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Coincident Observations by the Kharkiv IS Radar and Ionosonde, DMSP and Arase (ERG) Satellites, and FLIP Model Simulations: Implications for the NRLMSISE-00 Hydrogen Density, Plasmasphere, and Ionosphere

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Key Points:
- The NRLMSISE-00 model underestimated thermospheric hydrogen density by ~100% during 2016-2018
- An unusually strong response to the minor storm of 24 December 2017 was observed from the inner plasmasphere to the F2-layer peak region
- The Kharkiv IS radar results are consistent with ionosonde, DMSP, and Arase (ERG) satellite measurements

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Abstract This paper reports the results of ionosphere and plasmasphere observations with the Kharkiv incoherent scatter radar and ionosonde, Defense Meteorological Satellite Program, and Arase (ERG) satellites and simulations with field line interhemispheric plasma model during the equinoxes and solstices of solar minimum 24. The results reveal the need to increase NRLMSISE-00 thermospheric hydrogen density by a factor of ~2. For the first time, it is shown that the measured plasmaspheric density can be reproduced with doubled NRLMSISE-00 hydrogen density only. A factor of ~2 decrease of plasmaspheric density in deep inner magnetosphere ($L \approx 2.1$) caused by very weak magnetic disturbance ($D_{st} > -22$ nT) of 24 December 2017 was observed in the morning of 25 December 2017. During the next night, prominent effects of partially depleted flux tube were observed in the topside ionosphere (~50% reduced H^+ ion density) and at the F2-layer peak (~50% decreased electron density). The likely physical mechanisms are discussed.

Plain Language Summary Our planet is surrounded by an extensive envelope of hydrogen gas that stretches a quarter of the way to the moon. It is called the geocorona because it can be seen in ultraviolet light analogous to the corona surrounding the sun during a total eclipse. This hydrogen gas is the source of ionized hydrogen that forms the plasmasphere, which is important because it affects radio wave propagation and therefore the accuracy of global positioning systems. The ultimate source of the hydrogen is the dissociation of water vapor near 100-km altitude. Both the geocorona and plasmasphere have their source from the atomic hydrogen near 500 km in the thermosphere. For almost half a century, scientists have been using hydrogen density deduced from the observations of Atmospheric Explorer satellite missions. Our study with Kharkiv incoherent scatter radar shows that the hydrogen density is actually ~100% higher than the earlier measurements. This result is supported by independent observations with satellites. Our finding means that many of calculations related to the important aspects of space weather influence need to be revisited. And, in a broader sense, our result points the way to better understanding of long-standing unresolved problems of solar-terrestrial interaction.

1. Introduction

It is well known that the ionosphere, plasmasphere, and thermosphere are a strongly coupled system through the accidentally resonant charge exchange reactions $H + O^+ \rightarrow H^+ + O$ and $H^+ + O \rightarrow H + O^+$. Thus, atomic hydrogen (H) in the Earth's upper thermosphere is primarily responsible for the formation the plasmasphere. It directly impacts plasmasphere refilling after strong magnetic storms (Kersley et al., 1978;

Krall et al., 2018; Richards & Torr, 1985). Hydrogen from the upper thermosphere is also the source of the geocorona, which significantly affects the ring current decay during the recovering phase of magnetic storms (Ilie et al., 2013; Krall et al., 2018). Thus, accurate knowledge of the upper thermosphere H density is crucially important for comprehensive investigations of a wide range of important space weather phenomena in the near-Earth environment.

The NRLMSISE-00 atmospheric model (Picone et al., 2002) continues to be the main source of thermospheric H density for ionosphere-plasmasphere calculations. It is primarily based on ion chemistry and the H^+ and O^+ ion density data collected by the Atmospheric Explorer satellites during 1974–1980. Over several decades, some efforts have been undertaken to obtain new measurements of the H density, mainly by the emissions measurements of Balmer-α (Anderson Jr. et al., 1987; Bishop et al., 2004) and Lyman-α (Bishop et al., 2001; Nossal et al., 2012; Waldrop & Paxton, 2013). The results of these studies are contradictory. For example, for the minimum of solar cycle 23, Waldrop and Paxton (2013) reported that NRLMSISE-00 overestimates the H density by ~36–67% whereas the observations of Nossal et al. (2012) imply that the H density is a factor of ~2 higher than that from the NRLMSISE-00 model. The integrated nature of the H emission measurements and consequent lack of altitude information is a disadvantage of this method. Nevertheless, the Nossal et al. (2012) results are supported by the IS radar measurements of Kotov et al. (2015, 2016). By combining observations of the H^+ ion density and other key parameters of the ionosphere from the Kharkiv incoherent scatter (IS) radar (49.6°N, 36.3°E) with the field line interhemispheric plasma (FLIP) model, it was found that the NRLMSISE-00 model H density had to be increased by a factor of 2 to 3 to bring the ionosphere model H^+ density into agreement with the data in all seasons during the 2006–2010. In contrast, recent simulations with WACCM-X model (Liu et al., 2018) gave upper thermosphere H density close to NRLMSISE-00 values under solar minimum conditions (Qian et al., 2018).

