Cosmic Research, Vol. 38, No. 5, 2000, pp. 502–513. Translated from Kosmicheskie Issledovaniya, Vol. 38, No. 5, 2000, pp. 536–548.
Original Russian Text Copyright © 2000 by Bezrukikh, Verigin, Kotova, Lezhen, Lemaire, Venediktov.

Plasmapause Dynamics and Distribution of Cold Plasma Density in the Earth's Plasmasphere in the Course of Development of Geomagnetic Storms: Results of the *Auroral Probe*/Alpha-3 Experiment

V. V. Bezrukikh[1], M. I. Verigin[1], G. A. Kotova[1], L. A. Lezhen[1], J. Lemaire[2], and Yu. I. Venediktov[3]

[1] *Space Research Institute, Russian Academy of Sciences, ul. Profsoyuznaya 84/32, Moscow, 117810 Russia*

[2] *Institute of Aeronomy and Space Physics, Brussels, Belgium*

[3] *State Polytechnic University, Odessa, Ukraine*

Received March 30, 2000

Abstract—During the *Auroral Probe*/Alpha-3 experiment, the data about the dynamics of the H^+ ion density deep in the plasmasphere were obtained before and in the course of the development of several geomagnetic storms in the postmidnight and noon plasmasphere sectors. It was found that, in the postmidnight sector, the development of weak and moderate geomagnetic storms is accompanied by a considerable decrease of the H^+ ion density inside the plasmasphere. This seems to be explained by cold plasma escaping into the ionosphere. In the daytime sector, at the initial phase of a storm, a considerable decrease of the H^+ ion density inside the plasmasphere was observed, which then was replaced by a considerable increase. Variations of the H^+ ion density in the daytime plasmasphere seem to be a result of variations of cold plasma fluxes from the ionosphere into the plasmasphere during ionospheric storms. In contrast to the model of propagation of plasmasphere deformations during magnetic substorms from the night sector into the daytime sector with the corotation rate proposed by the authors [6], the practically simultaneous beginning of the plasmapause displacement to the Earth in the night and daytime sectors is found. It is also found that the plasmapause displacement to the Earth in the daytime sector lasts for 10–12 h, once the night plasmapause begins to move away from the Earth. The last fact seems to be explained by the arrival (from the nightside to the dayside as a result of corotation) of magnetic field tubes with a plasma of reduced density as a result of a magnetic substorm.

1. INTRODUCTION

At present, one of the aspects influencing the geomagnetic disturbances on the plasmasphere is the dependence of the plasmapause position (the boundary of the area of the geomagnetosphere nearest to the Earth, where cold plasma of an ionospheric origin is contained) on the level of geomagnetic activity. This dependence has been investigated in sufficient detail. Another, not less important, aspect of this dependence is the dynamics of distribution of cold plasma density inside the plasmasphere, connected with emptying and refilling geomagnetic tubes by cold plasma during geomagnetic disturbances. This aspect has been investigated to a much lesser extent. In this paper, the results of monitoring the plasmapause position and cold plasma density inside the plasmasphere in the daytime and postmidnight sectors of the plasmasphere immediately before and during the geomagnetic substorms on September 4–5 and 9–10, 1996, and June 8–9, 1997, are presented.

Beginning in the 1960s, empirical dependences of the plasmapause position on the level of geomagnetic activity, generally, rather similar among themselves, were obtained by different research groups [1–5]. The value of the K_p index was used as a parameter characterizing the level of geomagnetic disturbances. In some papers, the maximum value of the K_p index during the 24 h preceding the measurements of the plasmapause [1, 3] was used as the K_p index; in other papers, the maximum value of the K_p index during the 12 h before measurements of the plasmapause position [4, 5] was used. Generally, these investigations have shown with certainty a connection between the plasmapause position and the level of geomagnetic activity. At the same time, in our opinion, they are one of the reasons of the widespread views about the considerable time lag of the plasmapause response to the changing level of geomagnetic activity.

