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RESPONSES OF THE IONOSPHERIC D-REGION TO PERIODIC AND TRANSIENT VARIATIONS OF THE IONIZING SOLAR Lyα RADIATION

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Abstract: Solar radiation has the most important role in periodical variation of terrestrial atmospheric properties. Under unperturbed ionospheric conditions, the solar Lyα line has a dominant influence on ionization processes in the lowest ionospheric layer, the so called D-region. In this paper, we present periodical and transient variations in influences of the Lyα radiation on this ionospheric layer. In the case of periodical lower ionospheric changes we consider diurnal, seasonal and solar cycle variations and show analysis of acoustic and gravity waves induced by solar terminator. Influences of solar flares and eclipses on this atmospheric layer are analyzed as examples of sudden ionospheric disturbances. For decades, Very Low Frequency radio signals (3 – 30 kHz) are successfully used as a tool for monitoring of changes in the lower ionosphere, based on radio wave propagation through Earth-ionosphere waveguide along given trajectories and registration of their physical parameters (amplitude and phase delay). For the analysis conducted in this paper, we used records of the VLF DHO signal, emitted on 23.4 kHz frequency from transmitter in Germany and received in Serbia.

Keywords: Lyα line, solar radiation, ionospheric D-region, VLF signal propagation

Introduction

Processes in the terrestrial atmosphere are very complex due to occurrence of different events and their affects to considered geographical locations (Nikolić, Radovanović, & Milijašević, 2010; Malinović-Milićević, Radovanović, Stanojević, & Milovanović, 2015; Mihajlović, Ducić, & Burić, 2016; Milanović Pešić & Milovanović, 2016; Todorović Drakul et al., 2016; Mihajlović, 2017; Vyklyuk et al., 2017). As a part of the atmosphere, the lowest ionospheric layer called the D-region is permanently under different influences from outer space

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(Nina, Simić, Srećković, & Popović, 2015) and our planet (Kumar, NaitAmor, Chanrion, & Neubert, 2017, Nina, Čadež, Popović, & Srećković, 2017; Nina et al., 2017b) primarily induced by processes originating in the Sun (Mihajlov, Ignjatović, Srećković, Dimitrijević, & Metropoulos, 2013; Ignjatović, Mihajlov, Srećković, & Dimitrijević, 2014). One of the most important extraterrestrial influences on chemical processes in the plasma located within D-region altitude range (50–90 km) is coming from the solar hydrogen Lyα line (121.6 nm) whose presence is being periodically intensified during the daytime.

Generally, the Lyα line participates in several processes in local plasma such as the oxygen and water cluster dissociation, and chemistry of minor species such as water vapor, ozone and nitric oxide (Woods, Tobiska, Rottman, & Worden, 2000). Formation of the D-region in the daytime is primarily the result of the photo-ionization by Lyα photons (Nicolet & Aikin, 1960). Reversely, reduction of the incoming solar flux, including the Lyα line, is followed by disappearance of the lowest ionospheric layer during the nighttime conditions. These changes induce time variations in conditions for propagation of electromagnetic waves including telecommunication signals which, in addition to scientific importance in astro and geoscience, gives a practical application of ionospheric investigations.

The electron production by the Lyα line depends on the incident radiation flux at relevant energy, its attenuation during propagation through higher atmospheric layers and on the NO density in local plasma. As numerous studies have shown, all these parameters are variable in space and time and they can be calculated from experimental data obtained by various observational techniques. Thus, variations in the Lyα irradiance during solar cycles and seasons are presented in Woods et al. (2000), Fröhlich (2009) and Correia, Kaufmann, Raulin, Bertoni, and Gavilan (2011) and results given in Kockarts (2002) exhibit a strong zenith angle dependency of Lyα line absorption coefficients in the atmosphere. Also, measurements of the NO density show values within a wide range at fixed altitudes (Aikin, Kane, & Troim, 1964; Pearce, 1969; Barabash, Osepian, Dalin, & Kirkwood, 2012; and references therein). As the incident flux of the Lyα line, its absorption coefficient, and the NO density at considered altitudes may have different values, the resulting rate of related photo-ionization process varies within 3 orders of magnitudes (Aikin, 1969).