Long-term changes of the thermospheric and exospheric hydrogen density are of special interest for the understanding of the evolution of the plasmasphere through the decades and as an indicator of changes in greenhouse gas density (Nossal et al., 2016). The current solar minimum 24 (from about 2016) is especially interesting because it follows a historically weak solar maximum.

In this paper, we present the thermospheric hydrogen density estimated from the Kharkiv IS radar observations and calculations by the FLIP model for dates close to the fall equinox of 2016, summer and winter solstices of 2017, and vernal equinox of 2018. Satellite data from Defense Meteorological Satellite Program (DMSP; Rich, 1994) and Arase (ERG) (Miyoshi et al., 2018) are used as independent support for our conclusions.

In the course of this study, a surprising effect was uncovered. Namely, there was a significant (factor of ~2) plasmasphere density depletion observed by the Arase satellite at the relatively low Kharkiv L shell (≈2.1) following a weak magnetic storm of 24 December 2017 (maximum of K_p = 3+, minimum of $D_{st} \approx -22$ nT). Prominent effects likely related to this depletion were observed by other facilities in the topside ionosphere and even at the F2-layer peak during the evening of 25 December and night of 26 December. Total electron content (TEC) also show signatures of the effects. The observational results are compared with simulations by the FLIP model, and possible explanations are provided in terms of ionosphere-plasmasphere coupling.

2. Research Tools

2.1. The Kharkiv IS Radar and Ionosonde

The Kharkiv IS radar is located in Ukraine (49.6°N, 36.3°E, 45.3° inv, solar apparent time LT ≈ UT + 2.4). It operates at 158 MHz and uses a large zenith-directed 100-m diameter fixed antenna that enables the observation of the H^+ ion fraction in addition to other standard IS plasma parameters. An ionosonde located at the same observatory is used to calibrate the IS radar electron density data. The results presented in this paper were obtained with 20-min temporal resolution and with ~100-km-altitude resolution. Detailed information on the specialized topside mode of the Kharkiv IS radar, the data analysis techniques, and the error analysis were described by Kotov et al. (2015). In this study, data on the plasma parameters were obtained in the altitude range from ~200 to ~600 km encompassing the region of the F2 layer and the topside ionosphere.

2.2. DMSP Satellites

Additional topside ion data are provided by the DMSP-F15 satellite, which was in the nighttime magnetic local time (MLT) sector (~3.2–3.8 MLT) during the period of our study. The satellite has a near-circular orbit

(~845 km), which provides ion data approximately 250 km above the maximum altitude of the Kharkiv IS radar. The DMSP total ion density is provided by the scintillation meter, which is the part of the Special Sensor Ions, Electrons, Scintillation suite of instruments on DMSP-F15 (Rich, 1994). This study also uses validated ion composition (fractions of O^+, He^+, and H^+ ions) from the retarding potential analyzer to confirm the dominance of H^+ ions at the altitudes of the DMSP-F15 orbit (~845 km) during the nighttime.

2.3. Arase Satellite

The Arase satellite was launched in December 2016 and started regular observations in its full operation mode in March 2017 (Miyoshi et al., 2018). The Plasma Wave Experiment (PWE)/Onboard Frequency Analyzer (OFA) and High Frequency Analyzer (HFA) instruments onboard the Arase satellite routinely measure the frequency spectrum below 20 kHz and that from 10 kHz to 10 MHz, respectively (Kasahara et al., 2018; Kumamoto et al., 2018). The ambient plasma density can be derived along the satellite orbit from the frequency of the upper hybrid resonance emissions observed by OFA and HFA and the local cyclotron frequency measured by the magnetometer (Matsuoka et al., 2018). The Arase electron density data used in this study was obtained in the plasmasphere near 5,000-km altitude.

2.4. FLIP Model

The FLIP model is a one-dimensional physical model of ionosphere and plasmasphere (Richards, 2001; Richards et al., 2010). An important advantage of the model is that the measured F2-layer peak height h_mF_2 and topside electron temperature T_e can be used as constraints for the model.

