrno jezero, Serbia, June 15 -19, 2015

To: Dr Vladimir Srećković

Institute of Physics,
University of Belgrade ,
11080 Zemun ,
Serbia

GROUP FOR ASTROPHYSICAL SPECTROSCOPY
Astronomical Observatory, Volgina 7
11160 Belgrade, Serbia
Tel/Fax ++-381-11-2419-553

Belgrade, 15 March 2015

Dear Dr Vladimir Srećković,

On behalf of the Scientific Committee we are pleased to invite you to participate and to present your work "*VLF Remote Sensing of the Lower Ionospheric Disturbance Caused by Intense Solar Radiation"* at **10th Serbian Conference on Spectral Line Shapes in Astrophysics**, to be held in Srebrno jezero, Serbia, June 15-19, 2015.
(http://servo.aob.rs/scslsa10/, http://www.scslsa.matf.bg.ac.rs).

We will be pleased if you accept our invitation, and we are looking forward to seeing you at 10th SCSLSA meeting.

Yours Sincerely,

Luka Č. Popović
Co-Chairman of the SOC

Milan S. Dimitrijević
Co-Chairman of the SOC

10th Serbian Conference on Spectral Line Shapes in Astrophysics
(10th SCSLSA) Srebrno jezero, Serbia, June 15 -19, 2015

To: Dr Vladimir Srećković

Institute of Physics,
University of Belgrade ,
11080 Zemun ,
Serbia

GROUP FOR ASTROPHYSICAL SPECTROSCOPY
Astronomical Observatory, Volgina 7
11160 Belgrade, Serbia
Tel/Fax ++-381-11-2419-553

Belgrade, 15 March 2015

Dear Dr Vladimir Srećković,

On behalf of the Scientific Committee we are pleased to invite you to participate and to present your work "*Non-elastic processes in atom - Rydberg atom collisions: Review of state of art and problems"* at **10th Serbian Conference on Spectral Line Shapes in Astrophysics**, to be held in Srebrno jezero, Serbia, June 15-19, 2015.
(http://servo.aob.rs/scslsa10/, http://www.scslsa.matf.bg.ac.rs).

We will be pleased if you accept our invitation, and we are looking forward to seeing you at 10th SCSLSA meeting.

Yours Sincerely,

Luka Č. Popović
Co-Chairman of the SOC

Milan S. Dimitrijević
Co-Chairman of the SOC

BigSkyEarth Workshop in Brno

BigSkyEarth COST Action organizes its first workshop, with the topic "*Research Matchmaking – Building Bridges Between Disciplines*", in **Brno, Czech Republic, on April 14-16, 2016**. The workshop participants will have an opportunity to present their research in astroinformatics, geoinformatics, Big Data, data visualization or Big Data outreach, suggest how to expand their work into larger collaborations and seek potential research partners among the workshop participants.

PROGRAM = PDF

Submit your abstracts HERE (i.e. suggestions for collaborations with other research groups)

BigSkyEarth will provide quite a number of reimbursements for travel and accommodation to workshop participants. Below you can find a form where you can pre-register for the workshop and apply for the reimbursements. The final number of participants selected for reimbursement will be based on the available budget.

Updates on the workshop preparation are distributed to BigSkyEarth members – if you are not a member, follow instructions for registration in "Become a Member" section (see the right column on this page).

Workshop Venue

The workshop will take place at the Faculty of Information Technology, Brno University of Technology, located in an old Kartuzian Monastery, Bozetechova Street 2, Brno (and the modern building across the street – see the Google Map).

Accommodation

Hotels can be easily booked via booking.com or similar services. *Nove Semilasso Apartments* are the closest to our faculty. *Hotel Grandezza*, *Royal Ricc* and *Barceló Brno Palace* are in the centre, on the tram line no. 1 or 6. They will cost you about 100+ € per night but they offer good quality for the price. *Sono Hotel* is close to the centre too. You can also get a special rate 50 Eur for single room in *Hotel Continental* – just mention "Big Sky Earth" when booking via e-mail **info@continentalbrno.cz**.

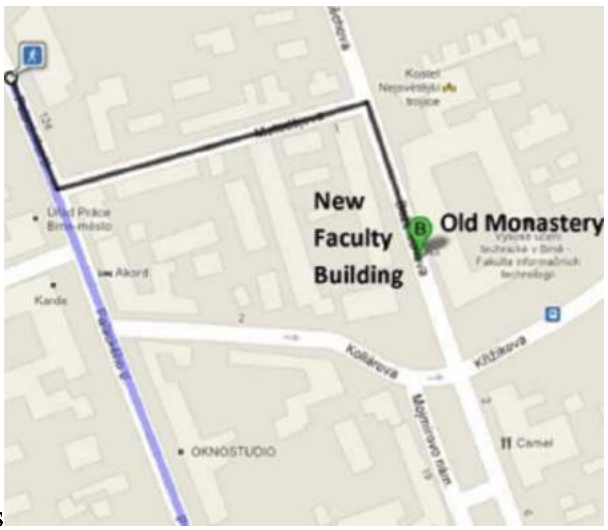
Travel Information

There is only a small airport in Brno. Regular flights (2-6 days a week) are limited to Munich, London Stansted/Luton and Eindhoven. If flying directly to Brno is not an option, you can go to Vienna or Prague and continue by bus, train or rent a car. The trip should take about two hours from Vienna and two and half hours from Prague by car. There is an excellent direct bus connection from/to the Vienna airport (2.5 h) and, not so direct, to the Prague airport (4 h, 1 change at the bus terminal in Prague where you wait an hour – if the first bus arrives on time, try to get on an earlier one for the connection). You can buy tickets online. Trains are less convenient and, surprisingly, often provide worse quality of service than buses.

