

CONTRIBUTION OF SOLAR HYDROGEN Ly α LINE EMISSION IN TOTAL IONIZATION RATE IN IONOSPHERIC D-REGION DURING THE MAXIMUM OF SOLAR X-FLARE

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SUMMARY: The solar Ly α line emission can be considered as the dominant source of ionization processes in the ionospheric D-region at altitudes above 70 km during unperturbed conditions. However, large sudden impacts of radiation in some other energy domains can also significantly influence the ionization rate and, in this paper, we present a study on the contribution of Ly α radiation to the ionization rate when the ionosphere is disturbed by solar X-flares. We give relevant analytical expressions and make calculations and numerical simulations for the low ionosphere using data collected by the VLF receiver located in Serbia for the VLF radio signal emitted by the DHO transmitter in Germany.

Key words. solar-terrestrial relations – Sun: activity – Sun: flares – Sun: X-rays, gamma rays

1. INTRODUCTION

A specific property of the ionospheric medium located in the terrestrial atmosphere at altitudes between around 50 km and 1000 km is presence of charged particles which play a significant role in numerous physical and chemical processes and have influence on various natural and man induced features occurring in this area. Consequently, the investigations of particle densities in the ionosphere and par-

ticularly in its lowest part which is in focus of our investigations, are very important for scientific studies such as analyses of plasma parameters changes induced by solar X-flares (Nina et al. 2011, Schmitter 2013), solar eclipses (Sing et al. 2011), lightnings (Inan et al. 1988), or induced harmonic and quasi-harmonic hydrodynamic motions (including soliton formation and vortices) (Jilani et al. 2013, Nina and Čadež 2013, Maurya et al. 2014, Zhang and Tang 2015). There is also a significance of practical

applications in telecommunications as the low ionosphere electron density variations have the greatest effect on radio wave propagation, primarily within the low (30 kHz-300 kHz), very low (3 kHz-30 kHz) and ultra-low (0.3 kHz-3 kHz) frequency bands. Prediction and forecasts of such events is important for variety of reasons including the remote sensing detection of narrow bipolar events in clouds (Ushio et al. 2014), monitoring acoustic and gravity waves in the atmosphere (Nina and Čadež 2013), monitoring specific perturbations in the ionosphere that might precede seismic activity (Hayakawa et al. 2010) and tropical cyclones (Price et al. 2007), and analysis of radio signal propagation characteristics (Bajčetić et al. 2015).

Although the low ionosphere is permanently under different ionizing radiation influences, some of them dominate under the considered conditions. Thus, the ionization of its lowest daytime region, the D-region (60 km - 90 km altitude), is primary caused by the $L\gamma\alpha$ radiation from the solar hydrogen. However, intensive events can significantly perturb this part of the atmosphere. For example, solar X-flares can induce large electron density increase in daytime ionosphere (Šulić and Srećković 2014). This event makes the contributions of relevant parts of electromagnetic spectrum in ionization processes time dependent which may change the dominant source of electron productions. Also, contrary to the most important influence of electromagnetic waves in electron production during daytime conditions, the ionization of nighttime low ionosphere is controlled by the eventual high energy corpuscular particles (Žigman et al. 2014).

One of the most important sudden perturbation source is the increase of the X radiation from the Sun during solar X-flares. In some of these cases when the flux of photons in the X domain is sufficiently large, this radiation dominates in ionization processes of the D-region. In literature, this is usually considered as approximately the total ionization during the time period around the maximum X-radiation intensity (Ratcliffe 1972, Budden 1988, Žigman et al. 2007). However, there are no quantitative analyses of contribution of $L\gamma\alpha$ photons in electron production based on data obtained by monitoring a particular part of the D-region during considered time period. Consequently, there are no relevant procedures found in the literature that would justify the exclusion of $L\gamma\alpha$ photons from calculations in such cases.