In this paper, we present different kinds of variation in the lower ionospheric plasma that are induced by changes in Lyα ionization resulting from different astrophysical phenomena such as Earth's rotation and revolution, variations of sunspot number during solar cycle, solar eclipses and solar flares. For monitoring the lower ionosphere we use a method based on very low frequency (VLF) radio waves propagation, as used in numerous published studies (Clilverd, Thomson, & Rodger, 1999; Ilić et al., 2017; Inan, Cummer, & Marshall, 2010; Nina, Čadež, Šulić, Srećković, & Žigman, 2012; Kolarski, Grubor, & Šulić, 2011; Kolarski & Grubor, 2014; Nina & Čadež, 2014; A. K. Singh, A. K. Singh, R. Singh, & R. P. Singh, 2014; Šulić & Srećković, 2014; Šulić, Srećković, & Mihajlov, 2016; Bajčetić, Nina, Čadež, & Todorović, 2015).

Observations and discussion

Conducted analysis is based on the monitoring of the lower ionosphere by the 23.4 kHz VLF signal emitted by the DHO transmitter located in Rhauderfehn (Germany) and received by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) VLF receiver in Belgrade (Serbia). We present the considered signal amplitude variation A(t) during day, year and solar cycle, give calculations of oscillation periods of acoustic and gravity waves (AGWs) induced by the Lyα line during solar terminator (ST) and show detection of D-region variations induced by decreasing and increasing photoionization rate due to a solar eclipse and solar flares, respectively.

Keeping in mind that we have been monitoring the lower ionosphere with the Belgrade AWESOME receiver for nine years only during current 24th solar cycle, in order to present variations during the entire solar cycle of 11 years, we show amplitudes of the signal emitted by the NAA (24.0 kHz) and NSS (21.4 kHz) transmitters (both located in the USA) and received at Faraday, Antarctica presented in Thomson & Clilverd (2000) to visualize changes during the 22th solar cycle.

Diurnal variations

The shape of the recorded signal amplitude during one day shown in the Figure 1 clearly indicates three different VLF electromagnetic wave propagation conditions:

1. The nighttime propagation (“N”);
2. Presence of complex processes induced by ST perturbing atmospheric layers and causing highly non-stationary propagation conditions for the recorded VLF waves at sunrises and sunsets (solar terminator —“ST”);
3. The daylight propagation (“D”).

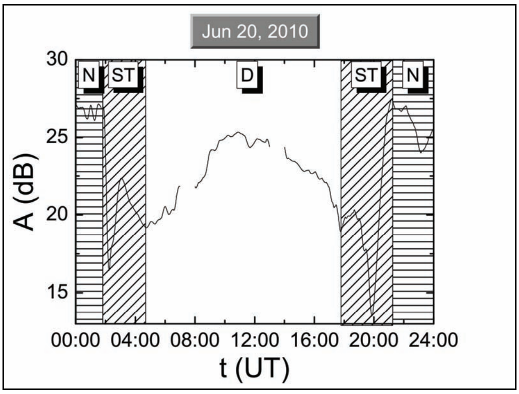

Figure 1. Diurnal variations of Lyα influences on lower ionosphere detected by the DHO VLF signal as recorded in Serbia on June 20, 2010

The solar radiation (including Lyα photons) does not contribute to ionospheric processes in the "N" domain while its influence is present in the "ST" and "D" domains. In the case of "D" period the amplitude shape does not exhibit sharp changes which would allow us to connect the VLF amplitude tendency with electron density variations and, approximately, with the Lyα photoionization. As can be seen, the maximum occurred in the period of maximal radiation influence on the part of the D-region between the transmitter and receiver locations. In the presented case, the difference in amplitude during the "D" period on June 20, 2010 is around 6 dB.

Seasonal variations

To visualize seasonal variations we present signal amplitudes for 12 days (by 3 day intervals around the summer and winter solstices, and equinoxes) in the period between June 11, 2010 and March 25, 2011. As we can see in the Figure 2 the global separation of the diurnal lower ionospheric detection by VLF signals (characteristic for daytime and nighttime propagation in unperturbed ionospheric conditions) exists during all seasons but the amplitudes for the days presented in different panels are not the same. Such changes indicate seasonal variations in the lower ionosphere whose explanation is very complex. Namely, the chemical compositions in this atmospheric layer, as well as at altitudes above, is being changed which influence both photoionization of the Lyα radiation and absorption (Gupta, 1998). Also, during the considered time period the variation in emitted solar radiation within solar cycle is visible (Woods et al., 2000). As a result, the annual VLF signal amplitude variation is not a fixed function of the noon solar zenith angle. Instead, it varies from year to year through the solar cycle as can be seen in Correia et al. (2011).