You can plan your transport at here.

If you arrive with a car, you can park either in front of the building or use an underground parking (the entrance from the Metodejova street)

Public Transport in Brno

Brno has 

an excellent public transport (covered by Google Maps). The faculty can be easily reached by tram 1 or 6 (going every 5 minutes or so). The direction is *Reckovice* (tram no 1) or *Kralovo Pole – nadrazi* (tram no 6) and the stop you should get off is *Semilasso*. The ride should take only 10 minutes so it is enough to buy a 15-minutes ticket for 20 CZK (Czech Korunas). You can find vending machines on some stops or buy tickets in kiosks. Drivers also sell tickets (35 CZK) but they usually ask for exact cash. From *Semilasso*, go down the *Metodejova Street* and turn right.

Local Organizing Committee

Pavel Smrz – smrz at fit.vutbr.cz
Sylva Otáhalová – otahala at fit.vutbr.cz
Renata Kohlová – kohlova at fit.vutbr.cz

Submit your abstracts

You can submit multiple abstracts (i.e. proposals for collaboration) and upload your photo or some graphics that you would like to attach to the abstract(s):

ABSTRACT SUBMISSION FORM IS AVAILABLE HERE

Apply for Reimbursements

We will have a considerable number of reimbursement grants covering travel and accommodation expenses. Selected candidates will have to give a short (10-15min) presentation on their idea for research/project collaboration. Fill out the pre-registration form to apply.

NOTE: reimbursements are possible only to participants coming from institutions in BigSkyEarth member countries: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, fYR Macedonia, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Serbia, Slovenia, Spain, United Kingdom. Members of the Byurakan Astrophysical Observatory from Armenia are also eligible for grants.

THE PRE-REGISTRATION FORM IS AVAILABLE HERE

Registered Participants

- Areg Mickaelian, Byurakan Astrophysical Observatory, Armenian Virtual Observatory, Armenia
- Atanas Hristov ,University of Information Science ant Technology, Macedonia
- Bianca Schoen-Phelan, Dublin Institute of Technology, Ireland
- Blagoj Delipetrev, University Goce Delcev Faculty of Computer Science, Macedonia
- Bojan Pečnik, Hipersfera LLC, Croatia
- Darko Jevremovic, Astronomical Observatory, Serbia
- Dejan Vinkovic, Science and Society Synergy Institute, Croatia
- Denis Korablev, Brno University of Technology, Czech Republic
- Giovanni Nico, Consiglio Nazionale delle Ricerche (CNR), Istituto per le Applicazioni (IAC), Italy
- Giuseppe Longo, University Federico II – Napoli, Italy
- Gyula M Szabó, ELTE GAO MKK, Hungary
- Jamal JOKAR ARSANJANI, Heidelberg University, Germany
- Jaroslav Dytrych, Brno University of Technology, Czech Republic
- Jouni Peltoniemi, University of Helsinki, Finland
- Jovan Aleksić, University of Belgrade, Faculty of Mathematics, Serbia

- Lubomir Otrusina, Brno University of Technology, Czech Republic
- Lukas Polok, Brno University of Technology, Czech Republic
- Marco Quartulli , Vicomtech-IK4, Spain
- Maria Gritsevich, Finnish Geospatial Research Institute, Finland
- Michal Kapinus, Brno University of Technology, Czech Republic
- Michal Španěl, Brno University of Technology, Czech Republic
- Mihran Vardanyan, Byurakan Observatory, Global Map Data analysis center, Armenia
- Nikolay Kirov, New Bulgarian University, Bulgaria
- Ognyan Kounchev, Institute of mathematics and informatics, Bulgarian Academy of Sciences, Bulgaria
- Olga Kurasova, Vilnius University, Lithuania
- Pavel Smrz, Brno University of Technology, Czech Republic
- Pavel Zemčík, Brno University of Technology, Czech Republic
- Peter Baumann, Jacobs University | rasdaman GmbH, Germany
- Petr Škoda, Astronomical Institute Czech Academy of Sciences, Czech Republic
- Petr Škoda, Brno University of Technology, Czech Republic
- Prof. Javad Zarbakhsh, Carinthia Universitz of Applied Sciences, Austria
- Robert Ross, Dublin Institute of Technology, Ireland
- Sven Lončarić, Univ. of Zagreb Faculty of Electrical Engineering and Computing, Croatia
- Uroš Kostić, AALTA LAB, Slovenia
- Veljko Vujcic, Astronomical Observatory Belgrade, Serbia
- Victor Debattista, University of Central Lancashire, UK
- Viktor Medvedev, Vilnius University, Lithuania
- Vítězslav Beran, Brno University of Technology, Czech Republic
- Vladimir Privalov, Brno University of Technology, Czech Republic
- Vladimir Sreckovic, Institute of Physics, Belgrade, Serbia
- Yehia TAHER, DAVID Lab, University of Versailles, France
- Zdeněk Materna, Brno University of Technology, Czech Republic
- Zeinab Amin-Akhlaghi, ZAMSTEC, Austria