In this paper our attention is focused on contribution of the $L\gamma\alpha$ emission in ionization of the ionospheric D-region at the time around the maximum of X radiation during a solar X-flare, and on estimates of its relative significance depending on altitude. The derived theoretical equations are applied to a particular case of the D-region perturbation induced by a solar X-flare occurred on May 5, 2010. For the low ionosphere observation we used the method based on very low frequency (VLF) radio signals as also done in numerous published studies (Clilverd et al. 1999, Inan et al. 2010, Kolarski et al. 2011, Nina et al. 2012a,b, Singh et al. 2014).

2. EXPERIMENTAL SETUP AND OBSERVED DATA

The low ionosphere is monitored by three suitable techniques based on very low frequency (VLF) radio waves, rocket, and radar measurements (see for example Grubor et al. 2005, Strelnikova and Rapp 2010 and Chau et al. 2014). The first of them, which is used in this work, is based on continuously emitted and recorded radio signals by numerous, worldwide distributed, transmitters and receivers.

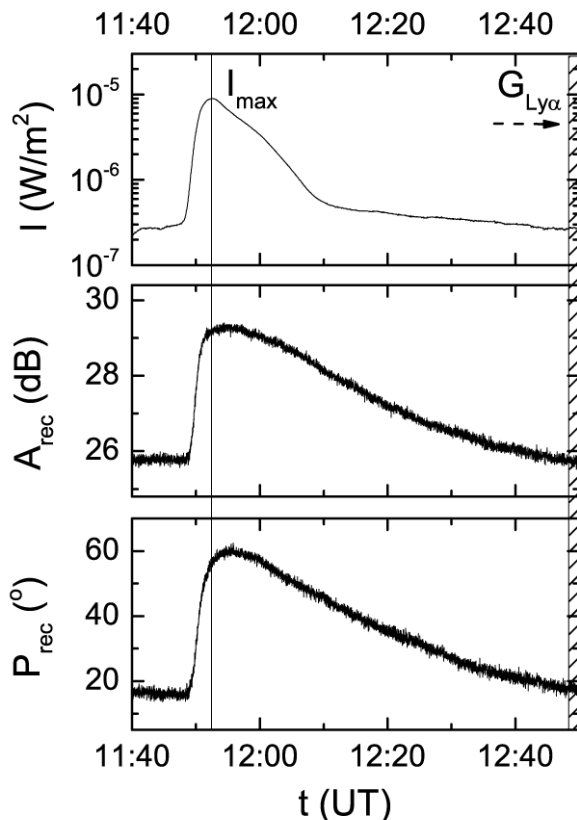


Fig. 1. Increase of X-radiation registered by the GOES-14 satellite on May 5, 2010 in wavelengths domain 0.1 nm - 0.8 nm (upper panel), and reaction of amplitude (middle panel) and phase (bottom panel) of the VLF signal emitted by the DHO transmitter located in Germany and received by the AWE-SOME receiver in Serbia. The vertical line indicates the time of X radiation maximum and the shaded domain represents the relaxation period analyzed in calculation of $\mathcal{G}_{L\gamma\alpha}$ in Nina and Čadež (2014).

Our analysis is based on data obtained from the low ionosphere monitoring using the 23.4 kHz VLF signal emitted by the DHO transmitter in Rhauderfehn (Germany) and received in Belgrade (Serbia). This transmitter was chosen because it pro-

vides the best quality of the recorded signal due to its high emission power of 800 kW and suitable signal frequency for the location of the receiver, and a relatively short signal propagation path. The latter property is important as it excludes significant variations in vertical stratification of parameters in the ambient ionospheric plasma.

