Investigation of hydrogen ion behavior by the incoherent scattering (IS) method. Comparison of Kharkov IS radar results with Arecibo and Millstone Hill radar observations, Atmosphere Explorer space data, and FLIP model calculations

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Kharkov, Arecibo, and Millstone Hill radar measurements of the H^+ ion concentration in the ionosphere (up to the altitudes of 1000–1300 km) are compared for winter and summer conditions, as well as for minimum and maximum solar activity. The altitude and diurnal H^+ ion variations in the ionosphere over the Eastern and Western Hemispheres are shown to be principally similar. A considerable longitudinal effect is found in the relative H^+ ion concentration for the midlatitude Kharkov and Millstone Hill radars. The effect is explained by different L parameters and magnetic flux tube volumes caused by non-coincidence of the Earth's geographic and geomagnetic poles. The Kharkov radar data are also compared with the Atmosphere Explorer (AE) satellite data and FLIP model calculations for the midlatitude region, day and night local conditions, and minimum solar activity. The comparison demonstrates a similar character of the altitude distribution of H^+ ions and conditions of ionosphere–plasmasphere interaction. At the same time, the Kharkov radar data exceed the AE findings and model calculations. This discrepancy is explained by different heliogeophysical conditions.

Introduction

As it is known, hydrogen ions form an important component of the topside atmosphere. Their behavior is a sensitive indicator of space weather and its perturbations, which are reflections of geospace storms – a complex phenomenon that covers the Earth's magnetosphere and the near-Earth space and is driven by solar processes. The storms considerably effect the technological human activity and the "health" of the entire Earth's biosphere. The morphology and dynamics of light ions in the outer ionosphere are investigated on the global scale with modern ground-based and spaceborne instruments, including satellites and the global network of incoherent scatter radars (ISR). The complexity and high cost of investigations are repaid due to high value of the obtained information. The observational results are used to study solar-terrestrial relationships and to solve applied problems, including refinement of global reference models of the ionosphere, prediction of space weather and the radio wave propagation conditions, as well as calibration of the satellite data on the Earth's magnetosphere, etc.

The use of the global ISR network is a key point in investigations of latitudinal and longitudinal variations of the ion composition in the topside atmosphere. The investigations are conducted in the coordinated observation days of the POLITE (Plasmaspheric Observations of Light Ions in the Topside Exosphere) International Program, which is a part of the NSF CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions) Project.

Within the framework of such investigations, a comparison of observation results is of considerable interest. The results from different regions of the globe are important for understanding of ionospheric processes on the global scale. The results obtained with different instruments are needed for testing experimental techniques.

Systematic measurements of the altitude distribution of hydrogen ions by the ISR method over Kharkov have been conducted since 1996. The incoherent scatter radar of the Kharkov Institute of the Ionosphere is a single instrument of this kind in mid-latitudes of the European region. There are a total of eight IS radars in the world, four of them belong to the USA, and the other four are located in Northern Europe, Japan, Russia, and Ukraine. In this paper we compare the Kharkov radar data with the results obtained by Arecibo and Millstone Hill radars located on the American continent for the winter and summer conditions, as well as for the conditions of minimum and maximum solar activity (SA). In addition, the altitude distributions of hydrogen ions in the outer ionosphere measured by the Kharkov radar are compared with the satellite Atmosphere Explorer (AE) data and with the results of calculation by the FLIP model for the mid-latitude region. These data correspond to the inner plasmasphere (L = 2) and the invariant altitude range of 40–50°, that is, roughly

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to the coordinates of the Kharkov radar, for summer and winter conditions, as well as local day and night time at the minimal solar activity.

1. Investigations of the ionosphere with the incoherent scatter radar in Kharkov

The Kharkov Institute of the Ionosphere conducts investigations by the incoherent scatter method for more than 30 years. This method provides the most complete and accurate information about parameters of the ionosphere plasma in the altitude range from 100 to several hundreds of kilometers. The radar is located near Kharkov (geomagnetic coordinates: 45.7 and 117.8°, geographical coordinates: 49.6 and 36.3°). The Kharkov latitude almost coincides with that of Irkutsk (Russia) and is close to the latitude of Millstone Hill (USA). Besides, the radar is located at almost the same geomagnetic longitude with the EISCAT radars. Due to this location, the Kharkov radar well complements the global ISR network for investigation of the latitudinal-longitudinal effects in the behavior of the ionosphere. The meter-range radar operates at the frequency of 158 MHz with the maximum transmitter power ~ 3.6 MW (mean power of about 100 kW) and circular polarization. A 100-m zenith Cassegrain parabolic antenna has the gain coefficient of about 12700 (effective surface of about 3700 m^2, beam width ~ 1°), the system temperature varies from 570 to 1320 K, and the noise temperature of the high-sensitivity receiver is from 120 to 240 K.