Program

Thursday 14.04.2016

10:00 – 10:30 Registration
10:30 – 10:45 Opening
10:45 – 11:00 Talk: Funding opportunities for BigSkyEarth projects

11:00 – 11:15 Short presentation
11:15 – 11:30 Short presentation
11:30 – 12:00 Coffee break + poster view
12:00 – 12:15 Short presentation
12:15 – 12:30 Short presentation
12:30 – 13:30 Discussion
13:30 – 15:00 Lunch + poster view
15:00 – 15:15 Short presentation
15:15 – 15:30 Short presentation
15:30 – 15:45 Short presentation
15:45 – 16:00 Short presentation
16:00 – 16:30 Coffee break + poster view
16:30 – 18:00 Discussion
18:00 – 19:00 –
19:00 – ——- Dinner

Friday 15.04.2016

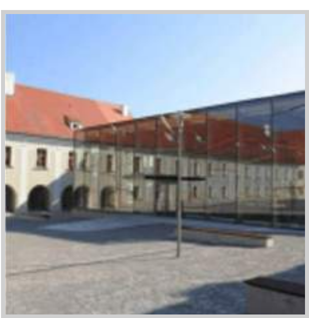
10:00 – 10:15 Short presentation
10:15 – 10:30 Short presentation
10:30 – 10:45 Short presentation
10:45 – 11:00 Short presentation
11:00 – 11:15 Short presentation
11:15 – 11:30 Short presentation
11:30 – 13:30 Coffee break + poster view
13:30 – 15:00 Lunch + poster view
15:00 – 15:15 Short presentation
15:15 – 15:30 Short presentation
15:30 – 15:45 Short presentation
15:45 – 16:00 Short presentation
16:00 – 16:30 Coffee break + poster view
16:30 – 18:00 Speed-project-dating
18:00 – 19:00 –
19:00 ——— Dinner

Saturday 16.04.2016

9:30 – 10:00 Opening of WG meetings
10:00 – 11:30 Spliter meetings of WG1,2,3,4
11:30 – 12:00 Coffee break
12:00 – 12:30 Conclusion of WG meetings
12:30 – 13:30 Discussion
13:30 – ——- Lunch

What is BigSkyEarth?

With the current emergence of Terabyte(TB)-scale astronomical and Earth observation systems, the traditional approach to basic functions such as data searching, analytics or visualization are becoming increasingly difficult to handle. Simple database queries can result now in data subsets so large that they are incomprehensible, slow (or even impossible) to handle, and impossible to visualize with commodity visualization tools. Astronomy and remote sensing complement each other, as they are on the quest for new Big Data interpretation capabilities: both disciplines have peculiar data, typical data processing and analysis chains, and specific models to be fed with data. However, both disciplines lack the capabilities for easily accessible semantics-oriented browsing (usage of higher level descriptive expressions) in large data archives. Therefore, joint efforts to design and develop innovative Big Data tools should help users in many different fields and set new standards for many communities. This has identified several broad challenges to this line of reasoning that need multidisciplinary approach through international networking of experts and professionals. These challenges are then channelled into Action Objectives:
Challenge A: Digital curation and data access
Challenge B: New frontiers in visualization
Challenge C: Adaptation to new high performance computing (HPC) technologies
Challenge D: New generation of scientists in the age of interdisciplinarity
For more detail see the description of the Action in Memorandum of Understanding.





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1. Register here
2. Select Working Groups of your interest
For industrial partners:
Why Should My Company Join Big-Sky-Earth?

Recent Posts

- WG2 and 4 Meeting in Finland
- Data preservation in the age of Big Data
- BigSkyEarth Conference – Education in Big Data Era
- Material from the 1st BigSkyEarth Training School – Oberpfaffenhofen 2016
- WG1 and WG3 Meeting in Bucharest

Archives

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Footer

COST is supported by the EU Framework Programme Horizon 2020

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Thursday 14.04.2016

10:00 - 10:30	Registration
10:30 - 10:45	Opening
10:45 - 11:15	Funding opportunities for BigSkyEarth projects Darko Jevremovic, Gottfried Schwarz
11:15 - 11:30	Application of Signal Processing on networks for Big Data problems Ognyan Kounchev
11:30 - 12:00	Coffee break + poster view
12:00 - 12:15	Consequences of meteoroid impacts based on atmospheric trajectory analysis Maria Gritsevich
12:15 - 12:30	Transient events in LSST survey data Jovan Aleksić
12:30 - 13:30	Discussion
13:30 - 15:00	Lunch + poster view
15:00 - 15:15	Detection and classification of transient astronomical objects in real time using complex event processing Veljko Vujčić
15:15 - 15:30	Application of remote sensing data to environmental monitoring, assessment and planning Ana Jurjević, Josip Križan
15:30 - 15:45	The Digitized Markarian Survey and the Armenian Virtual Observatory Areg M. Mickaelian
15:45 - 16:00	Machine Learning, spectra, GPU, Cloud Petr Škoda
16:00 - 16:30	Coffee break + poster view
16:30 - 18:00	Discussion
18:00 - 19:00	-
19:00 -	Dinner