The final theoretical results of the study and numerical procedure for modelling the D-region plasma are applied to a case of perturbation induced by the solar X-flare occurred on May 5, 2010 with the X radiation intensity I registered by the National Oceanic and Atmospheric Administration (NOAA) satellite GOES-14, (Fig. 1, the upper panel) at wavelengths range 0.1 nm - 0.8 nm. The ionosphere perturbations were detected as amplitude ΔA_{rec} and phase ΔP_{rec} variations of the considered VLF signal recorded by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modelling and Education) VLF receiver (Cohen et al. 2010) (bottom and middle panels, respectively). In Fig. 1, the time evolutions of recorded data are shown for the whole perturbation period. However, the presented study is related to the time of the X-radiation intensity maximum $t_{I_{max}} = 11 : 52 : 40$ UT indicated by the vertical line while the shaded domain designates the period considered in calculation of the Ly α photoionization rate $\mathcal{G}_{Ly\alpha}$ as presented in Nina and Čadež 2014.

3. D-REGION MODELLING

The electron gain rates induced by the Ly α line and X radiation, $\mathcal{G}_{Ly\alpha}$ and \mathcal{G}_X , respectively, during the time of the X radiation maximum can be calculated from the equation for the D-region electron density dynamic (McEwan and Phillips 1978):

$$\frac{dN_e(\vec{r}, t)}{dt} = \mathcal{G}(\vec{r}, t) - \alpha_{eff}(\vec{r}, t)N_e^2(\vec{r}, t). \quad (1)$$

where the influence of transport processes is neglected as they become important only at altitudes above 120-150 km (Blaunstein and Christodoulou 2006). The total electron gain rate \mathcal{G} can be written as:

$$\mathcal{G}(\vec{r}, t) = \mathcal{G}_{Ly\alpha}(\vec{r}, t) + \mathcal{G}_X(\vec{r}, t). \quad (2)$$

The satellite observations show that increasing of the Ly α radiation is not always recorded during periods of solar X-flares (Raulin et al. 2013). In the cases without important changes in the Ly α line intensity it can be taken that $\mathcal{G}_{Ly\alpha}$ does not vary significantly in time if the considered time period is sufficiently short. Thus, the total electron gain rate can be taken constant in time around the X radiation intensity maximum ($d\mathcal{G}_X(\vec{r}, t)/dt = 0$). At the same conditions, also the coefficient $\alpha_{eff}(\vec{r}, t)$ can be considered practically stationary (Žigman et al. 2007). Using these approximations, the time derivative of Eq. (1) gives:

$$\frac{d^2N_e(\vec{r}, t)}{dt^2} = -\alpha_{eff}(\vec{r}, t_{I_{max}}) \frac{dN_e^2(\vec{r}, t)}{dt}. \quad (3)$$

Finally, Eqs. 1 and 3 yield the following expression for $\mathcal{G}(\vec{r}, t_{I_{max}})$:

$$\mathcal{G}(\vec{r}, t_{I_{max}}) = \left. \frac{dN_e(\vec{r}, t)}{dt} \right|_{t=t_{I_{max}}} - \left. \frac{d^2N_e(\vec{r}, t)}{dt^2} \left[\frac{dN_e^2(\vec{r}, t)}{dt} \right]^{-1} N_e^2(\vec{r}, t) \right|_{t=t_{I_{max}}}. \quad (4)$$

The procedure to calculate $\mathcal{G}_{Ly\alpha}(\vec{r}, t)$ is presented in Nina and Čadež (2014), while the electron density time evolution and, consequently, its time derivatives can be obtained from comparisons of the recorded amplitude ΔA_{rec} and phase ΔP_{rec} changes with the corresponding values resulting from the LWPC (Long-Wave Propagation Capability) numerical modeling the VLF signal propagation (Ferguson 1998) as explained in Grubor et al. 2008. The procedure is based on finding the combination of input parameters, the signal reflection height H' (in km) and sharpness β (in km $^{-1}$), that gives the best matching of the recorded and modeled signal characteristics. The electron density $N_e(h, t)$ (in m $^{-3}$) at fixed altitude h (in km) is calculated from these parameters by applying Wait's model of the ionosphere considering the vertical electron density gradient (Wait and Spies 1964):

$$N_e(h, t) = 1.43 \cdot 10^{13} e^{-\beta(t)H'(t)} e^{(\beta(t)-0.15)h}. \quad (5)$$