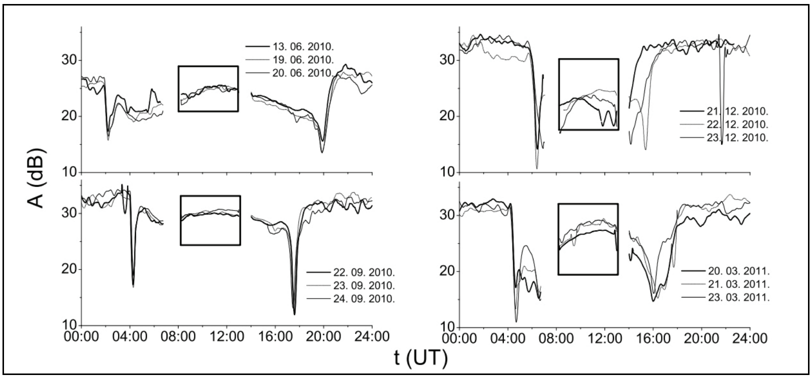

Figure 2. Seasonal variations of Lyα influences on the lower ionosphere detected by the DHO VLF signal recorded in Serbia from June 2010 to March 2011

The influence of Lyα radiation on diurnal DHO VLF signal amplitude variations is visible the in the Figure 1 through the duration of daytime sections "D" and their changes during the year as seen in the Figure 2. However, other influences dominate in amplitude variations, too. This can be seen from the mean values for the periods noticed in related panels (Figure 2) with fitted curves shown in the Figure 3 (left graph). Namely, as the largest recorded amplitude is seen around both equinoxes in September and March, meaning that the amplitude is lower around the summer solar solstice when the solar radiation is the most intense. In addition, the relevant shapes are different for March and September despite of similar Sun's positions at equinoxes. Although the absolute amplitude values cannot be connected with the solar zenith angle, its influence is visible if we calculate changes of daytime amplitude maxima (we used maxima of fitted curves in calculations) relative to mean nighttime amplitudes.

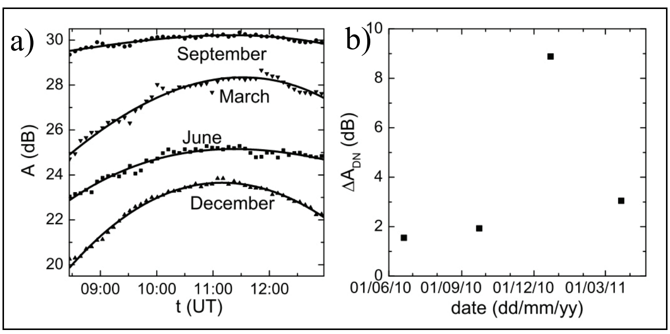

Figure 3. a) Fitted average amplitude and b) differences between the average night amplitudes and maxima of fitted mean daytime amplitudes for periods presented in Figure 2

In the Figure 3 (right graph) we can see that the maximum difference ΔA_{DN} occurs in winter and minimum in summer as expected due to the smallest and largest Lyα photoionization rates, respectively.

Solar cycle variations

The intensity of Lyα radiation penetrating into the D-region depends on its emission from the solar hydrogen. The flux of Lyα emission depends on the sunspot number that varies during the solar cycle (with a period of approximately 11 years).

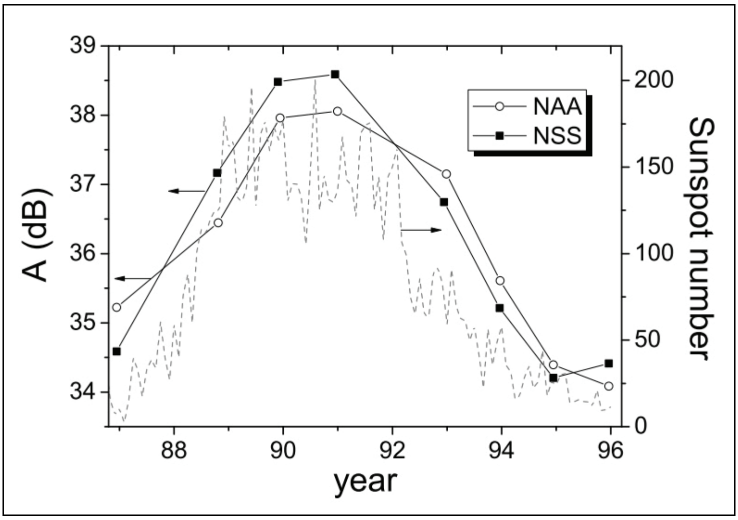

Figure 4. The comparison of the changes in the average mid-day amplitudes for December during 22nd solar cycle emitted by NAA and NSS transmitters and received at Faraday, Antarctica (taken from Thomson and Clilverd, 2000) with average monthly value of sunspot number (Source: www.sidc.be/silso/datafiles)