3. Estimation of the Neutral Hydrogen Density

The method to estimate thermospheric H density was explained by Kotov et al. (2015, 2016). The FLIP model is constrained to follow the diurnal variations of h_mF_2 and topside T_e as measured by the Kharkiv IS radar to minimize the most significant errors inherent to physical simulation of midlatitude ionosphere due to large uncertainties in the thermospheric wind velocity and the heat flux into the topside ionosphere from the plasmasphere. Note that, at midlatitudes, electric fields cause vertical plasma motion similarly to horizontal winds. Winds and electric fields are taken into account by the FLIP model procedure to reproduce the observed h_mF_2.

The simulation begins 5 days prior to the period of IS observations to allow the plasmasphere densities to settle down from the initial conditions. The measured variations of h_mF_2 and topside T_e for the first day of observational period are used for all 5 days prior to IS observations. The FLIP model uses the actual values of daily $F_{10.7}$ and 3-hr A_p indices to govern the NRLMSISE-00 model neutral densities for the simulation. As a check on the reliability of the NRLMSISE-00 neutral temperature and O and N_2 densities, the FLIP model ion temperature T_i and N_mF_2 are compared to the observed values. This study and our previous studies (Kotov et al., 2015, 2016) for the equinoxes of 2006–2010, winter season of 2007–2010, and summer of 2010 confirm the consistency of the NRLMSISE-00 model and the IS radar/FLIP model for all of the standard IS plasma parameters.

In our previous studies, it was found that even when the FLIP model accurately matched the measured h_mF_2 and N_mF_2, the model H density had to be increased by factors of 2 to 3 in order for the FLIP model to match the observed topside H^+ density. It is important to note that the higher H density not only brought the FLIP topside H^+ ion density into very good agreement with the IS radar observations but also helped to resolve other long-standing model-data discrepancies. For example, the higher H density brings the model into better agreement with (1) IS observations of the heavy to light ion transition height, (2) IS and ionosonde measurements of high values of N_mF_2 at night, and (3) the satellite measurements of high plasmasphere refilling rates (Kotov et al., 2015, 2016, and references therein). These results provide a high level of confidence in the validity of our estimation of thermospheric H density.

4. Results and Discussions

In this study we consider observational results obtained by the Kharkiv ISR and ionosonde, DMSP-F15, and Arase satellites and observationally constrained simulations made with FLIP model for the following periods: 23–25 September 2016, 20–22 June 2017, 22–26 December 2017, and 29 March 2018. During these periods, solar and magnetic activities were generally low (daily $F_{10.7}$ ~ 69–85 solar flux units, A_p less than 5 nT for the period of observations and the previous day). The only exception was December 2017 when the daily A_p value was 12 nT on 24 December.

4.1. Thermospheric Hydrogen Density

Figures 1 and 2 show the diurnal variations of the F2-layer peak height and density and the plasma parameters in the topside ionosphere measured by the Kharkiv IS radar for all four intervals. These figures also show the variations produced by the FLIP model when it was constrained to follow the observed h_mF_2 and topside T_e.

The simulated N_mF_2 is generally in very good agreement with the observations (except for the night of 25 and 26 December when the observed N_mF_2 value was a factor of ~1.5 lower than the FLIP calculations). The measured T_i variations agree well with the FLIP ones within the ~10% error of the measurements. This good agreement supports the NRLMSISE-00 neutral temperature and O and N_2 for these periods.

A feature of all four periods under consideration is that the FLIP model nighttime H^+ density simulated with H density from NRLMSISE-00 model (dashed red lines) at 601 km is clearly significantly underestimated (by a factor of ~1.5 to ~2.5) compared to the IS radar observations. To bring the model results into a good agreement with the measured values, it is necessary to double the NRLMSISE-00 H density as seen by the solid green lines in Figures 1 and 2.

It should be noted that doubling the H density does not significantly affect the FLIP N_mF_2 values for the September, March, and June periods but does improve the model N_mF_2 during the night of 24 and 25 December very much (by ~50%). Similar results were obtained for the winter nights of the years of 2007–2010 when the solar and magnetic activities were similar (Kotov et al., 2016). N_mF_2 enhancements at midlatitudes on the long winter nights are a well-known phenomenon (e.g., Bertin & Papet-Lepine, 1970) and are due to strong H^+ flow from the plasmasphere to ionosphere. From our previous and current studies, such a strong flux can only be obtained when the NRLMSISE-00 H density is increased, which further supports the need of this increasing.