Friday 15.04.2016

10:00 - 10:15	An unmanned airship platform for remote sensing and astronomy applications Bojan Pečnik
10:15 - 10:30	Storage and indexing of point cloud data Bianca Schoen-Phelan
10:30 - 10:45	Physical Interpretation of big optical dana from planetary and terrestrial surfaces Jouni Peltoniemi
10:45 - 11:00	VLF Data Acquisition and database storing Vladimir Sreckovic
11:00 - 11:15	Flexible, scalable, standards-based services on spatio-temporal datacubes Peter Baumann
11:15 - 11:30	Mining meteorological information from EO data and Numerical Weather Models simulations Giovanni Nico
11:30 - 13:30	Coffee break + poster view
13:30 - 15:00	Lunch + poster view
14:55 - 15:00	The Gothard Datascope project Gyula M Szabó
15:00 - 15:15	Simulations of galaxy formation in the era of Gaia Victor Debattista
15:15 - 15:30	Interactive rich-media data visualization for the masses Dejan Vinković
15:30 - 15:45	Deep Learning methods for satellite enhanced high fidelity pastureland Robert Ross
15:45 - 16:00	Cloud computing application for water resources based on open source software and open standards – a prototype Blagoj Delipetrev
16:00 - 16:15	Image processing and analysis for sky and earth observation Sven Loncaric
16:00 - 16:30	Coffee break + poster view
16:30 - 18:00	Speed-project-dating
18:00 - 19:00	-
19:00 -	Dinner

Saturday 16.04.2016

9:30 - 10:00	Opening of WG meetings
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XI BULGARIAN-SERBIAN ASTRONOMICAL CONFERENCE 14 - 18 MAY, 2018, BELOGRADCHIK, BULGARIA

XI BULGARIAN-SERBIAN ASTRONOMICAL CONFERENCE

PRELIMINARY PROGRAM

XI Bulgarian - Serbian Astronomical Conference
14-18 May 2018
Belogradchik, Bulgaria

Conference venue: hotel Skalite

14 May
17:00 - 19:00 Arrival and registration
19:00 - Welcome party

15 May
8:30 - 9:30 Registration
9:30 - Opening the conference

Session I: *Databases, astroinformatics (chairman: E. Semkov)*

9:50 – 10:20 Milan Dimitriević – Atomic spectral line broadening and databases for stellar plasma research – **invited talk**
10:20 – 10:50 M.Tsvetkov, M.Dimitrijević, K.Tsvetkova – Twenty Years Bulgarian-Serbian Cooperation in Astronomy: Joint Astronomical Conferences
10:50 – 11:10 S.Kashuba, N.Bazyey, M.Tsvetkov – The current state of the Odessa collection of astrophotonegatives

11:10 Coffee break

11:30 – 11:50 N.Kirov, M.Tsvetkov – New capabilities of the software to support digitization of astronomical photographic plates
11:50 - 12:10 O.Kounchev – Application of Nonparametric regression to Big data in Astroinformatics

12:10 – 14:00 Lunch Time

Session II: *Sun and solar system (chairman: M. Dimitriević)*

14:00 Kamen Kozarev – Early-stage SEP acceleration by CME-driven shocks with realistic seed spectra – **invited talk**
14:30 – 14:50 A.Nina – Low ionospheric disturbances induced by different terrestrial and extraterrestrial phenomena
14:50 – 15:10 L. Kashapova, D. Zhdanov, S. Lesovoi, A. Kudryavtseva and Lomonosov BDRG collaboration – Why we are interesting in study in weak solar flares?
15:10 – 15:30 R.Miteva, K.Koleva, M.Dechev, A.Veronig, K.Kozarev, T.Temmer, P. Duchlev, K. Dissauer – Hard X-ray diagnostic of proton-producing solar flares compared to other emission signatures
15:30 – 15:50 S. Vidojević, M. Dražić, M. Maksimovic, M. Abada-Simon – An algorithm for type III solar radio bursts recognition

15:50 Coffee break

16:30 – 16:50 Ts. Tsvetkov, E. Ivanov, N. Petrov – Atmospheric phenomena during the total solar eclipse on 21 August 2017
16:50 – 17:10 Ts. B. Georgiev – Titius-Bode relations in the exoplanet systems
17:10 – 17:30 P.Vuca – Milivoj Jugin (1925-2013) great popularizer of astronautics and cosmic flights

16 May
Session III: *Stars and stellar evolution (chairman: I. Stateva)*

9:00 Goran Damljanovic – The first GAIA data release – DRI and Serbian-Bulgarian astronomical activities – **invited talk**
9:30 – 9:50 N.Tomov, M.Tomova – Evolution of the accretion structure in the symbiotic binary BF Cyg during its last optical outburst began in 2006
9:50 – 10:10 R. Konstantinova-Antova, A.Lebre, M. Auriere, S.Tsvetkova, R.Bogdanovski, A. Borisova, P. Mathias, B. Thessore – Magnetic field variability in RZ Ari - an evolved M giant
10:10 – 10:30 S. Boeva, G. Latev, P. Nikolov, R. Zamanov, Ts. Georgiev, G. Damljanovic, M. Sekulic, Z. Cvetkovic, R. Pavlovic, O. Vince – Detailed analysis of the low state multicolor light curve of KR Aurigae on 23.02.2017
10:30 – 10:50 U. Wolter, A. Borisova, R. Konstantinova-Antova, K.P. Schröder – Doppler imaging and activity evolution of the Hertzsprung gap star OU Andromedae

10:50 Coffee break

10:50 – 11:10 G.Djurasevic – Accretion disk in massive close binary system
11:10 – 11:30 Z.Cvetković, R.Pavlović – New linear solutions for 13 double stars
11:30 – 12:00 Rumen Bachev – Blazar optical variability: 20 years of observations at Belogradchik Observatory – **invited talk**