The outer ionosphere is studied in the mode of sensing by single ~ 800-μs pulse, which provides for light ion measurements up to the altitude of ~ 1500 km. Signal accumulation for 1–15 min at the input signal-to-noise ratio from 10 to 0.1 allows the ionospheric signal to be measured with the accuracy of about 3–20%. The temperature and ion composition are determined from the measured autocorrelation functions (ACF) of the scattered signal through least-square fit to theoretical ones. The sine and cosine signal ACF components are used for simultaneous determination of the vertical ion speed. A detailed description of the radar design and the techniques for measurement and processing of data in different radar operating modes determined by the program of scientific research is given, for example, in Refs. 1–4.

2. Comparison of observations and discussion

2.1. Kharkov and Arecibo IS radar data obtained at minimum and maximum solar activity

Figure 1 depicts the measured results on the relative concentration of hydrogen ions $n(\mathrm{H}^+)/n_\mathrm{e}$ obtained by the IS radars in Arecibo (Λ = 30°N, L = 1.4, Refs. 5 and 6) and Kharkov (Λ = 45.7°N, L = 1.9) under similar heliogeophysical conditions of low solar activity (1996 and 1997 for Kharkov and 1965 and 1976 for Arecibo). Here Λ is the geomagnetic latitude, L is the McIlwain parameter in the units of the Earth's radius R_E, n_e is the electron concentration. It can be seen that the character of the diurnal behavior of H$^+$ ions in winter and summer in different Earth's hemispheres is principally similar. At the same time, there are some differences connected with latitudinal and longitudinal peculiarities in the behavior of the outer ionosphere.

These peculiarities can be reduced to the following. The peak of the H$^+$ concentration in the diurnal cycle at night, reaching the same value $n(\mathrm{H}^+)/n_\mathrm{e} \sim 100\%$, is observed by the two radars before the sunrise. In daytime, as known, plasma diffuses upward into the protonosphere due to the thermosphere heating and pressure increase in the F region. The concentration of light ions, in particular, H$^+$, decreases. The value of $n(\mathrm{H}^+)/n_\mathrm{e}$ in Arecibo in this case is almost triple as large as that in Kharkov. This fact can be explained by the longitudinal effect in the behavior of light ions due to different volumes of magnetic flux tubes[7]: $V \cong \frac{2}{3} R_\mathrm{E} L^4$. Parameter V is the half-volume of a geomagnetic flux tube with the unit cross section at the altitude of the bottom boundary of the outer ionosphere. For Kharkov and Arecibo the difference in volumes is ~ 3.4 times. A smaller volume V of a geomagnetic flux tube determines a higher concentration of H$^+$ in Arecibo. This effect is more pronounced against the background of low daytime values of $n(\mathrm{H}^+)/n_\mathrm{e}$, while at night both radars (in Kharkov and Arecibo) measured almost ultimate values of the relative concentration of H$^+$ ions. To be noted are also the latitudinal effects in the behavior of the outer ionosphere connected with the peculiarities of Arecibo location in the near-equatorial geographic sector (to the south from the northern tropic). Thanks to this, the nighttime duration in Arecibo, unlike Kharkov located in the mid-latitudes, is almost equal to the daytime duration, and this factor also affects the diurnal variations of H$^+$ ions.

In Kharkov the nighttime H$^+$ concentration is higher than the daytime one (see Fig. 1). At the altitude of 550 km the seasonal difference is almost twofold. As is known, it is caused by the fact that the winter thermosphere includes a larger amount of neutral hydrogen as compared to the summer one. Some effect of sunrise at a magnetic conjugate point (MCP) on the behavior of H$^+$ ions over Kharkov is observed as well. Thus, in winter the decrease in the concentration of hydrogen ions begins after sunrise at MCP (about 4 a.m. LT), while the local sunrise occurs ~ 2.5 h later. As known,[7] this effect is caused by thermal expansion of the still non-illuminated winter ionosphere due to heating of plasma in the flux tube by photoelectrons of the summer hemisphere. The magnetic conjugate point for Kharkov lies near Madagascar.