Distributions of charged particle densities inside the plasmasphere were presented and discussed in the papers of a number of authors, for example, in [5–7]. A complete bibliography on this problem can be found in [8]. We will concentrate our attention only on papers where the dependence of the distribution of charged particles in the plasmasphere on the level of geomagnetic disturbances is considered.

In 1962 (even before the existence of the plasmasphere and plasmapause were recognized), Carpenter

0010-9525/00/3805-0502$25.00 © 2000 MAIK "Nauka/Interperiodica"

[9] reported about the strong dependence of the electron density in the magnetosphere on geomagnetic disturbances. He recorded a 4- to 16-fold decrease in the electron density in the magnetosphere, which had occurred as a result of a geomagnetic storm. In [9], the coordinates of the area where the indicated effect was observed were not given, and, therefore, it was impossible to judge with reliability the reasons for the density decrease. For example, if it is assumed that the considered area was at $L = 3$–4, then at the present time, when we know about the existence of the plasmasphere and its dynamics, one of possible explanations for the decrease of the electron density noted in [9] can be a change of the plasmapause position caused by a magnetic storm. The authors [10, 11] have presented a schematic illustration of the dynamics of electron density close to the plasmapause in connection with geomagnetic storms. Park [12] observed the increase of cold plasma flows from the plasmasphere into the ionosphere in night hours, which, in our opinion, is the reason for the density increase in the night winter ionosphere. In [12], the author also reported about his observation of considerable flows of plasma during some substorms, which flew from the plasmasphere into the ionosphere even in the daytime. In this connection, he suggested that the indicated processes, in many cases, determine the response of both areas to geomagnetic substorms. The empirical model of distribution of the H^+ ion density in the Earth's plasmasphere developed on the basis of results of measurements by the RIMS device onboard the *DE-1* satellite was presented in [13]. The model of the distribution of cold plasma density for an interval of local time 21–06 MLT was presented in [14]. These models enable one to estimate the distribution of cold plasma density in the plasmasphere at low and medium geomagnetic latitudes in different intervals of local time and geomagnetic activity; however, as other models based on statistical methods, the models of the plasmasphere [13, 14] do not allow one to trace the dynamics of cold plasma inside the plasmasphere in the course of the development of concrete geomagnetic disturbances. Lemaire [15] notes that "... there are essentially no experimental data documenting detailed aspects of the depleting".

2. EXPERIMENTAL RESULTS

In this section, only the results of measurements and brief comments about them are presented. To characterize geomagnetic disturbances, the classification from [16, 17] is used. The results of measurements are discussed in Section 3.

For representation of the *Auroral Probe* orbit position in space, in this paper, we use projections on the meridional plane with the polar coordinate geocentric distance R_E for the polar angle above the geomagnetic equator plane, and on the equatorial plane with coordinates L (the McIlwain parameter) and MLT (magnetic local time).