A comparison of changes in average mid-day amplitudes for December during the time interval from 1987 to 1996 for a radio signal emitted by the NAA (24.0 kHz) and NSS (21.4 kHz) transmitters (both located in USA) and received at Faraday, Antarctica (presented in Thomson & Clilverd, 2000) with average monthly value of sunspot number (http://www.sidc.be/silso/datafiles) shows amplitude maxima during the 22nd solar cycle maximum in 1990, with maximum rates of change of about 1 dB/year both prior to and after 1990/91 when the solar minimum conditions were approaching (see Figure 4).

AGWs induced during ST

As previously mentioned in the Introduction, the Lyα photons rapidly change the electron density in the D-region with respect to nighttime conditions. Consequently, intense changes in the lower ionosphere are present at the time of sunrise and sunset. The investigation published in Nina and Čadež (2013) shows that ST induces acoustic and gravity waves (AGWs) at the considered altitudes. To find the oscillation periods of AGWs excited by the Lyα radiation impact at sunrise we applied a given procedure based on comparison of Fourier amplitudes $A_F(\omega)$ of the recorded VLF amplitudes A(t) during distinct time sections of 30 min at nighttime and daytime, shaded and labeled by N and D, respectively:

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

where $\omega = 2\pi/T$ and T are the wave oscillation frequency and oscillation period, respectively. In case of DHO signal recorded in Belgrade on November 2, 2010 and presented in the Figure 5, these intervals are shaded and labeled by N and D, respectively. The obtained values for $T > 1$ min are shown on the left panels in the Figure 6, while their ratio $r_{DN}(T)$:

$$r_{DN}(T) = \frac{A_F(T;D)}{A_F(T;N)} \qquad (2)$$

exhibits peaks for periods T between 60 s and 100 s, around 400 s, and after 1000 s as shown in the right panel .

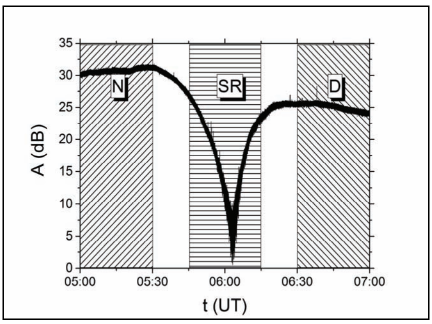

Figure 5. The time evolution of the DHO signal amplitude at sunrise recorded in Belgrade on November 2, 2010. The shaded domains designate the 30 min time intervals before and after the sunrise

These values are also obtained in Nina & Čadež (2013) for both the sunrise and sunset where a more detailed study, statistical analysis and consideration of hydrodynamic wave excitation during ST and their attenuations after strong perturbations which extract influence of Lyα effects from more other sources of perturbations can be found. Our results regarding the lower ionosphere are very similar to those obtained for higher altitudes (Afraimovich, 2008; De Keyser & Čadež, 2001a; De Keyser & Čadež, 2001b; Hernández-Pajares, Juan, & Sanz, 2006).

Variations induced by solar eclipse

In addition to previously mentioned periodical variations of the Lyα radiation intensity entering the terrestrial atmosphere, its transient decrease also appears during solar eclipses. As an example of detection of the D-region response to this phenomenon we show in the Figure 7 the amplitude deviation during the solar eclipse occurred on March 20th, 2015 from its expected time evolution for three referent days (one day before and two days after this eclipse).

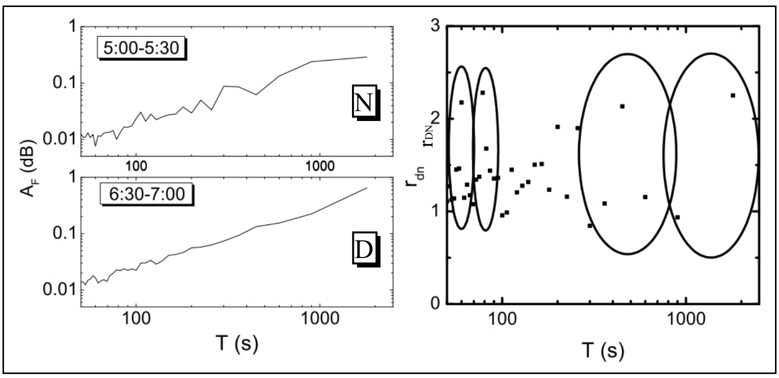

Figure 6. Fourier amplitudes of the DHO signal registered in Belgrade on November 2, 2010 for domains N (upper left panel) and D (bottom left panel). The right panel shows ratios of Fourier amplitudes related to domains D and N

In the Figure 7 we see that contrary to the amplitude increase in morning hours in absence of sudden intensive perturbations, during the eclipse the amplitude first slowly decreases and increases faster to the usual shape after the eclipse maximum.