Further support comes from DMSP-F15 satellite observations at altitudes near 845 km where H^+ ions are normally dominant at night (the satellite retarding potential analyzer data show that there were more than 90% of light ions at the orbit at $L \approx 2.13$). Figure 3 shows the DMSP and FLIP model total ion (electron) densities. It should be noted that comparisons of models with satellite data are particularly uncertain near sunrise because of timing issues. The rapid increase in plasma temperatures at sunrise causes a rapid increase in O^+ density along with a rapid decrease in H^+ density. Small mismatches in time or space can lead to large model-data differences under these conditions. This situation is likely for all the June nights and also for the night of 25 and 26 December. However, the sunrise problem is not an issue for the September and March data, and also for the night of 24 and 25 December. These periods clearly indicate that the DMSP total ion density is closer to the FLIP H^+ values when calculated with the doubled NRLMSISE-00 H density.

Additional support for increasing of the H density is provided by the electron density observations conducted by the Arase satellite at plasmaspheric altitudes (~5,000 km) in close proximity to Kharkiv's flux tube (see Figure 4) in December 2017. There is very good model-data agreement on the morning of the quiet day of 23 December with the NRLMSISE-00 model H density doubled. The standard NRLMSISE-00 H density causes the FLIP model plasmaspheric density to be ~50% less than the observed value.

Also, our results are supported by the need in increase of the electron density scale height above F2-layer peak recently confirmed with direct radio occultation GPS measurements (Hernández-Pajares et al., 2017; Olivares-Pulido et al., 2016).

4.2. Strong Response of Plasmasphere and Ionosphere on the Weak Magnetic Disturbance of 24 December 2017

The Arase satellite observations indicate that on the morning of 25 December 2017, the plasmaspheric electron density was a factor of ~2 lower than on the morning of 23 December even though both passes were close in MLT, altitude, latitude, and longitude (Figure 4). Arase passed very close to the Kharkiv flux tube at ~5.13 UT of 25 December.

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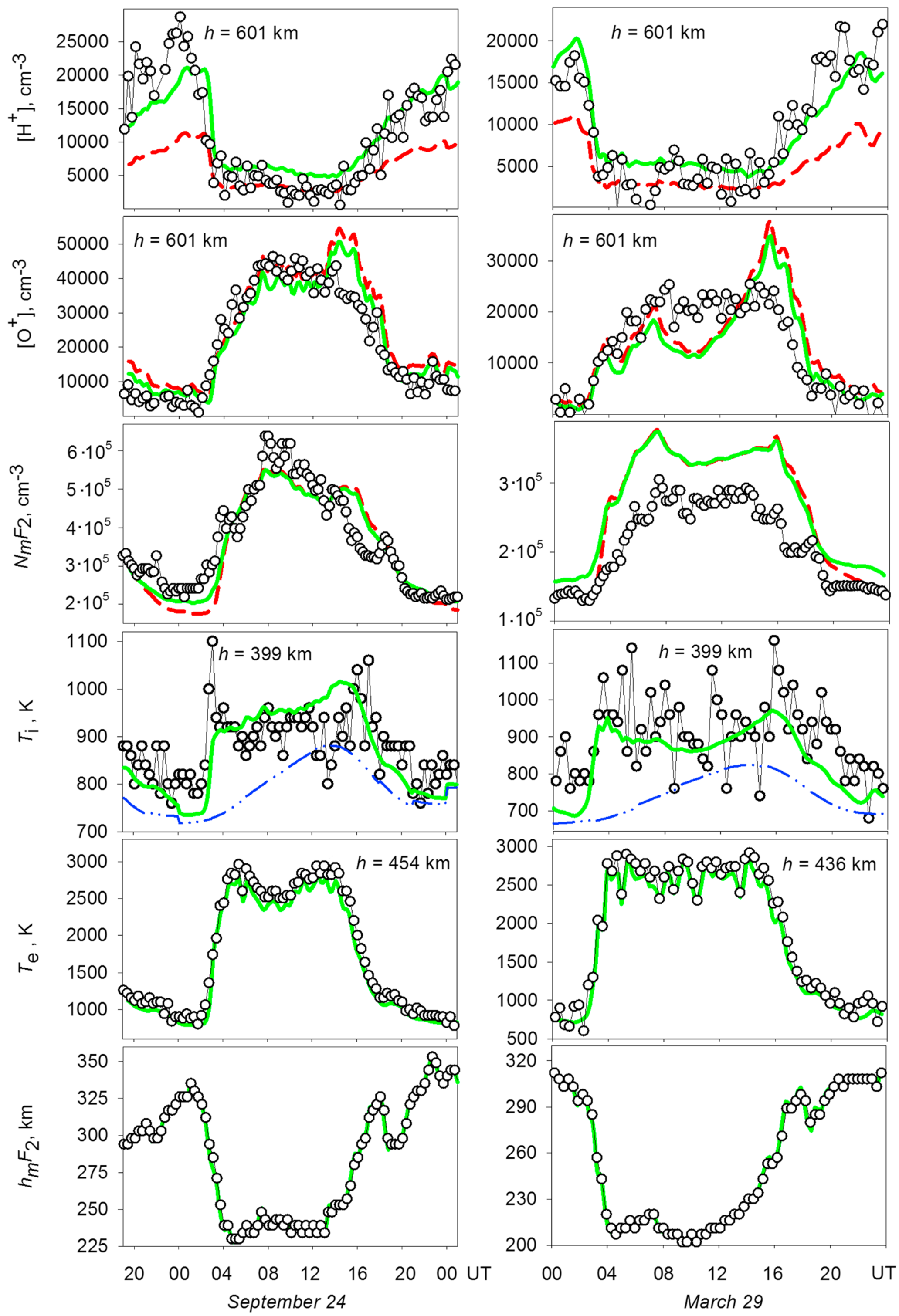

