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Research Paper

Night-time light ion transition height behaviour over the Kharkiv (50°N, 36°E) IS radar during the equinoxes of 2006–2010

Dmytro V. Kotov [a,*], Vladimír Truhlík [b], Phil G. Richards [c], Stanimir Stankov [d], Oleksandr V. Bogomaz [a], Leonid F. Chernogor [a], Igor F. Domnin [a]

[a] Institute of Ionosphere, Kharkiv, Ukraine
[b] Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[c] George Mason University, School of Physics Astronomy and Computational Science, 4400 University Drive, Fairfax, VA, USA
[d] Royal Meteorological Institute, Belgium

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A B S T R A C T

This research investigates anomalous nighttime ion density behaviour over the Kharkiv, Ukraine incoherent scatter radar (49.6° N, 36.3° E, 45.3° inv) during the equinoxes of 2006–2010. The observations show that the altitude of the transition from O^+ to lighter ions was much lower than empirical and physical models predict. The standard physical model produces very good agreement for the O^+ densities but underestimates the H^+ densities by a factor of 2 in March 2006 and a factor of 3 in March 2009. The anomalously low transition height is a result of similar lowering of the ionospheric peak height and also of significantly increased H^+ density. The lower ionospheric peak height may be caused by weaker nighttime neutral winds. The calculations indicate that the higher measured topside ionosphere H^+ densities are most likely due to higher neutral hydrogen densities. Both factors could be the result of weaker than usual magnetic activity, which would reduce the energy input to high latitudes. Prolonged low activity periods could cause a global redistribution of hydrogen and also allow more neutral hydrogen to settle down from the exosphere into the mid-latitude ionosphere. The finding of the need for higher H densities agrees well with recent H-alpha airglow measurements and it is important for accurate modelling of plasmasphere refilling rates and night-time N_mF_2 values.

1. Introduction

The ion composition of the ionosphere, topside ionosphere, and plasmasphere has been studied for decades (e.g., Johnson, 1966; Taylor, 1973; Köhnlein, 1981; Heelis et al., 1981; González et al., 1992; Craven et al., 1995; Truhlík et al., 2005; Borgohain and Bhuyan, 2010; Gladyshev et al., 2012; and many others). Most of the important processes are now well understood and the dominant variation patterns have been reproduced by theoretical models and are included in recent empirical models like the International Reference Ionosphere (IRI) (Bilitza et al., 2014). However, the variation of the ion composition with solar activity exhibits some peculiarities which are not accurately reproduced by empirical models. One of the most important parameters characterizing ion composition is the altitude where the ion gas consists of 50% O^+ and 50% light ions (mostly H^+, some He^+). This altitude is called the upper transition height or light ion transition height (H_T). It depends strongly on latitude and local time and may be used as an anchor point for empirical models of the ionospheric ion composition profile (Bilitza, 1991). Several studies in the past investigated the behaviour of H_T, mostly dealing with data from low and medium solar activity (e.g., Goel et al., 1976; Titheridge, 1976; Miyazaki, 1979) or with the low altitude OGO-6 data from the solar cycle 20 maximum, which yielded only the night H_T (Kutiev et al., 1980). Třísková et al. (2001) used ion mass spectrometer data to study H_T at low and high solar activity up to 2500 km and found a dramatic change of H_T from solar minima to solar maxima.

There have been few theoretical model-data comparisons of H_T (MacPherson et al., 1998; Richards et al., 2000; Nanan et al., 2012) because few models are capable of modelling the ionosphere with sufficient precision to compare measured and modelled transition heights. This is because the absolute electron density and its altitude distribution are heavily influenced by neutral winds at mid-latitudes (MacPherson et al., 1998). Unfortunately, neutral winds

* Corresponding author.
E-mail addresses: dmitrykotoff@gmail.com (D.V. Kotov), vtr@ufa.cas.cz (V. Truhlík), prichar1@gmu.edu (P.G. Richards), sstankov@meteo.be (S. Stankov), albom85@yandex.ru (O.V. Bogomaz), Leonid.F.Chernogor@univer.kharkov.ua (L.F. Chernogor), domninpro@mail.ru (I.F. Domnin).

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are hard to measure and empirical models are too unreliable for detailed model-data comparisons. This wind effect is most clearly manifested in the changes in the height of the peak electron density (h_mF_2). The problem of uncertainty in neutral wind can be addressed by adjusting the neutral wind to closely match the observed h_mF_2 as it steps in time, as done, for example, by the field line interhemispheric plasma (FLIP) model (Richards, 1991). Richards et al. (2000) modelled the H^+/O^+ ratio at 500 km for January 6–12, 1997 at Millstone Hill and found good agreement, although there was a lot of scatter in the data.

During the last solar minimum, extremely low solar activity in 2008–2009 led to significant changes in the geospace environment. For instance, the thermospheric density and temperature were at record low values during this period (Solomon et al., 2010). The topside ionosphere was also significantly contracted, as demonstrated by anomalous H_T values observed by in situ measurements and incoherent scatter radar (Heelis et al., 2009; Klenzing et al., 2011; Aponte et al., 2013). Using C/NOFS satellite data, Klenzing et al. (2011) found that H_T moved down to 475–490 km after midnight. The smallest H_T values (450–470 km) were recorded over the Arecibo IS radar (Aponte et al., 2013). However, the C/NOFS mission was limited to $\pm 13°$ latitude. The Arecibo IS radar is located at 18° geographic latitude but, with a magnetic latitude of approximately 30°, it has some characteristics of a mid-latitude station. This is significant because the plasmasphere plays an important role in determining the upper transition height. However, until now there have been no data on the H_T behaviour at middle latitudes during the 2007–2009 extreme solar minimum.