XI BULGARIAN-SERBIAN ASTRONOMICAL CONFERENCE 14 - 18 MAY, 2018, BELOGRADCHIK, BULGARIA

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- Images

14:30 - Excursion
19:00 - Official dinner

17 May
Session IV: *Galaxies and cosmology (chairman: Z. Cvetković)*

9:30 Daniela Kirilova – BBN cosmological constraints on Physics Beyond Standard Model – **invited talk**
10:00 – 10:20 Z.Simić – Stark broadening data for spectral lines of rare-earth elements
10:20 – 10:50 M.Stojanović, S.Ninković, N.Martinović, M.D.Jovanović, G.Marković – Potential of Milky Way given analytically

10:50 Coffee break

10:20 – 10:40 M.Churalski, P.Nedialkov, A.Valcheva – A search for new variable objects in the field of OB81 association in M31 galaxy
10:40 – 11:00 V.Srećković, M.Dimitrijević, L.Ignjatović – Chemi-ionization/recombination Atomic Processes in the AGNs Broad-Line Region
11:00 – 11:20 Ž.Mijajlović, N.Pejović, V.Radović – First Serbian works on Theory of Relativity
11:20 – 11:40 E.Mikhailov – Russia Rectangular torus dynamo model and magnetic fields in the outer rings of galaxies
11:40 – 12:00 A.Bajić, M.Dimitrijević – Arheoastronomsko istraživanje Feliks Romulijane

12:00 – 14:00 Lunch Time

Session V: Stars and stellar evolution

14:00 – 15:00 Poster session (chairman: M. Dechev)

15:00 Coffee break

15:30 – 16:30 Poster session

18 May
9:30 - Closing the conference
10:30 - Departure

X Serbian-Bulgarian Astronomical Conference (X SBAC)
30. May – 03. June 2016, Belgrade, Serbia

GROUP FOR ASTROPHYSICAL SPECTROSCOPY
Astronomical Observatory, Volgina 7
11160 Belgrade, Serbia
Tel/Fax ++-381-11-2419-553

Dr Vladimir Srećković
Institute of Physics, Belgrade

Dear dr Vladimir Srećković

On behalf on the Scientific Organizing Committee of the "X Serbian Bulgarian Astronomical Conference" it is our pleasure to invite you to take part in the Conference that will be held in Belgrade, Serbia, from 30. May – 03. June 2016 with an invited talk.

Co-Chairman of the LOC

dr Zoran Simić

BigSkyEarth Workshop in Sopron

BigSkyEarth COST Action organizes its second workshop, with the topic "*Big Data processing and management concepts for new platforms*", in **Sopron, Hungary, on February 23-24, 2017**. The workshop participants will discuss the future of Big Data platforms in Earth Observations and astronomy, suggest how to expand their work into larger collaborations and seek potential research partners among the workshop participants (if you wonder, **here is why your company should join BigSkyEarth**)

Workshop Description

If we look at future space-borne or airborne experiments with high data rates to be launched within the next five to ten years, what kind of modern data management and data analysis environment do we need or expect?

- **Data Processing and Analysis**: What technical progress can we expect within the next 10 years? What are and will be typical overall concepts combining data processing, databases, visualization, quantitative data analysis, and data understanding? What will be the expected progress in the processing and analysis of distributed big data, existing and future functionalities, scalable algorithms, code splitting, load balancing, routine and interactive processing, access to dedicated external databases and models, overall data analysis concepts, and user interfaces? What will be our tools and what do we need in terms of data volumes, data transfer rates, and data management?
- **Databases**: What technical progress can we expect within the next 10 years? What are and will be typical performance characteristics? What is the expected progress in real time data ingestion, storage capacity, data organisation and handling, data rates, querying and analysis tools? How can we efficiently store, administer and handle instrument data together with external supplementary information, and higher level data content descriptors? Shall we expect distributed and/or embedded architectures and scalable configurations, fast interfaces to interactive visualization, and concurrent operations with data ingestion?
- **Visualization**: What technical progress can we expect within the next 10 years? What are and will be typical performance characteristics? What will be the expected progress in access to big data, data rates, data management and dimensionality reduction, role within general data analysis concepts, orchestration of tasks, and user interfaces? How can we efficiently select, group, classify, compare, analyse, display data and data descriptors, and store selected results? Shall we expect universal or dedicated visualization concepts? What will be the role of Virtual&Augmented Reality in visual analytics?
- **Education**: What changes can we expect within the next 10 years? Shall we expect more general or more task-oriented education? What educational support tools do we need that have to be developed? What feed-back tools do we need? Can everything be solved by Data Science?

Register and/or submit your abstracts and/or promote your idea for collaboration: HERE

(see our Book of Abstracts from the workshop in Brno **HERE**: *Research Matchmaking: Building Bridges Between Disciplines*)

BigSkyEarth will provide travel and accommodation reimbursements to a limited number of

Become a Member

1. Register here 2. Select Working Groups of your interest For industrial partners: Why Should My Company Join Big-Sky-Earth?

Recent Posts

- Apply to the BigSkyEarth Training School 2017: Visualization for large scale analytics
- BigSkyEarth Workshop in Sopron
- GalaxyFlyer – an interactive visualisation of a billion of particles
- Building collaborations – report from the BigSkyEarth meeting in Helsinki
- Presentations from the BigSkyEarth conference

Archives

- January 2017
- December 2016
- November 2016
- August 2016
- July 2016
- June 2016
- May 2016
- April 2016
- January 2016
- December 2015
- September 2015
- August 2015
- July 2015

workshop participants. Below you can find a form where you can register for the workshop and apply for the reimbursements. The final number of participants selected for reimbursement will be based on the available budget.