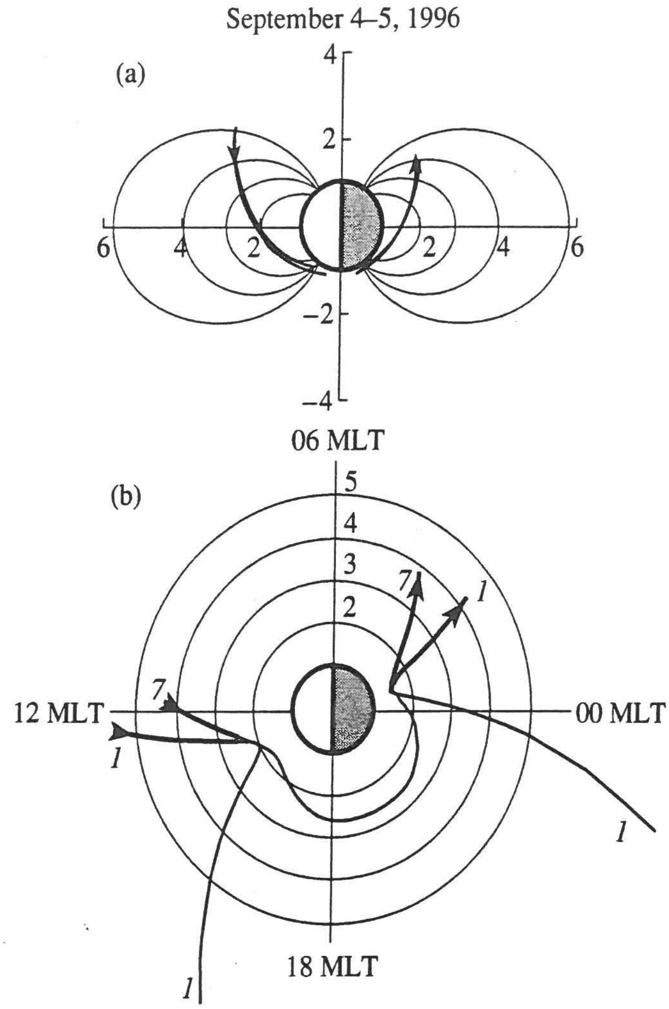

Fig. 1. Projection of the 1st and 7th orbits of the *Auroral Probe* in the period of September 4–5, 1996. (a) Projection of orbits onto the meridional plane; (b) onto the equatorial plane.

Results of Measurements on September 4–5, 1996

Figures 1a and 1b show projections of the first and seventh (the last) *Probe* orbits for the period under consideration. It is seen from Figs. 1a and 1b that the orbit meridional projections are rather close to each other; the descending and ascending orbit segments are in the noon and postmidnight sectors of the plasmasphere, respectively. In Fig. 1b, the segments of orbits along which distributions of the H^+ ion density were measured are marked by thick lines; the directions of the *Probe* flight are indicated by arrows on the projections of orbits. Distributions $n_{H^+}(L)$ in the daytime and predawn sectors of the plasmasphere measured over seven consecutive passages of the *Auroral Probe* through the plasmasphere in the period of September 4–5, 1996, are presented in Fig. 2a. Figure 2b shows variations of the D_{st} index for the same period. On the time axis, the instants (and durations) of each *Probe* passes are marked by thick dashes; each *Probe* passes is numbered. The same numbers of passages are shown on