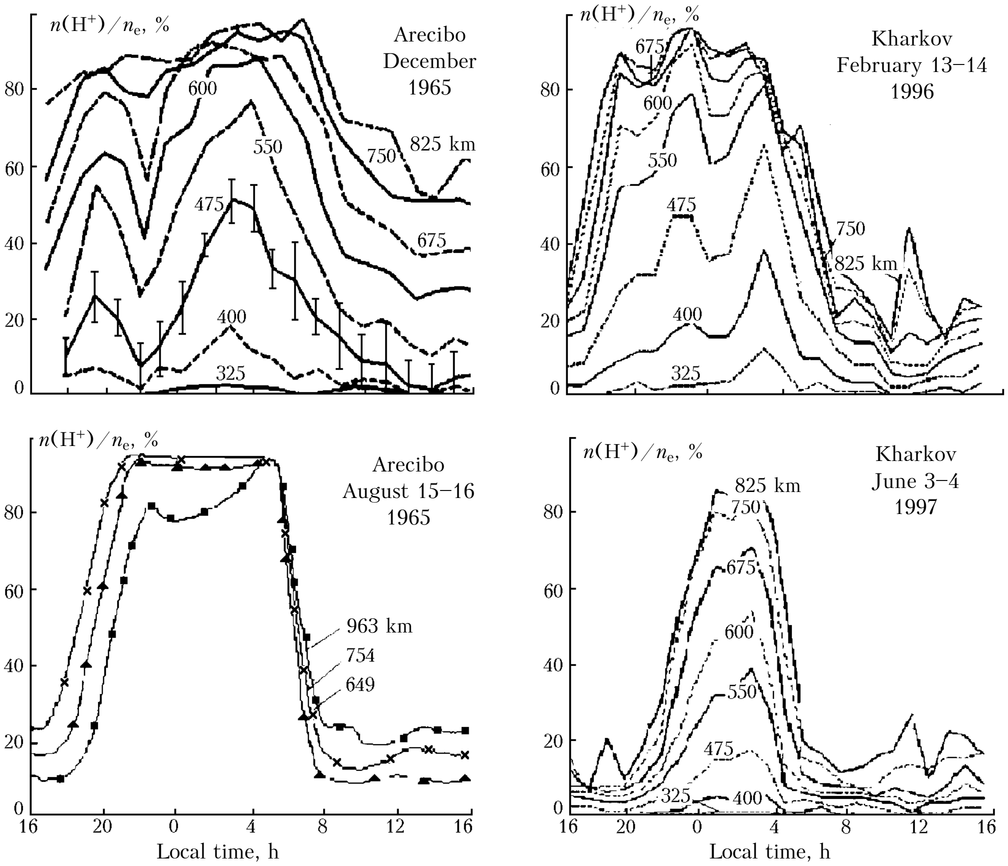

Fig. 1. Diurnal variations of the relative concentration of H^+ ions over Kharkov and Arecibo in winter and summer at the minimum solar activity.

Figure 2 depicts the altitude profiles of main components of the ionospheric plasma for winter at maximum SA as measured by radars in Kharkov and Arecibo.[8] Comparison of the results shows a close agreement on the whole. The differences are likely connected with different values of the solar radiation flux $F_{10.7}$ in the considered date, to which the behavior of H^+ ions is very sensitive.[9] The data for Arecibo correspond to the averaged (for 81 days) flux $F_{10.7} \sim 220$ units, while the data for Kharkov correspond to the flux $F_{10.7} \sim 180$ units. This explains the daytime excess of the maximum H^+ concentration in Kharkov ($\sim 3.5 \cdot 10^4\,\text{cm}^{-3}$) as compared to the Arecibo data ($\sim 1.5 \cdot 10^4\,\text{cm}^{-3}$). At night, longitudinal effects likely prevail, and the H^+ concentration in Arecibo ($\sim 2 \cdot 10^4\,\text{cm}^{-3}$) exceeds that in Kharkov ($\sim 1 \cdot 10^4\,\text{cm}^{-3}$). The level of the boundary h_t between the ionosphere and protonosphere, where $n(H^+) = n(O^+)$, is higher in Arecibo than in Kharkov roughly by 250 km during daylight hours and 50 km at night. As known, it is determined by the joint variations of the O^+ and H^+ concentrations that have an opposite character.

The altitude distributions of H^+ ions obtained over Arecibo and Kharkov give an additional information about the character of ionospheric-plasmaspheric interaction at different observation sites. Analyzing the altitude profiles of $n(H^+)$ (see Fig. 2), we can assume that in the daytime in winter the upward flux of hydrogen ions $\Phi = n_i V_{iz} > 0$ in Kharkov was close to some critical value, while in Arecibo it was smaller. At night the downward flux $\Phi < 0$ from the protonosphere, which is a source of plasma for the nighttime F region, was observed.