Figure 1. Comparison of h_mF_2, N_mF_2, and topside T_i, T_e, and O^+ and H^+ ion densities observed by the Kharkiv IS radar (open circles) and simulated with field line interhemispheric plasma model (lines). Here and in all subsequent figures, the field line interhemispheric plasma model followed the observed h_mF_2 and topside T_e, the dashed red lines show the results calculated using the standard NRLMSISE-00 H density, while the solid green lines are for the case of doubled NRLMSISE-00 H density. The dash-dotted blue line shows T_n at 399 km from the NRLMSISE-00 model. Left panels are for the period of 23–26 September 2016; right panels are for 29 March 2018.

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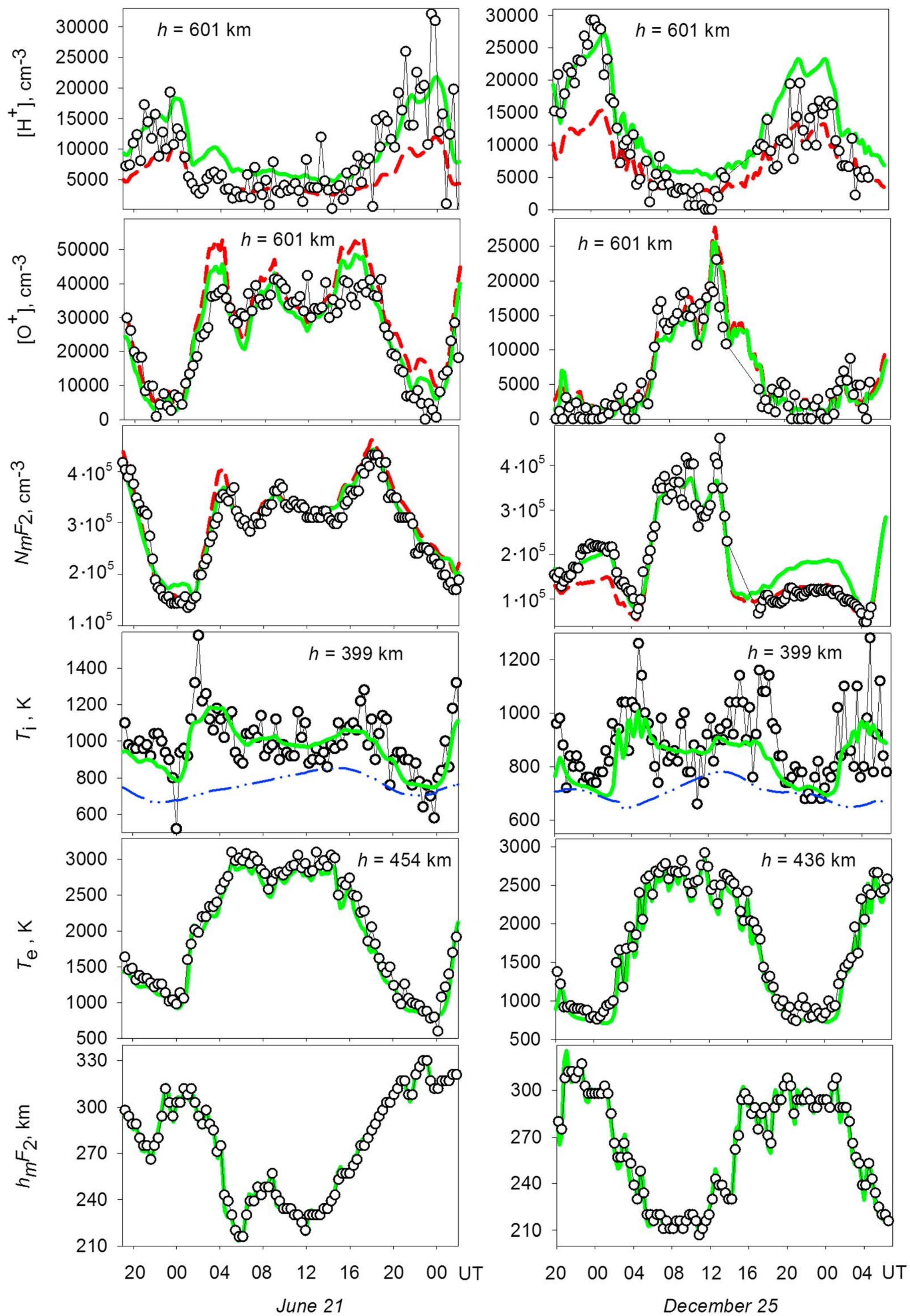