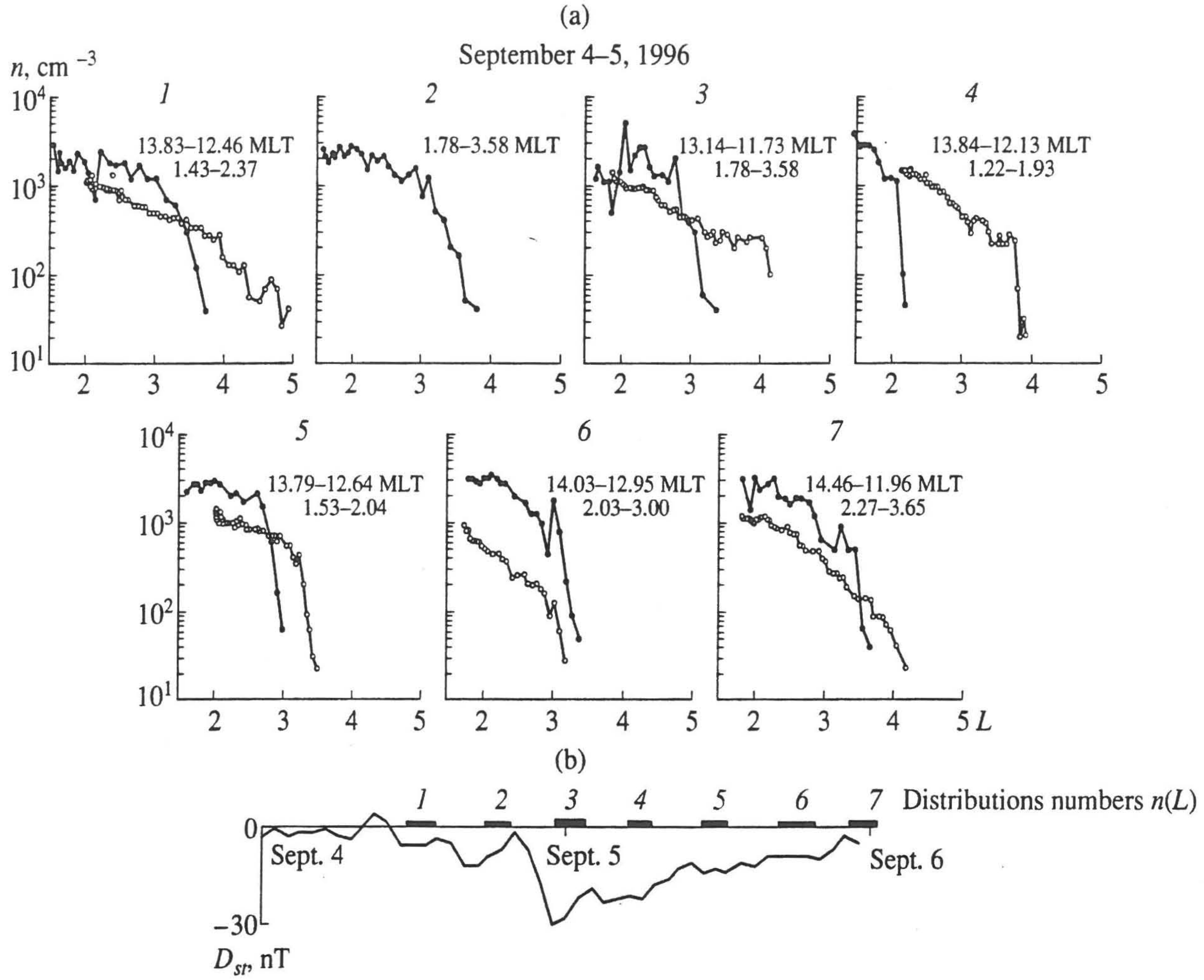

Fig. 2.
(a) Postmidnight and daytime distributions $n_{H^+}(L)$ measured during 7 consecutive passages of the *Probe* through the plasmasphere in the period of September 4–5, 1996 (each distribution is numbered from 1 to 7). Night distributions $n_{H^+}(L)$ are shown by points and daytime distributions by open circles; (b) plot of the D_{st} variation in the period of September 4–5, 1996.

each pair of $n_{H^+}(L)$ distributions. The results of the measurement in other time intervals are also shown in a similar way.

Let us first consider the dynamics of $n_{H^+}(L)$ distributions in the plasmasphere and of the plasmapause position in the postmidnight sector. It can be seen from Fig. 2b that, generally, the period of September 4–5, 1996, is characterized by low geomagnetic activity. Up to 23:00 UT on September 4, $D_{st} \sim -10$, and at ~23:00 UT a rather moderate isolated storm was recorded ($D_{st\min} \sim -30$ nT, $K_{p\max} = 4.3$).

The distributions $n(L)$ measured before the beginning of the storm during *Probe* passages through the plasmasphere *1* and *2* are similar to each other and, presumably, can be considered as typical for quiet periods in the predawn and, probably, night sectors. Let us note also that, in both cases considered, the plasmapause position practically was not changed ($L \sim 3.6$). The third distribution was measured in the course of the development of the storm that began at ~23:00 UT. Presumably, the considerable indentation, which distinguishes the third night $n_{H^+}(L)$ distribution from the first two, can be explained by the storm development. One should call attention to the fact that, in this case too, 3 h after reaching the maximum of the storm, the plasmapause position has changed insignificantly (it was recorded at $L = 3.4$).