Comparison of the Kharkov and Arecibo radar data indicates a great significance of simultaneous measurements conducted within the framework of coordinated international ionospheric programs. An example of such comparison is given below.

2.2. Simultaneous measurements of the H^+ ion concentration over Kharkov and Millstone Hill

The measured results in the form of the altitude-time profiles of H^+ ion relative concentration are illustrated in Fig. 3. The data over the American continent were obtained at the Millstone Hill Haystack Observatory (Massachusetts Institute of Technology, USA). The measurements were conducted within the POLITE CEDAR program.

The radars are located on close geographical latitudes, but in different longitudinal sectors. Geographic coordinates of the radar in Millstone Hill are: 42.6°N, 71.5°W, and in Kharkov: 49.6°N, 36.3°E.

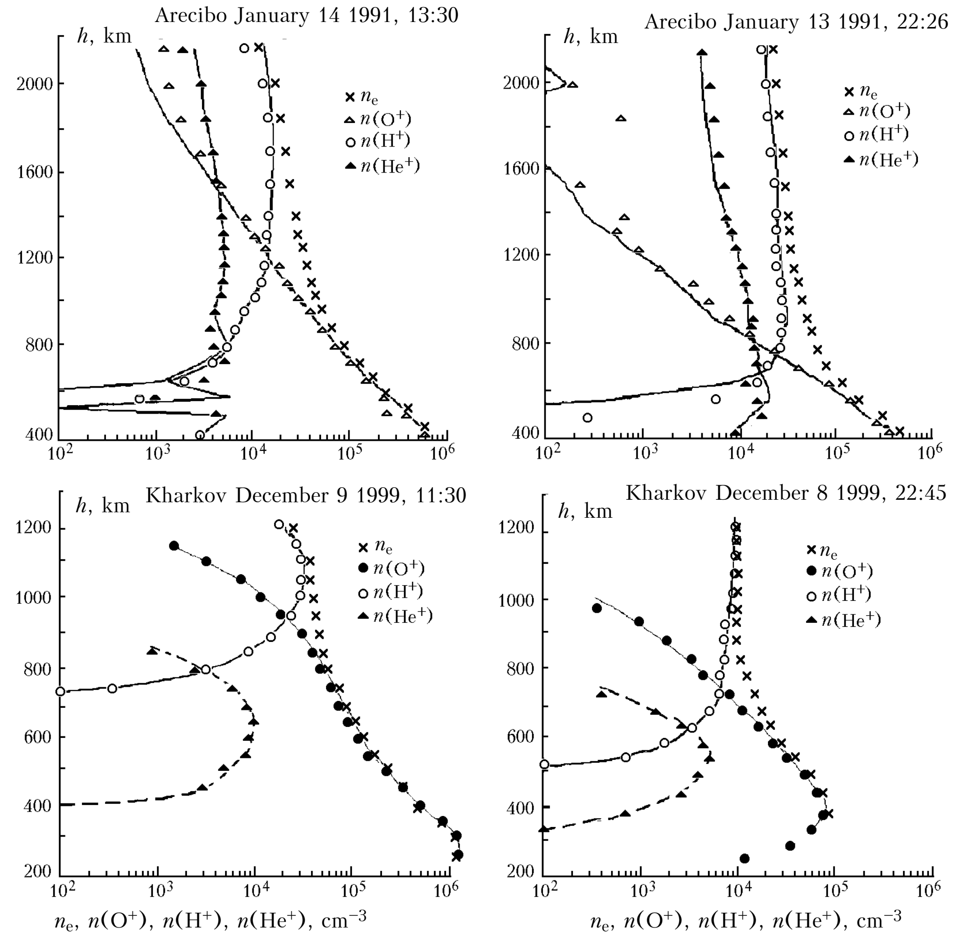

Fig. 2. Altitude profiles of concentration of O^+, H^+, He^+ ions and electrons in the years with maximum SA.