Observations of Lyα line changes during solar flares

The analysis presented in Nina et al. (2011) shows that the influence of Lyα line on photoionization processes in the D-region is not so important during solar flares even in the cases when a significant increase of the Lyα line intensity occurs simultaneously with rising of radiation in X spectral domain. Namely, this study based on comparisons of time evolution shapes of radiation intensities in X domains and Lyα line (upper panel in the Figure 8), and the D-region electron density (bottom panel in the Figure 8) during two relevant solar flares occurred on April 22, 2011 indicates a more important influence of lines and continuum within the X spectrum then one of the considered line. The observations presented in Raulin et al. (2013) confirm these conclusions.

Conclusion

In this paper we show detections of lower ionospheric responses to variations in intensity of the Lyα line emitted by solar hydrogen and entering the considered medium. The observational technique used in this paper is based on propagation and analysis of very low frequency (VLF) radio signals. The presented amplitude variations of the 23.4 kHz signal emitted by the DHO transmitter in Germany and received by the VLF Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) receiver in Belgrade, Serbia, show characteristic responses of the lower ionosphere to variations in the Lyα photoionization during the day, year, and solar cycle.

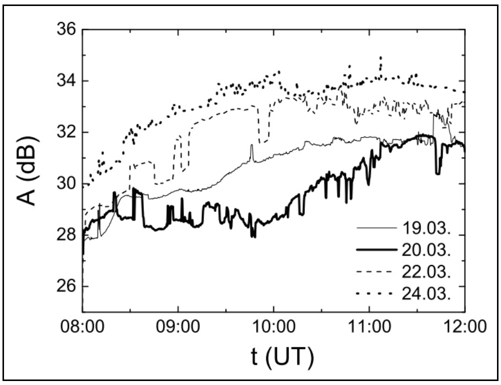

Figure 7. Deviation of the DHO signal amplitude recorded in Belgrade during solar eclipse of March 20th, 2015 (from 9:41 UT to 11:50 UT with maximum at 9:43 UT) from expected amplitude time evolution with respect to three referent days

Also, we present calculations of the oscillation periods of AGWs induced by rapid changes in impact of this radiation in the domain of solar terminator, and detection of sudden ionospheric variations induced by solar eclipse and flares.

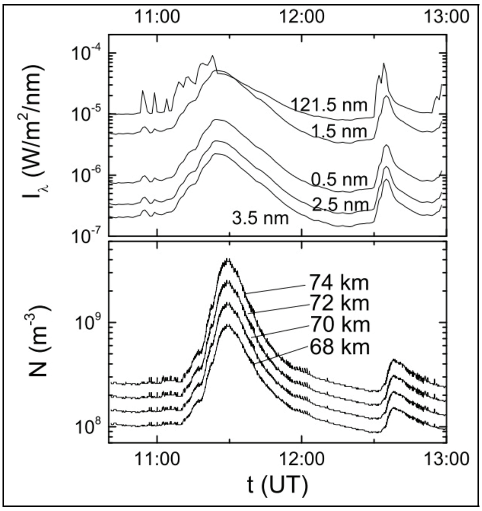

Figure 8. Comparison of electron density at different altitudes related to the two flares of classes C7.7 and C3.0 with time distribution of the solar radiation intensity I which has the dominant role in perturbing the ionospheric D-region (Nina et al., 2011)

As can be seen from this study, different astro and geophysical phenomena can change the Lyα line influence on the physical properties of terrestrial lower ionosphere. Variations in the Lyα influence can be detected through the ionospheric monitoring by VLF signals with exception of time intervals when some other radiation (like solar X-ray flares) induce intense ionospheric disturbances. On the other side, a strong influence of Lyα radiation on propagation of electromagnetic waves is noticeable in the lower ionosphere. For this reason, further investigation of Lyα influence on processes in this atmospheric part and, consequently, on radio signal propagation will be of great importance in telecommunications.

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