Radical changes in the postmidnight sector were recorded during the forth *Probe* passes through the plasmasphere. Approximately at 06:00 UT, 7 h after the beginning of the storm, the plasmapause was found at $L = 2.2$ (i.e., at an altitude of less than 8000 km in the plane of the geomagnetic equator!). Measurements of the H^+ ion density during the fifth *Probe* passes through the plasmasphere have shown that after 6 h the geocentric distance of the plasmapause already was $\sim 3R_E$. Further, during the 6th and 7th *Probe* passages through the plasmasphere, a gradual displacement of the plasmapause away from the Earth was recorded. In the early part of September 6, the plasmapause was transferred at

$L = 3.6$, i.e., to the position where it was before the beginning of the storm.

In contrast to the postmidnight sector of the plasmasphere, where a sharp displacement of the plasmapause to the Earth was recorded in the course of the development of a rather moderate storm, during the greater part of the same storm, in the daytime sector a slow monotonous approach to the Earth was found, and only at the end of the considered period and at the end of the recovery phase of the storm was the return of the plasmapause to the initial (recorded during the first *Probe* passes) position noted. The dynamics of the plasmapause in the postmidnight and daytime sectors of the plasmasphere during the considered period is shown in Fig. 3a. Figure 3c shows the time dependence of the K_p index and D_{st} variations. Data comparison in Figs. 3a and 3c shows that before the storm beginning the position of the night plasmapause was practically stable. The plasmapause displacement to the Earth began only after the beginning of the storm, and ~6 h later the plasmapause was recorded at $L \sim 2.2$. In the following 6 h the plasmapause occurred at $L \sim 3$, and at the end of considered period, the night plasmapause was recorded at $L = 3.6$. Presumably, the motion of the daytime plasmapause to the Earth also began with the storm beginning, simultaneously with the beginning of motion of the night plasmapause to the Earth, and continued after the geocentric distance of the night plasmapause began increasing. As follows from Fig. 2a, the daytime plasmapause reached the nearest distance to the Earth (at $L = 3$) 12 h later than the night plasmapause (at $L = 2.2$).

Some knowledge (far from complete!) about the dynamics of the H^+ ion density inside the plasmasphere under quiet conditions and during geomagnetic disturbances can give the analysis of the variation of the H^+ ion density at a fixed value of the L parameter. We chose a fixed value of the L parameter so that the altitude of a chosen point above the Earth's surface, remaining in the plasmasphere, would be the highest. In the considered case, it was chosen as $L = 2.4$. Figure 3b shows the curves characterizing variations of the H^+ ion density in the daytime (open squares and the gray curve) and postmidnight (full squares and the thick curve) sectors. Each curve is normalized on the value of density n_0 in the first point (the normalization coefficients for the night and daytime sectors are $n_0 = 1300$ and $n_0 = 900$, respectively). The above values of normalization coefficients show that, in the daytime, the H^+ ion density is much lower than in the night sector.

The results obtained are discussed in Section 3.