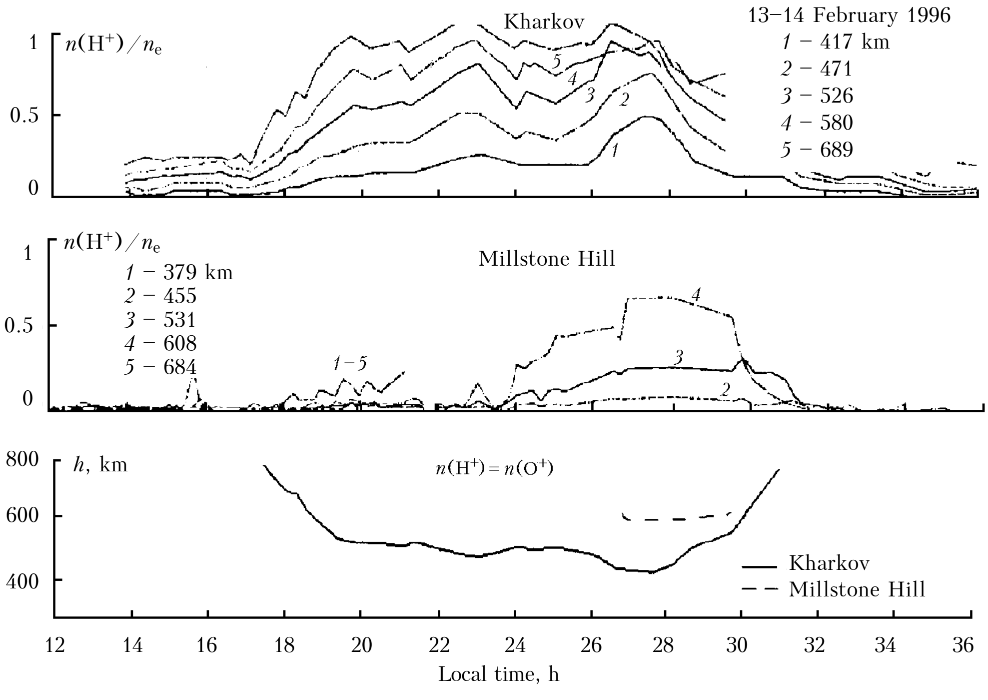

Fig. 3. Relative concentration of H^+ ions and the altitude of the boundary between the ionosphere and the protonosphere h_t, in km, where $n(H^+) = n(O^+)$ as measured by IS radars in Kharkov and Millstone Hill within the POLITE CEDAR program.

The non-coincidence of the geographic and geomagnetic Earth's poles leads to significant difference in geomagnetic latitudes of the radars: 52.9 and 45.7°N, and in the parameters L: 3.3 and 1.9 for Millstone Hill and Kharkov, respectively. The difference in the parameter L leads to the roughly nine times difference in the volumes of magnetic flux tubes. This fact explains the high relative concentrations of H^+ ions over Kharkov. They about six times exceed the $n(H^+)/n_e$ values in Millstone Hill, for example, in the nighttime at the altitude of ~ 450 km. The ionosphere/protonosphere boundary over Kharkov lies at the altitudes h_t = 400–800 km, while over Millstone Hill h_t it lies 100–200 km higher and is observed only late at night. To be noted is also the different contribution to the state of the winter ionosphere over the considered sites of the extra heating induced by photoelectrons from the illuminated (summer) hemisphere. For Millstone Hill the conjugate area is located behind the southern polar circle, where the sun does not set at that time, providing the continuous heat influx from the plasmasphere to the nighttime winter ionosphere of the Northern Hemisphere and causing a decrease in the H^+ concentration. For Kharkov the sunrise at MCP occurs about 4 a.m. LT and causes the beginning of the morning decrease of $n(H^+)$ over Kharkov roughly 2.5 h before the local sunrise.

The results of simultaneous investigations confirmed the presence of longitudinal variations in the behavior of H^+ ions in the outer ionosphere.

2.3. Factors controlling the altitude distribution of hydrogen ions

To analyze the peculiarities in the altitude distribution of H^+ ions in the multicomponent outer ionosphere for the cases considered below in Section 2.4, we examine some theoretical concepts.[7,10]

The behavior of the outer ionosphere is determined by the competitive effects of two factors: the ionizing solar radiation and the plasma exchange with the plasmasphere lying above. As known, in the process of the exchange, the plasma is transformed from oxygen to hydrogen one and back in accordance with the charge exchange reactions: $H + O^+ \Leftrightarrow H^+ + O$. The process of plasma transfer (from the ionosphere to the protonosphere and vice versa) is the ambipolar diffusion, which has some peculiarities connected with large spatial scales of the process in far regions. The altitude distribution of the hydrogen ion concentration $n(H^+)$ in the general case can be found through numerical integration of the system of continuity and motion equations for O^+ and H^+ ions and electrons. The continuity equation for hydrogen ions has the form

$$\frac{\partial n(H^+)}{\partial t} = q(H^+) - L(H^+) - \operatorname{div}\{\Phi(H^+)\},$$

where $q(H^+)$ is the rate of formation of hydrogen ions; $L(H^+)$ is the rate of loss due to chemical processes; $\operatorname{div}\{\Phi(H^+)\} = \operatorname{div} n(H^+)\mathbf{V}_\mathrm{d}$ is the local source of ion formation and loss due to transfer (diffusion) processes, $\mathbf{V}_\mathrm{d}$ is the diffusion velocity vector. Prevalence of photochemical or diffusion processes depends on the ratio of their time constants, which are determined by parameters of charged and neutral atmospheric components. These constants become equal at some altitude, usually, at 350–550 km for H^+ ions. The conditions of photochemical equilibrium prevail below this level, and those of diffusion equilibrium prevail above it.