Updates on the workshop preparation are distributed to BigSkyEarth members – if you are not a member, follow instructions for registration in "Become a Member" section (see the right column on this page).

Workshop Venue

The workshop will take place at **Hotel Pannonia** in Sopron. The hotel is located downtown, just opposite the medieval and renaissance parts of the town, inside the ruined fortress walls. The conference room, the restaurant, and some wellness facilities are inside the hotel

Accommodation

We have a block reservation for 30 rooms at the hotel, available until 23 January at a very favorable price for approximately 70 EUR per day with taxes, including accommodation, breakfast, lunch, and coffee breaks (without dinner). Please confirm your participation by 23 January in an email to the sales manager to **sales@pannoniahotel.com**. Of course, you can ask for a longer stay if you want.

Travel Information

Sopron is very close to the **Wien/Schwechat International Airport** (the hotel is 68 km away), and you are strongly recommended to arrive to Schwechat airport, **NOT Budapest**. Regular and frequent ÖBB trains travel to Sopron (toward the final station of Deutschkreutz) from Vienna.

If you arrive by car, you can take the highways in Austria, and from the direction of Croatia and Slovenia, the roads suggested by google maps. There is no border control currently, but may be some Austrian policemen will take a quick look at your ID when entering Austria from the direction of Hungary.

The parking inside the hotel is available at additional (approx.) 11 EUR per day.

Public Transport in Sopron

Everything is within walking distance from the hotel, so you do not need public transportation.

Local Organizing Committee

Gyula Szabo: szgy at gothard.hu

Register and submit your abstracts

You can register here and promote your collaboration idea/project by submitting your abstracts (including calls for collaboration) and apply for a reimbursement grant covering travel and accommodation expenses. Selected candidates will have to give a short (10-15min) presentation (There will be special considerations with respect to supporting COST policies on promoting gender balance, enabling Early Career Investigators and broadening geographical inclusiveness):

CLICK HERE FOR REGISTRATION & ABSTRACT SUBMISSION FORM

NOTE: reimbursements are possible only to participants coming from institutions in BigSkyEarth member countries: Austria, Belgium, Bulgaria, Bosnia and Herzegovina, Croatia, Czech Republic, Denmark, Estonia, Finland, France, fYR Macedonia, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Serbia, Slovenia, Slovakia, Spain, United Kingdom. Members of the Byurakan Astrophysical Observatory from Armenia are also eligible for grants.

Program

Thursday 23.04.2017

8:30 – 9:00	Registration
9:00 – 9:15	Opening (Vinković)
9:15 – 10:00	Gottfried Schwarz Future Functionalities for Earth Observation Image Analysis: Realistic Versus Unrealistic Goals

May 2015

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10:00 – 10:45	Peter Baumann Datacubes as a Modern Spatio-Temporal Service Paradigm
10:45 – 11:15	COFFEE BREAK
11:15 – 11:30	Mariangela Liuzzi The Advent of Machine Learning & Remote Sensing Methods in Earthquake Risk Management: pre-event vulnerability assessment and near-real time damage mapping.
11:30 – 11:45	Ognyan Kounchev 1. Satellite based Integrated Systems for Applications in Civil Security 2. Application of Multiscale methods in Network Analysis of Big Data
11:45 – 12:00	Jovan Bajčetić Broadband radio spectrum analysis created on continuous measurements – detection of natural made disturbances and pattern finding
12:00 – 12:15	Dimitrios Marmanis Looking into the Future of Unsupervised Machine Learning Algorithms using Generative Adversarial Networks
12:15 – 12:30	Srđan Mitrović Inter-team education benefits for Big Data signal processing
12:30 – 12:45	Blagoj Delipetrev & Mirjana Kocaleva Proposal for collaborative projects
12:45 – 14:15	LUNCH
14:15 – 15:00	Marco Quartulli Big data analytics architectural standardization efforts
15:00 – 15:15	Szabolcs Mészáros Determining the Atmospheric Parameters and Chemical Composition of Stars in the Age of High Resolution Spectroscopic Sky Surveys
15:15 – 15:30	Peter Butka Architectures for Big Data processing
15:30 – 15:45	Veljko Vujcic Solution patterns for recognition of transient astronomical events
15:45 – 16:15	COFFEE BREAK
16:15 – 16:30	Uroš Kostić Using GPUs for GBSAR data processing
16:30 – 16:45	Alexandru-Cosmin Grivei Data Analytics for Spatio-Temporal Patterns in Satellite Image Time Series: Methods and Architectures
16:45 – 17:00	Bojan Pečnik Persistent Aerial Positioning as a Service: a remote sensing service of the future
17:00 – 17:15	Dejan Vinković The breakthrough remote sensing services possible with stationary or slowly moving airship platforms
17:15 – 17:45	Discussion

Friday 24.02.2017

9:15 – 10:00	Giuseppe Lugano The ERAdiate project: fostering interdisciplinary research and innovation in Intelligent Transport Systems at the University of Žilina
10:00 – 10:45	Engelbert Mephu Nguifo Big Graph Mining: Frameworks and Techniques
10:45 – 11:15	COFFEE BREAK
11:15 – 11:30	Areg Mickaelian Fine analysis of emission line spectra of active galaxies
11:30 – 11:45	Vladimir A. Sreckovic MolD a Database and a Web Service within the SerVO and the VAMDC