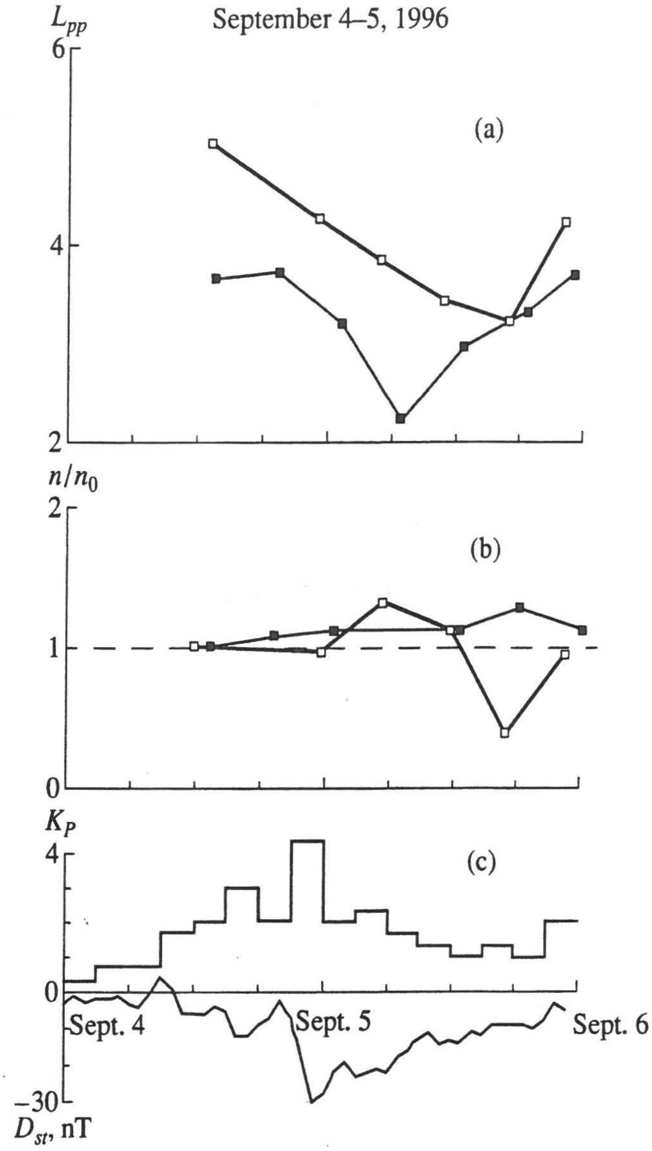

Fig. 3. (a) Dynamics of the plasmapause in the postmidnight (black squares) and in the daytime (empty squares) sectors in the period of September 4–5, 1996; (b) normalized variations of density in the plasmasphere at $L = 2.4$ in the postmidnight (black line) and daytime (gray line) sectors. Each plot is normalized to the value of density measured during the 1st passes of the *Probe*; (c) the K_p indexes and D_{st} variations in the period of September 4–5, 1996.

Results of Measurements on September 9–11, 1996

Projections of the *Auroral Probe* orbits on the meridional and equatorial planes in the considered period are shown in Figs. 4a and 4b. Figure 5a shows distributions $n_{H^+}(L)$ measured in the postmidnight and daytime sectors during 12 passages of the *Auroral Probe* through the plasmasphere in the period of September 9–12, 1996. Distributions 1–7 and 10–12 are measured with an interval of 6 h. During passages 8 and 9, the Alpha-3 instrument was turned off. Below, in Fig. 5b, variations of the K_p index and the D_{st} variations for the same period are shown. It is seen from the variations of the K_p index that, at the end of the generally magnetically quiet day of September 9 ($D_{st} > -20$, $K_p < 2$), the value of the K_p index suddenly increased by a step to 4.3 thus denoting the beginning of a storm, whereas at the same time the value of $|D_{st}|$ slowly and nonmonotonically increased, peaking only after 9 h. Taking into account the particularity of the definition of both geomagnetic indexes used by us, it is possible to conclude that, in the case under consideration, the level