Figure 2. The lines and symbols are the same as in Figure 1, but the left panels are for the period of 20–22 June 2017; right panels are for the period of 24–26 December 2017.

During the preceding night and evening of 24 December, the Kharkiv IS radar (Figure 2) and the DMSP-F15 satellite (Figure 3) observed high H^+ ion densities in the topside, and the Kharkiv ionosonde showed the development of a strong N_mF_2 enhancement in excellent agreement with FLIP calculations with the NRLMSISE-00 H density doubled. All these ionosphere observations may be explained by the presence of

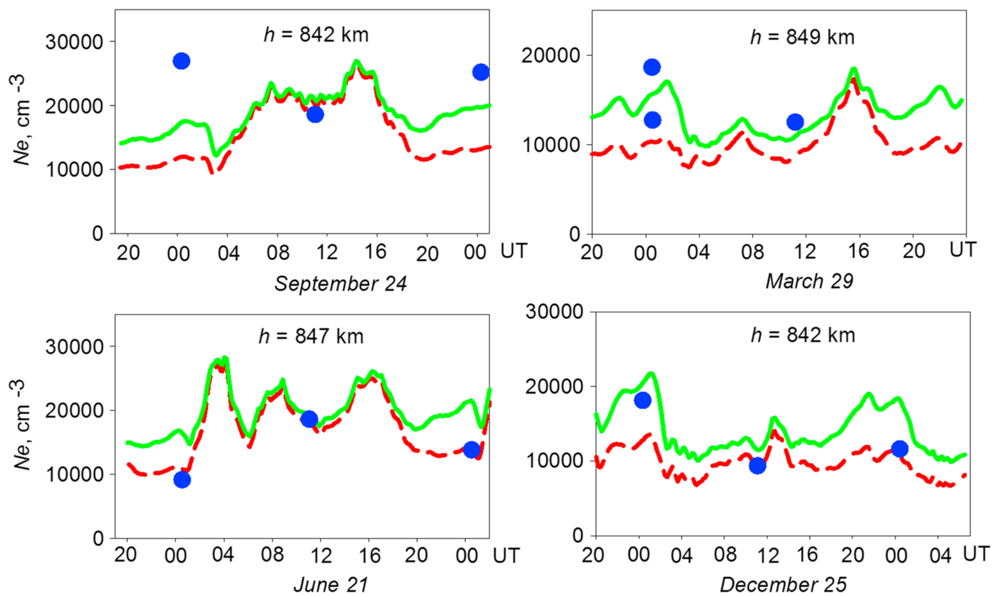

Figure 3. Comparison of total ion density simulated with the field line interhemispheric plasma model for the Kharkiv flux tube ($L \approx 2.13$) at the altitude of the DMSP-F15 satellite and the satellite density data (blue circles) for the periods of 23–26 September 2016, 29 March 2018, 20–22 June 2017, and 24–26 December 2017. DMSP-F15 data points are plotted with UT, which corresponds at Kharkiv to the same magnetic local time as for the satellite pass. The absolute UT differences between the incoherent scatter measurements at Kharkiv and corresponding DMSP observations do not exceed 1.34 hr, and the longitudinal differences between DMSP location and Kharkiv meridian are less than 15°. DMSP = Defense Meteorological Satellite Program.

typical strong downward plasmaspheric H^+ flux with the Kharkiv flux tube being full during the night of 24 and 25 December. So we conclude that the density in the Kharkiv flux tube was reduced sometime between ~2 UT and 5 UT of 25 December. This conclusion is supported also by the vertical TEC data (Figure 4), which shows that sharp TEC decrease (~33% at 50°N) was registered at ~4 UT of 25 December compared to the same time on preceding days.