11:45 – 12:00	Maria Gritsevich 1. Observing and modelling meteors in planetary atmospheres 2. Scattering and absorption of electromagnetic waves in particulate media
12:00 – 12:15	Gyula M. Szabó Cosmic Risks and Hazards
12:15 – 12:30	Petr Skoda How to Make Big Data from Small Astronomical Files
12:30 – 12:45	Darko Jevremovic Alertsim – update on new developements
12:45 – 14:15	LUNCH
14:15 – 14:30	Martin Vo Classifying of star objects and searching in astronomical databases by using LightCurvesClassifier
14:30 – 14:45	Aleksandra Nina Big databases in ELF/VLF/LF waves monitoring and data processing
14:45 – 15:00	Atanas Hristov Improved programmability for extra large scale systems
15:00 – 15:15	Andrea Manieri Data Science Skills for EO Research and Industry
15:15 – 15:30	Jean-Paul Smets Earth observation appstore
15:30 – 16:00	COFFEE BREAK
16:00 – 17:30	Discussion
17:30 – 17:45	Closing

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For more detail see the description of the Action in Memorandum of Understanding.

International Conference
NATURAL HAZARDS
Lessons from the past and contemporary challenges

5th October

17.00-20.00 Ice breaker party and registration

Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Nikole Pašića 6.

6th October

8.00-9.00 Registration

Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Nikole Pašića 6.

9.00-9.30 Opening ceremony

Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, Nikole Pašića 6.

Prof. Lazar Lazić, Director of Department for Geography, Tourism and Hotel Management

Prof. Milica Pavkov Hrvojević, Dean of Faculty of Sciences

Prof. Stevan Pilipović, President of Branch of the Serbian Academy of Sciences and Arts in Novi Sad

Prof. Slobodan B. Marković, Corresponding mmember of the Serbian Academy of Sciences and Arts

9.30-11.00 Plenary session

Chairmans: Mezősi Gabor and Slobodan B. Marković

1. Smalley I.
   Hydroconsolidation in loess ground: problems with subsidence leading to building collapse and infrastructure damage.
2. Janc N., Gavrilov M.B.
   Hail-related record keeping in Serbia
3. Forkapić S., Bikit-Šreder K., Mrđa D., Bikit I.

Indoor radon mapping of Vojvodina region and connected radiation risk for population

4. Matzarakis A., Muthers S.
   Heat Health Warning System and Communication Aspects in Germany
5. Cipiran Margarint M., Vaculisteanu, G., Niculita M.
   Landslides, floods and disappeared settlements in NE Romania
6. Komac B., Breg Valjavec M.
   Traditional versus modern settlement of torrential alluvial fans considering danger of debris flows: case study of the Upper Sava Valley (NW Slovenia)

11.00-11.30 Coffee break and poster presentation

11.30-12.45 Plenary session

Chairman: Ian J. Smalley and Andreas Matzarakis

7. Mezősi G., Blanka V., Ladányi Z., Bata T., Kovács F.
   Estimation of the change of soil erosion in the Carpathian Basin until 2035
8. Sipos G., Gál G., Borza T., Fiala K., Kiss T., Gergely Páll D., Hegyi A., Urdea P., Blanka V., Elsayed Hamed D.
   Temporal elevation change and structural difference of artificial levees along the Lower Tisza and Maros Rivers, Hungary
9. Zorn M., Ciglič R., Komac B., Hrvatin M.
   Adaptation to natural hazards with spatial planning – the case of floods and landslides in the Municipality of Idrija (W Slovenia)
10. Nina A., Nico G., Popović L.Č., Čadež V.M., Radovanović M.
    Remote sensing applications in research of natural disasters
11. Lukić T., Bjelajac D., Fitzsimmons K.E., Marković S.B., Basarin B., Mlađan D., Micić T., Schaetzl R.J., Gavrilov M.B., Milanović M., Sipos G., Mezősi G., Knežević-Lukić N., Milinčić M., Létal A., Samardžić I, Živanović M.
    Factors triggering landslide occurrence on the Zemun loess plateau, Belgrade area, Serbia

12.45-14.00 Lunch break

14.00-15.20 Thematic session I

Chairman: Matia Zorn and György Sipos

1. Bentley S.P., Smalley I.J.
   [TG] Another look at the thermogravimetric analysis of hazardous clay soils [sensitive clays, expansive soils, laterites, collapsible loess, etc.]
2. Božić S., Jovanović T., Miljković Đ., Vujičić M., Marković S., Lukić T., Vasiljević Đ.
   The effect of psychological factors on natural hazards risk perception and tourists' intention to visit

3. Langroudi A.A., Smalley I.
   The Teton Dam (Idaho) 1976 failure: using remoulded loess material in earth dam cores
4. Poręba G., Frechen M., Moska P., Śnieszko Z., Adamiec G.
   Multiproxy analysis of soil erosion and land use change from the agricultural loess area near Ujazd village (Southern Poland)
5. Srećković V.A., Šulić D.M.
   Influence of strong solar X-ray flares and its negative effects
6. Tičar J., Mihalič K.
   Presence of gases in karst caves as a source of threats to people: examples from Slovenia
7. Maris T., Lukić T., Basarin B., Micić T., Bjelajac D., Marković S.B., Pavić D., Gavrilov M.B., Mesaroš M.
   Rainfall erosivity and extreme precipitation in the Netherlands – preliminary results
8. Urdea P.
   Permafrost and natural hazards