Finally, Eq. (4) and the obtained values for N_e from Eq. 5 yield the percentage contribution $r_{Ly\alpha}(h) = 100\mathcal{G}_{Ly\alpha}(h)/\mathcal{G}(h)$ of the Ly α line in the ionization rate at time of the maximum X radiation intensity as follows:

$$r_{Ly\alpha}(h) = 100\mathcal{G}_{Ly\alpha}(h) \left[\left. \frac{dN_e(h, t)}{dt} - \frac{d^2N_e(h, t)}{dt^2} \left[\frac{dN_e^2(h, t)}{dt} \right]^{-1} N_e^2(h, t) \right]^{-1} \right|_{t=t_{I_{max}}}. \quad (6)$$

4. RESULTS AND DISCUSSION

As already said in Section 2, the obtained equation for the fractional contribution of the Ly α line in ionization rate at the maximum X radiation intensity and the needed characteristics of electron density are applied to the time period of the ionospheric perturbation induced by the solar X-flare from May 5, 2010. To examine the validity of approximation of stationary Ly α radiation photoionization rate as assumed in the procedure given in

Section 3, we compare rises of the X and Ly α radiation intensity using the model that determines radiation intensity spectra I_λ during solar flares given in Chamberlin et al. (2008). Fractional increases of the X and Ly α radiation intensity are presented by the parameter b_λ

$$b_\lambda = 100 \frac{(I_\lambda(t_{\text{Imax}}) - I_\lambda(t_{\text{up}}))}{I_\lambda(t_{\text{up}})}, \quad (7)$$

where t_{Imax} and t_{up} designate times of the flare maximum and unperturbed time period before X-flare, respectively.

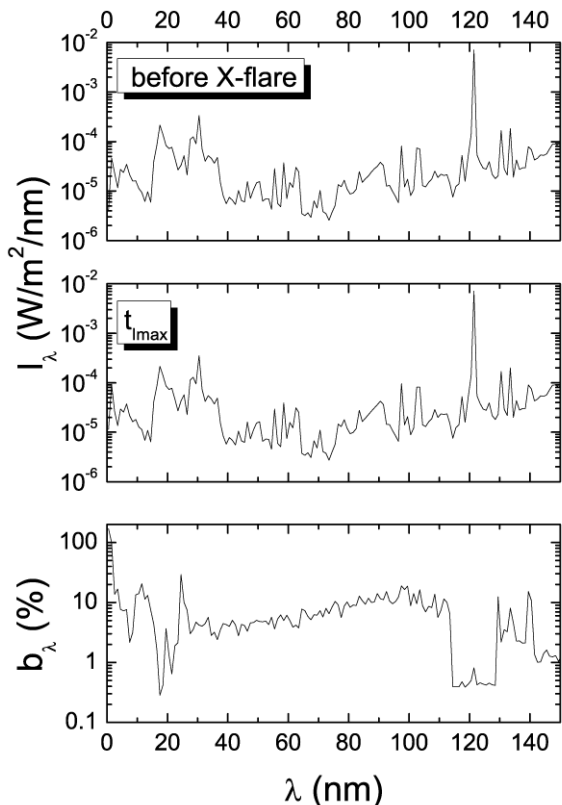


Fig. 2. Radiation spectra obtained by the model given in Chamberlin et al. (2008) at time periods before the X-radiation flare on May 5, 2010 (upper panel) and at the maximum X-radiation intensity (middle panel). The increasing b_λ of relevant values are given in the bottom panel.