One possible explanation for the Arase satellite observing the factor-of-2 lower density is that the minor magnetic storm on the afternoon of 24 December caused the partial depletion of plasma on some flux tube and that plasma was subsequently convected to be coincident with the Kharkiv flux tube (see, e.g., Richards et al., 2000).

During the daytime and preevening hours of the next day (25 December), the FLIP model reproduced the observed N_mF_2, topside O^+ density, and T_i very well (Figure 2) indicating the correctness of NRLMSISE T_n, O, and N_2 densities. This means that the factor-of-2 decrease of the topside H^+ density and F2-layer peak density observed by the Kharkiv IS radar and ionosonde during the night of 25 and 26 December (and the related changes seen in DMSP and TEC data), but not reproduced by FLIP model (Figure 2), may be the result of a depleted flux tube (the tube with $L \approx 2$ is unable to be fully filled during the period from the morning of 25 December to the evening of this date even under quiet conditions). The reduced plasmaspheric density would lead to a much weaker downward H^+ flux during the night of 25 and 26 December that could not support the higher densities of the night of 24 and 25 December.

It is interesting that the time delay between the density reduction and the time of the disturbance on 24 December as seen in the various indices (Figure 4) that are usually used for such studies is the same order of magnitude (~10 hr) as the delays estimated by Verbanac et al. (2015) for the plasmapause to respond to enhanced magnetic activity. It is important to note that the paper of Verbanac et al. (2015) and similar studies examine the response of plasmapause region, which is generally at a higher latitude than Kharkiv and expected to be much more sensitive to magnetic disturbances than the inner plasmasphere. Here we