It is well-known that in the transient zone between the topside $F2$ layer and the protonosphere, where O^+ prevail and H^+ ions form a secondary component, under the conditions of photochemical equilibrium, as in the case of diffusion equilibrium, the concentration of H^+ ions increases exponentially with height[11]:

$$n(H^+) \propto \exp[z'/H(7)],$$

where $H(7)$ is the reduced height with the "effective" ion mass of 7 a.u., and z' is the geopotential height. In the region, where H^+ ions dominate, under the conditions of statistical diffusion equilibrium the H^+ concentration decreases exponentially with the reduced plasma height:

$$n(H^+) \propto \exp[-z'/H(1/2)].$$

The maximum of the H^+ should obviously lie at the transient altitudes. The condition of static diffusion equilibrium, which was mentioned above, corresponds to the case of zero flux of charged particles in the static neutral atmosphere, when the term

$$\operatorname{div}\{\Phi(H^+)\} \approx \partial\Phi_z/\partial z = 0 \text{ and } \mathbf{V}_\mathrm{d} = 0$$

in the continuity equation for H^+ ions.

In the general case, in the multicomponent outer ionosphere the concentration distribution $n_j(s)$ of the charged component j, which diffuses through the fixed prevailing component i along the magnetic field line (with the coordinate s), is determined through solution of the continuity equation, which has the following form[7,10]:

$$\frac{\partial}{\partial s} n_j V_j = \frac{\partial}{\partial s}\left[-D_{ji}\left(\frac{\partial n_j}{\partial s} + \frac{n_j}{H_j} - \frac{n_j}{H_\mathrm{p}}\right)\right] = 0$$

under the stationary conditions in the absence of sources and loss and neglecting the divergence of magnetic force lines. Here H_j and H_p are the reduced heights of the jth component and plasma; D_{ji} is the coefficient of ambipolar diffusion of the jth component through the prevailing component i. In the general case of dynamic diffusion equilibrium, this equation has a solution with the constant nonzero flux

$$\Phi = n_j V_j = \text{const}$$

and the concentration distribution of the jth component:

$$n_j(s) = n_j^{(1)}(1 - \Phi/\Phi_L) + n_j^{(2)}\Phi/\Phi_L.$$

Here $n_j^{(1)}$ is the solution at $\Phi = 0$ and $n_j^{(2)}$ is that at $\Phi = \Phi_L$, where Φ is the flux at the top boundary and Φ_L is the limit (maximum possible) upward diffusion flux of ions (H^+ in our case).

Figure 4 illustrates the model concept on the processes of ionospheric-plasmaspheric interaction and on the altitude distribution of the concentration of H^+ and O^+ ions in the outer ionosphere at different values of Φ/Φ_L (Ref. 12).

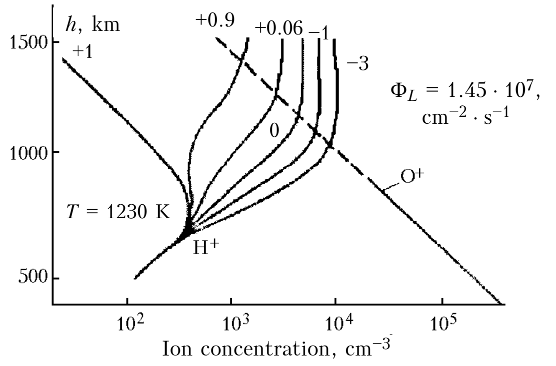

Fig. 4. Examples of numerical calculations of the altitude distributions of $n(H^+)$ and $n(O^+)$ for different values of Φ/Φ_L (Ref. 12).