The considered spectra shown in Fig. 2 (upper and middle panels) and the obtained coefficient b_λ plotted in the bottom panel of this figure show that variations of Ly α radiation are negligible. The obtained values for the X radiation within domains of wavelength between 0 nm and 1 nm (domain of X radiation observed by GOES satellite (Fig. 1) fall within this domain), and between 120 nm and 121 nm (Ly α photons fall within this domain) are around 170% and below 1% which shows that vari-

ations in Ly α radiation are negligible in comparison with the X radiation. Here we want to point out that the Ly α photons can ionize only NO molecules in the D-region. During solar X-flares the X radiation decreases the density of this molecule which, consequently, additionally decreases the $\mathcal{G}_{\text{Ly}\alpha}$. So, the real contribution of this line in total ionization is lower than what we obtained. The study of this difference will be subject of our future investigations.

Fig. 3, shows the calculated electron density evolutions N_e for indicated time periods at altitudes 70 km, 72 km, 74 km, 76 km, 78 km and 80 km. The obtained values are in good agreements with those shown in Žigman et al. (2007), Grubor et al. (2008) and Kolarski and Grubor (2014). Because of numerous simultaneously active influences, the calculated quantities cannot be smooth functions of time t . To extract the dominant influence of solar flare and to find a smooth time derivative of electron density we fitted the given discrete points with second order polynomials as shown in Fig. 3.

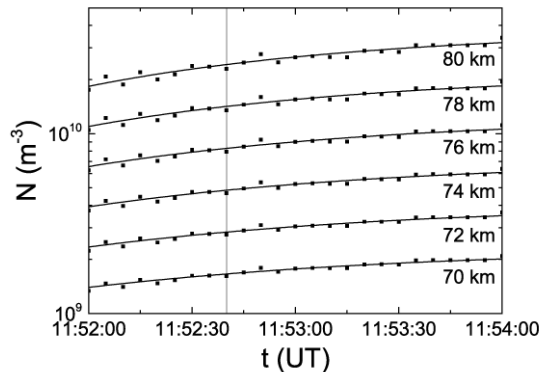


Fig. 3. Electron density time evolutions around the X radiation maximum (t_{Imax}) for altitudes 70 km, 72 km, 74 km, 76 km, 78 km and 80 km.

The first and second time derivative of electron density are shown in the upper panel in Fig. 4. It can be seen that the first derivative is positive while the second derivative takes negative values. For both of them, their absolute values increase with altitude indicating a larger influence of solar flares at higher altitudes.

Fig. 5 shows the resulting altitude dependencies of the relative contribution $r_{\text{Ly}\alpha}$ of the Ly α line in the ionization rate at the time of maximum X radiation intensity calculated from Eq. (6). We can see that this coefficient has values below 0.5% in the considered case. This justifies the assumption that the X radiation (including spectral lines and the continuum) dominate in ionization processes within the D-region during the period around the X radiation intensity maximum, as taken in literature (e.g. Žigman et al. 2007). It can also be seen that the significance of the Ly α radiation in ionization processes decreases with altitude under the considered conditions. In the case of the analyzed flare, our procedure gives values between around 0.1% and 0.4%.