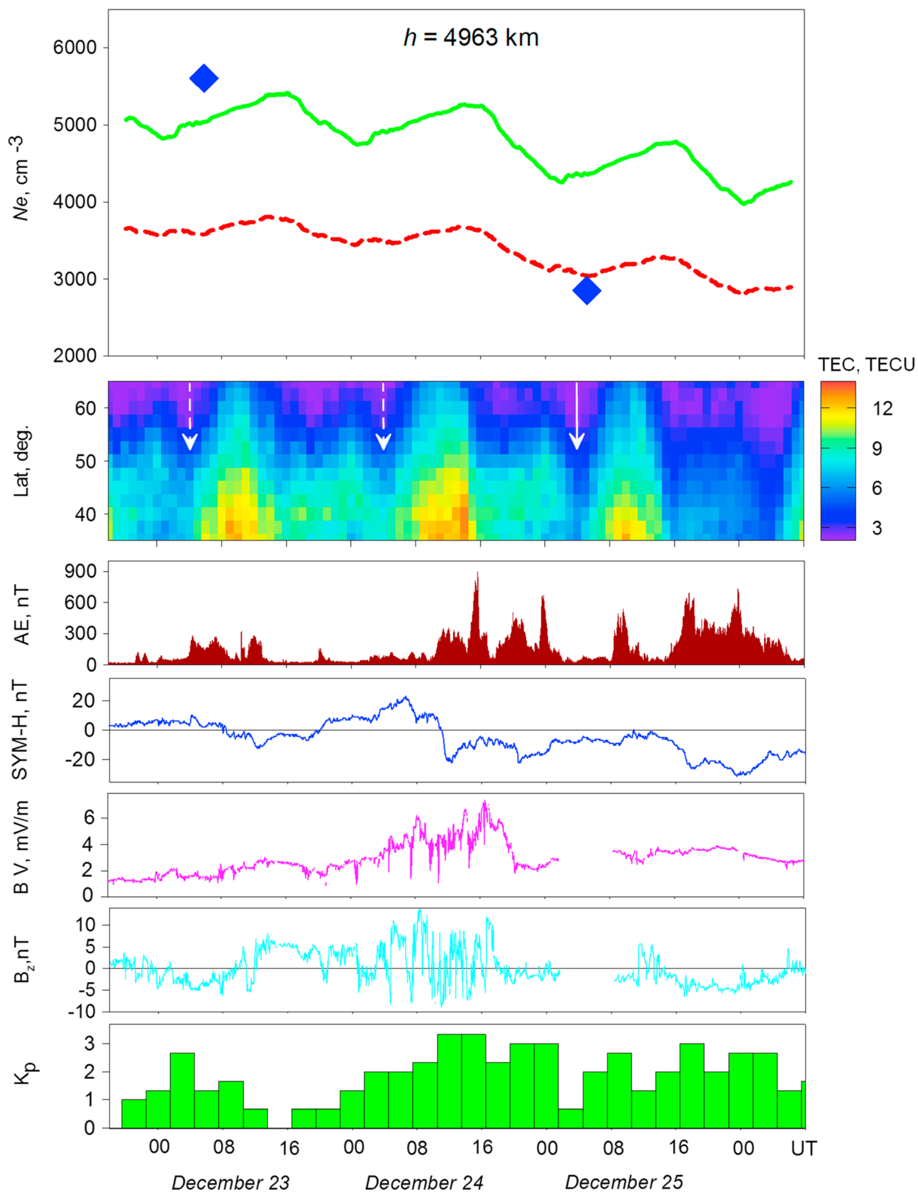

Figure 4. Comparison of the electron density from the field line interhemispheric plasma model for the Kharkiv flux tube ($L \approx 2.13$) at the altitude of Arase satellite orbit and the satellite density data (blue symbols) for the period of 22–26 December 2017 (top panel). Arase data points are plotted at UT, which corresponds at Kharkiv to the same MLT as for the satellite passes (23 December, MLT ≈ 8.17, 28.74°N, 29.08°E, altitude 4,927 km; 25 December, MLT ≈ 8.01, 29.12°N, 38.49°E, altitude 4,999 km). The second panel from the top shows vertical TEC at 35°E within the latitudes of 35°N to 65°N provided by UPC Global Ionospheric Maps. The solid white arrow indicates the time of sharp TEC decrease on the morning of 25 December, while the dashed white arrows indicate the same times for the preceding days. Other panels show variations of indices of magnetic activity (K_p, SYM-H, and AE), B_z component of interplanetary magnetic field, and *BV* parameter where *B* is the module of interplanetary magnetic field vector and *V* is solar find flow velocity. MLT = magnetic local time; TEC = total electron content.

show that the deep inner magnetosphere ($L \approx 2.1$) was strongly affected by the storm ($K_p = 3+$, $D_{st} > -22$ nT), which is not even classified as a storm in accordance with commonly used classifications (Gonzalez et al., 1994; Loewe & Prölss, 1997). Related ionospheric manifestations of such storms may be significant too. This case study shows that other indices of storm-time activities like *AE* and *BV* (see Figure 4) are better for the determination of the magnetic disturbances, which are effective in terms of their impact on plasmasphere-ionosphere system.

5. Conclusions

We investigated the state of ionosphere and plasmasphere during the periods close to the equinoxes (September 2016 and March 2018) and solstices (June and December 2017) of the current solar minimum 24. The main results are the following.

1. Thermospheric hydrogen density was a factor of 2 higher than predictions of NRLMSISE-00 model for all four seasons. This conclusion is supported by the observations with all used facilities. Similar result (2 to 3 times higher H density) was obtained by us for the last solar minimum 24 and for winter of solar minimum 23 (Kotov et al., 2015, 2016). This means that (a) the H density is similar for three solar minima (the same was pointed out by Nossal et al. (2008) but for the cycles 21–23) and (b) NRLMSISE-00 thermospheric H density is systematically underestimated by ~100% at low solar activity.
2. For the first time, using Kharkiv IS radar data, the plasmasphere electron density measured by Arase satellite, and observational based simulation with FLIP model, we showed that actual plasmaspheric density at $L \approx 2.1$ can be reproduced with doubled NRLMSISE-00 density only.
3. A significant (by a factor of 2) decrease of plasmaspheric density was observed by the Arase satellite at the relatively low L shell (≈2.1) at the end of the night of 25 December 2017. The likely reason was enhanced plasma convection induced by the minor magnetic storm on the afternoon of 24 December (maximum of K_p = 3+, minimum of $D_{st} \approx -22$ nT). Prominent ionospheric manifestations of this partial depletion of Kharkiv flux tube were seen during the next night of 25 and 26 December as a factor-of-2 decrease of the topside H^+ ion density and F2-layer peak density; corresponding decrease is seen also in TEC data. To our knowledge, this is the first time that such strong effects of such a weak geomagnetic disturbance were identified so deep into the inner magnetosphere.

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