15.20-15.40 Coffee break and poster presentation
15.40-16.50 Thematic session II

Chairman: Cezar Morar and Blaž Komac

1. Barta, K., Blanka, V., Ladányi Z., Mezősi, G., Fiala K., Szabó G.
   Soil response to drought: quantification of water scarcity in sandy soils, Hungary
2. Gulácsi A., Kovács F.
   Water cover changes of wetlands between 1984-2018 on the Danube-Tisza Interfluve
3. Hrvatin M., Komac B., Zorn M.
   Discharge trends and floods in Slovenia
4. Leščešen I., Dolinaj D., Pantelić M., Srđan P.
   Drought regionalization of Vojvodina based on a K-Means Cluster Analysis
5. Matzarakis A., Schlegel I.
   Application of Test Reference Years basic data for human-biometeorological issues
6. Panić M., Đorđević J., Gačić J.
   Understanding of Natural Disaster Awareness and Preparedness of Flood-Affected Residents in the Jaša Tomić Settlement, Municipality of Sečanj, Central Banat District
7. Srećković V.A., Jevremović D., Vujčić V.
   Examination of the solar activity, low ionospheric perturbations and natural hazards

17.00-20.00 Novi Sad-city walking tour
20.00-22.00 Conference dinner and short business meeting

Building of Branch of the Serbian Academy of Sciences and Arts in Novi Sad, *Nikole Pašića 6.*

7th October

9.30-10.50 Thematic session III

Chairman: Tin Lukić and Matea Breg-Valjavec

1. Dragović N., Vasiljević Đ., Stankov U.
   Methods of using social media during natural disasters – case studies from worldwide
2. Janc N., Gavrilov M.B., Marković S.B.
   Natural Meteorological Hazards Mentioned in the Text "Old Serbian Records and Inscriptions"
3. Leščešen I., Dolinaj D., Pantelić M.
   Hydrological Drought Assessment in Vojvodina (Serbia)
4. Létal A.
   Living with the hazards in the Czech Republic: The Czechs did not learn from their ancestors
5. Lukić T., Sakulski D., Micić T., Gavrilov M.B., Marković S.B., Basarin B., Vasiljević Đ.A., Vujičić M.D., Milanović M., Pavić D., Mesaroš M., Miljković Đ., Morar C., Mlađan D., Lukić A., Džakula D., Tadić E., Šojić A.
   Key pluvial parameter in assessing rainfall erosivity in the Vojvodina region, Serbia: application of Angot pluvial index
6. Matzarakis A., Fröhlich D., Gangwisch M.
   Living in cities: Human thermal comfort modelling in urban micro scale
7. Nagy G., Vida G., Boros L., Vujičić M.
   Decision trees in Environmental Justice research – the case study of Hungarian floods of 2001 and 2010
8. Ruman A.
   Determine of the climate types in Pannonian Basin

10.50-11.30 Coffee break and poster presentation

11.30-13.00 Thematic session IV

Chairman: Petru Urdea and Zdzisław Jary

1. Džakula D.P., Milošević D.D., Savić S.M.
   Intra-urban analysis of air temperature in Novi Sad during summer heat wave period
2. Gavrilov M.B., Janc N., Marković S.B., Lukić T., Basarin B.
   Application of the Forestry Aridity Index in Vojvodina, Serbia
3. Govedarica D.D., Al-Homigany H., Govedarica O.M., Bulić M.L., Gavrilov M.B., Marković S.B.

9. Morar C., Lukić T., Basarin B., Vujičić M.D., Vasiljević Đ.A., Stankov U, Lucian B., Bucur L., Marković S.B., Gavrilov M.B.

Factors triggering landslide occurrence in Oradea area - "Ciuperca Hill" case study, Romania

10. Petrović M., Fekete R., Ostojić M., Radaković M.G.

Extreme precipitation in July and its consequences on Ostrozub Mountain, Case Study: Bankovci, Serbia

11. Poręba G., Tudyka K., Moska P., Mroczek P. , Raczyk J., Rodzik J.

Holocene soil erosion - testing new approach of dose rate determination to increase quality in luminescence dating (Kolonia Celejów, E Poland)

12. Pucarević, M., Stojić, N., Štrbac, S., Tadić, E., Vujasinović, N., Milenković,B., Stajić, J., Nikezić, D.

Determination of selected polychlorinated biphenyls in soil of Kragujevac city using a QuEChERS-based method and gas chromatography

13. Ristanović B., Lukić T., Milanović M., Miljković Đ., Cimbaljević M., Perić Z.

The determination of torrential flooding using GIS, a case study of the Likodra catchment basin (Western Serbia)

14. Ryzner K., Jary Z., Owczarek P., Krawczyk M.

Gully erosion of the loess areas in SW Poland - case study

15. Skurzyński J., Skurzyński K., Korabiewski B., Jary J., Raczyk J.

Heavy metals in soil of the former artillery shooting area of reinforcement company – a case study from Jelcz-Laskowice (Lower Silesia, Poland)

16. Stojsavljević R., Marković S.B., Gavrilov M.B., Janc N., Stamenković I.

Impact of volcanic eruptions on extreme climate conditions in Serbia