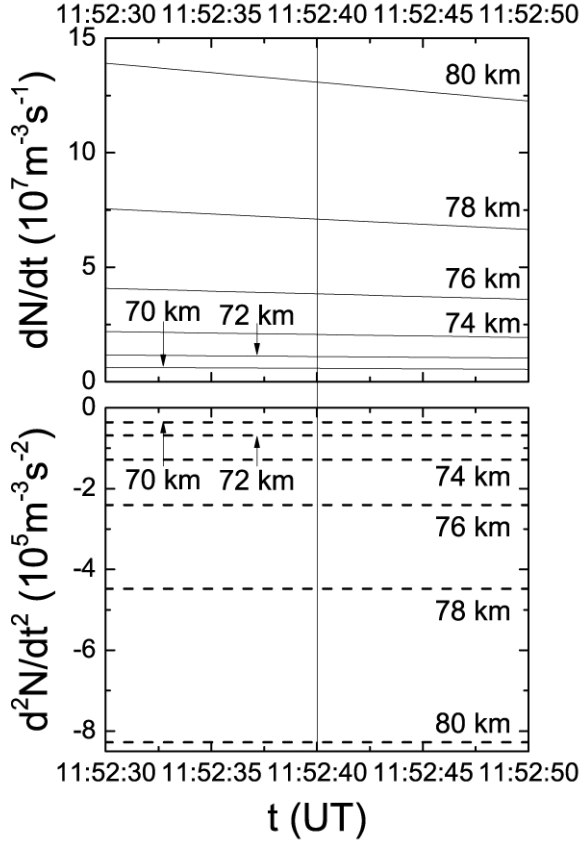


Fig. 4. Altitude dependence of the first and second time derivative of electron density around the time of X radiation maximum ($t_{I,max}$) at altitudes between 70 km and 80 km.

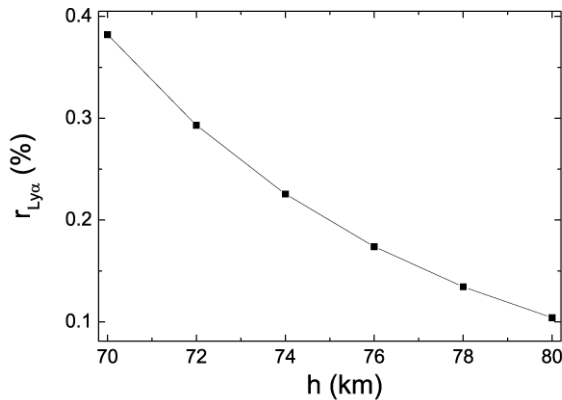


Fig. 5. The relative contribution $r_{Ly\alpha}$ of the Ly α radiation in total ionization rate around the time of X radiation maximum ($t_{I,max}$) at altitudes between 70 km and 80 km.

5. CONCLUSIONS

In this study we presented a procedure to determine contribution of the solar Ly α line photons in ionization of the ionospheric D-region at the time of the X radiation maximum intensity during solar X flare events. We applied the obtained theoretical result to the solar X flare of May 5, 2010 while the required input quantities for the electron density are calculated from data obtained experimentally from the D-region monitoring by VLF radio waves. The obtained altitude dependency of the Ly α line contribution in ionization rate shows that the Ly α line contributes less than 0.5% in the total ionization rate for the considered case. Although the given procedure indicates a larger importance of the Ly α line in ionization processes at lower heights, the corresponding small values of the coefficient $r_{Ly\alpha}$ imply the dominant ionization role of the X-radiation spectrum at all considered D-region altitudes.

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УДЕО ЕМИСИЈЕ Ly α ЛИНИЈЕ СУНЧЕВОГ ВОДНИКА У
УКУПНОМ СТЕПЕНУ ЈОНИЗАЦИЈЕ ЈОНОСФЕРСКЕ Д-ОБЛАСТИ
ТОКОМ МАКСИМУМА СУНЧЕВЕ ЕРУПЦИЈЕ У Х-ПОДРУЧЈУ

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Оригинални научни рад

Зрачење у Ly α линији се може сматрати доминантним извором јонизационих процеса у непоремећеној јоносферској Д-области на висинама изнад око 70 км. Међутим, интензивни упади зрачења у неким другим енергијским подручјима могу такође значајно утицати на брзину јонизације. У овом раду представљамо студију о уделу Ly α зрачења у

брзини јонизације током периода када је јоносфера поремећена Сунчевим ерупцијама у Х-области. Дати су одговарајући аналитички изрази и урађени прорачуни и нумеричке симулације за ниску јоносферу коришћењем података прикупљених VLF пријемником који се налази у Србији за VLF радио-сигнал емитован ДНО предајником у Немачкој.