In this study we present an analysis of the diurnal minimum of the light ion transition height H_{Tmin} using night-time equinox data from the Kharkiv incoherent scatter (IS) radar facility (49.6°N, 36.3°E, 45.3° inv) from 2006 to 2010. The IRI-2012 empirical model and the FLIP physical model are used to interpret some of the surprising features of the data.

2. IS facility and data set

The Kharkiv IS radar is located in Ukraine (49.6° N, 36.3° E, 45.3° inv). It operates at 158 MHz and uses a zenith-directed 100-m diameter fixed antenna (Domnin et al., 2013). Measured autocorrelation functions (ACFs) of IS signal (19 lags, sampling rate is 30.5 μs) are used to estimate ionospheric plasma parameters by least squares fitting to the theoretical ACFs. Some features of the fitting technique are distinctive. Details are presented in Appendix A.

In the topside mode, the transmitter is operated using 650-μs uncoded pulses with a 40-ms interpulse period giving data on the electron density, ion and electron temperatures, and ion composition with height resolution of 100 km. Our calculations demonstrate that in such a case biases in plasma parameters caused by the range smearing of measured ACFs are considerably smaller than the statistical errors. The main errors in H_T are statistical errors of the measured fractions of H^+ and He^+ ions (see Appendix A). The F2-layer peak height may be overestimated because of height smearing up to 5–10 km at night and up to 15–20 km during the day.

Measured the peak electron density (N_mF_2) values from an ionosonde located near the IS radar are used to calibrate the IS electron and ion densities profiles. The upper boundary altitude for the IS measurements depends on heliogeophysical conditions and ranges from 500 to 550 km in winter at solar minimum up to 900 to 1200 km in summer at solar maximum.

The results presented in this paper are obtained with one hour temporal resolution. All the obtained equinox data from 2006 to 2010 were used for the analysis: i.e. March 30, September 21, 2006; March 21, September 27, 2007; March 20, September 24, 2008; March 25, September 30, 2009; March 24, September 21, 2010.

3. Models used

3.1. IRI-2012

The International Reference Ionosphere (IRI) is an empirical standard model of the ionosphere based on a large database of monthly medians of electron density, ion composition, electron temperature, and ion temperature in the altitude range from 50 km to 2000 km (Bilitza et al., 2014). This paper used the Ne-Quick-option (Radicella, 2009), which is the recommended option for calculating the electron density in the topside ionosphere. The standard settings were used for calculating the N_mF_2 and the h_mF_2 values. The IRI ion composition was obtained from the model developed by Třísková et al. (2003), which is the recommended option since the deployment of IRI-2007 (TTS-03). This newer model takes advantage of better global coverage provided by satellite ion mass spectrometer measurements (Interkosmos-24, AE-C, AE-E) and uses the invariant dip latitude coordinate that is close to the magnetic inclination (dip) near the magnetic equator and closer to invariant latitude at higher latitudes and thus correlates well with the observed variation patterns of the topside ion distribution (Truhlík et al., 2001).

3.2. FLIP model

The Field Line Interhemispheric Plasma (FLIP) model is a one-dimensional model that calculates the plasma densities and temperatures along entire magnetic flux tubes from below 100 km in the Northern hemisphere through the plasmasphere to below 100 km in the Southern hemisphere (Richards, 2001; Richards et al., 2010a). The Earth's magnetic field is represented by a dipole that has a tilt that is adjusted as a function of longitude so as to produce a close representation of the actual field in the ionosphere.

The equations solved are the continuity and momentum equations for O^+, H^+, He^+, and N^+. The energy equations are solved for ion and electron temperatures. The equations are solved using a flux-preserving formulation together with a Newton iterative procedure that has been described by Torr et al. (1990). Electron heating due to photoelectrons is provided by a solution of the two-stream photoelectron flux equations using the method of Nagy and Banks (1970). The photoelectron solutions have been extended to encompass the entire field line on the same spatial grid as the ion continuity and momentum equations. Chemical equilibrium densities are obtained for NO^+, ${O_2}^+$, ${N_2}^+$, $O^+(^2P)$, and $O^+(^2D)$ ions below 500 km altitude in each hemisphere. The densities of minor neutral species NO, $O(^1D)$, $N(^2D)$, and $N(^4S)$ are obtained by solving continuity and momentum equations from ~100 to ~500 km in each hemisphere. The model also solves for the first five excited states of vibrationally excited N_2. Significant amounts of vibrationally excited N_2 can enhance the loss of O^+ by increasing the $O^+ + N_2$ reaction rate.

The solar EUV fluxes are important because they are not only responsible for ion production but also for the photoelectrons that heat the thermal electrons. The calculations in this paper use an accurate model of the solar EUV irradiances based on measurements by the SEE instrument on the TIMED satellite (Woods et al., 2008). The SEE solar EUV fluxes have been shown to produce very good agreement between measured and modelled N_mF_2 during the 2006–2009 solar minimum period (Richards et al., 2009, 2010b,