2.4. Kharkov IS radar findings as compared with Atmosphere Explorer satellite data and FLIP model results

In this section, we compare the H^+ concentrations in the outer ionosphere as obtained from the ground-based (Kharkov IS radar) and space (Atmosphere Explorer satellites) measurements, as well as those calculated by the ionosphere FLIP model. The satellite and model data were borrowed from Ref. 13. They are for a mid-latitude region corresponding to the inner plasmasphere ($L = 2$) and the interval of invariant latitudes $\Lambda = 40$–$50°$, that is, roughly to the coordinates of the Kharkov radar. Theoretical calculations in Ref. 13 were performed by the FLIP (Field Line Interhemispheric Plasma) model,[14] which describes the distribution of the topside atmosphere parameters along the magnetic flux line between two hemispheres.

For comparison, we took the findings of the Kharkov IS radar obtained in February of 1996 and in June of 1997. The data were obtained by one-hour averaging of 15-min measurement sessions (accumulated from initial 1-min sessions) for February 13–14 of 1996 and June 3–6 of 1997. These data correspond to magnetically calm days, low solar activity, and the flux $F_{10.7} \approx 70$ units.

The altitude profiles of $n(H^+)$ obtained from the Kharkov ISR findings, the data of AE satellites, and model calculations are shown in Fig. 5. Further they are discussed in more detail based on the above theoretical concepts.

Summer, midnight. The altitude profile of the H^+ concentration as calculated by the FLIP model data likely corresponds to the conditions of static diffusion equilibrium at $\Phi = 0$ or the weak downward flux $\Phi < 0$. At the same time, the data of the AE satellite have two peaks and more likely correspond to the upward flux $\Phi > 0$. Judging from the character of the altitude distribution of H^+ ions and the presence of a double peak in the profile, the Kharkov radar data agree with the AE results, but exceed them in the entire altitude range. For example, at the altitude of 600 km, where the difference is maximum, the values of $n(H^+)$ obtained from the AE data ($\sim 0.32 \cdot 10^4$ cm^{-3}) and the Kharkov radar findings ($\sim 1.78 \cdot 10^4$ cm^{-3}) differ more than five times.

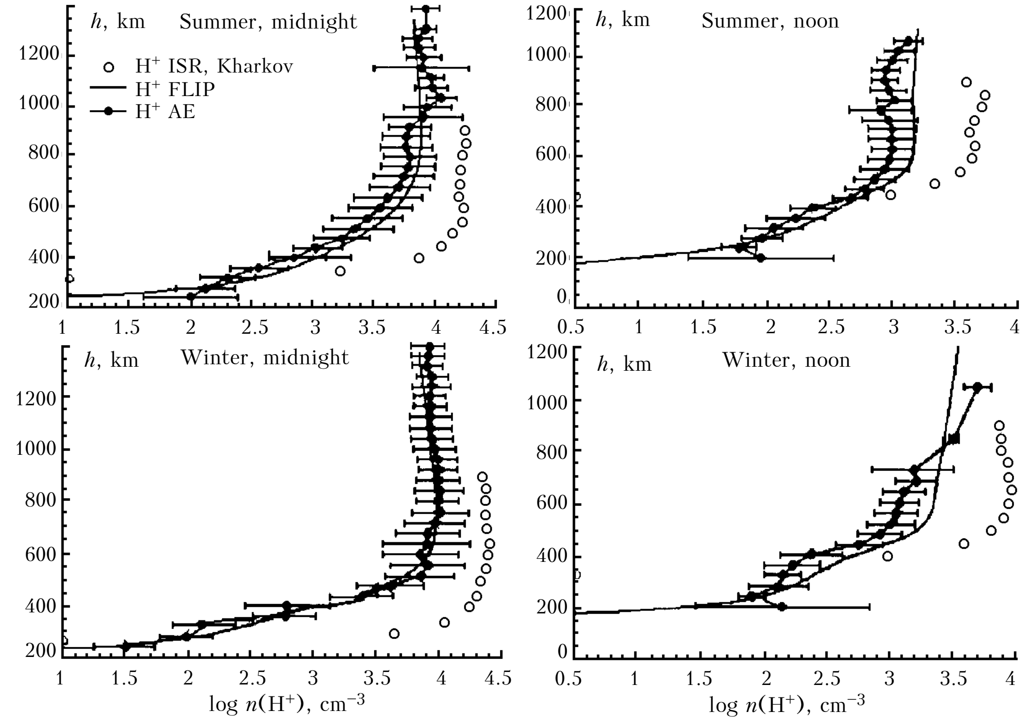

Fig. 5. Comparison of altitude profiles of $n(H^+)$ obtained from the Kharkov IS radar findings, AE data,[13] and calculations by the FLIP model.[14]

Summer, noon. Model calculations and the AE satellite results are close in both the shape and the values of $n(\mathrm{H}^+)$ and correspond to the upward flux $\Phi > 0$ with its value small as compared to the limiting flux Φ_L. The radar data have the similar character of the altitude distribution of $n(\mathrm{H}^+)$, but exceed the model calculations three times and the AE satellite data four times at the altitude of 600 km.

Winter, midnight. It is seen from Fig. 5 that the model calculations of $n(\mathrm{H}^+)$ and the AE satellite results almost coincide and likely correspond to the downward flux of plasma from the protonosphere, which is characteristic of the winter period at low SA. With the similar shape of the $n(\mathrm{H}^+)$ profile, the Kharkov radar data exceed the satellite and model values up to three times at the altitude of 600 km.

Winter, noon. The results compared correspond most probably to the conditions of the weak upward flux $\Phi > 0$. In this case, the radar data at the altitude of 600 km exceed the model value five times and the satellite results up to seven times.

Let us analyze briefly the possible reasons for this significant excess of the H^+ ion concentration measured by the Kharkov radar over the satellite data and model calculations.

It should be noted that the AE data[13] were obtained through averaging of voluminous findings of the Atmosphere Explorer satellites A, C, D, and E. Every point is the result of averaging for a 6-h interval centered with respect to the local noon or midnight for 3-month near-solstice periods and covers the range $F_{10.7} = 70$–120 units with the mean 92 units and all levels of geomagnetic activity. Besides, these data integrate the results of measurements in the both Earth's hemispheres. Calculation by the FLIP model was performed for similar conditions, in particular, for the flux $F_{10.7} = 100$ unit. Therefore, we could expect that the averaged satellite data and calculations performed for so wide range of heliogeophysical conditions will not correspond to the results of specific observations in Kharkov. It should be also noted that investigations of the outer ionosphere over Kharkov for 1996–2002 showed a strong dependence of the H^+ concentration on the SA level (flux $F_{10.7}$) (Ref. 15). Therefore, the difference in the values of $n(\mathrm{H}^+)$ can be explained by the fact that the index $F_{10.7}$ describing the SA minimum is different for the AE and model data[13] ($F_{10.7}$ = 100 units) and the Kharkov radar data ($F_{10.7}$ = 70 units).

Conclusion

Comparison of the results obtained with different ground-based and space measurement tools is necessary for checking the measurement techniques and adequate understanding of global-scale ionospheric processes. In this paper, we compare the concentrations of hydrogen ions $n(\mathrm{H}^+)$ in the outer ionosphere as measured by incoherent scatter radars in Kharkov, Arecibo, and Millstone Hill. The comparison has shown that under different heliogeophysical conditions (day and night, winter and summer, minimum and maximum solar activity), the altitude–time variations of $n(\mathrm{H}^+)$ over the Eastern and Western Earth's Hemispheres have no principal differences. The nighttime concentration of H^+ ions exceeds the daytime one both in winter and summer. For Kharkov this excess is twofold at minimum SA. The results of simultaneous observations conducted at Kharkov and Millstone Hill mid-latitude radars under the POLITE CEDAR Program have practically confirmed the existence of significant longitudinal variation in the behavior of hydrogen ions. This variation is explained by the difference in the L parameters and volumes of magnetic flux tubes due to non-coincidence of the Earth's geographical and geomagnetic poles. The contribution of additional heating by photoelectrons from the conjugate summer hemisphere to the behavior of hydrogen ions in the winter ionosphere over Kharkov and Millstone Hill has been analyzed.

The findings of the Kharkov radar have also been compared with the results of $n(\mathrm{H}^+)$ measurement at the Atmosphere Explorer satellite and with calculations of ion composition by the FLIP model. The comparison results are interpreted in view of current concepts on the processes of ionospheric-plasmaspheric interaction and the distribution of H^+ ions in the multicomponent outer ionosphere. The comparison has shown the principal agreement in the character of the altitude distribution of $n(\mathrm{H}^+)$ as judged from the Kharkov radar findings, the AE satellite data, and model calculations with the significant excess (several times) of the absolute values of the hydrogen ion concentration over Kharkov. This difference is likely explained by different values of the $F_{10.7}$ flux for the results compared.

The comparisons performed have demonstrated the capabilities of the Kharkov IS radar in investigation of the outer ionosphere (up to the altitudes ~ 1300 km) over the Eastern Europe. The results of measurement in Kharkov just fill the gap in the information obtained mostly with radars located on the American continent. They were used to test current models of the outer ionosphere, in particular, the FLIP model.[16]

Acknowledgments

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