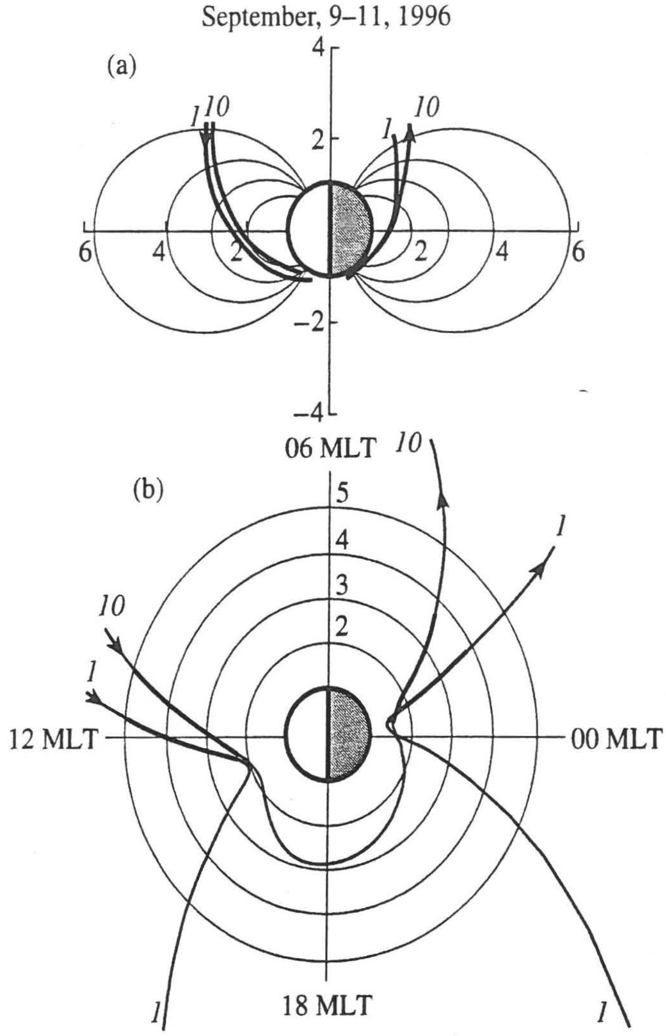

Fig. 4. Projection of the 1st and 12th orbits of the *Auroral Probe* in the period of September 9–11, 1996. Notation and coordinates are the same as in Fig. 1.

of the geomagnetic disturbance is determined by processes, mainly, at medium and, probably, at auroral latitudes. Another feature of the geomagnetic activity of the considered period is the superposition of several storms, which did not allow us, in this case, to determine the response of the plasmasphere and the plasmapause to different phases of the geomagnetic disturbances.

From Fig. 5b it follows that the first 2 passages through the plasmasphere occurred in quiet geomagnetic conditions, and the 3rd passes occurred in conditions when the K_p index increased from 2 to 4. Passages 5–7 and 10–12 occurred on the background of several substorms following one after another.

Distributions $n_{H^+}(L)$ measured in the period of September 9–12, 1996, are shown in Fig. 5a. In spite of the fact that passages 1 and 2 through the plasmasphere occurred in quiet conditions, distributions $n_{H^+}(L)$ measured during these passages, especially after midnight, are very indented. The postmidnight distributions $n_{H^+}(L)$ recorded during the 4th passes of the *Probe* after a sharp increase of the K_p index are strongly deformed. The distinct difference of this distribution from the previous one can be explained by cold plasma contained in the geomagnetic shells $L < 3$ escaping into the ionosphere. It is not improbable that the beginning of the process of the recovery of the content of the plasma at low L shells can be observed during the following, 5th passes of the *Probe*. Distributions $n_{H^+}(L)$ measured during passes 10–12 seem to reflect the process of recovery of the content of cold plasma at $L < 3$, which could decrease under the influence of a new storm that occurred on September 11, 1996, at ~05:00 UT.

Since the plot showing the dynamics of the plasmapause in the period of September 9–11, 1996, was already published in [24], it is not given in this paper.

Variations of the H^+ ion density inside the plasmasphere in the period of September 9–11, 1996, at $L = 2.4$ in the postmidnight and daytime sectors are shown in Fig. 6a. Again, as in Fig. 2b, both the postmidnight and the daytime values of the density are normalized on the value of density n_0 at $L = 2.4$ in the night and daytime sectors, respectively. Figure 6b shows the changes in the K_p index and D_{st} variations for the same period.

Results of Measurements on June 8–10, 1997

Projections of the *Auroral Probe* orbits on the meridional and equatorial planes in the indicated time interval are shown in Figs. 7a and 7b. During this time in the course of 10 consecutive *Probe* passages through the plasmasphere, 10 distributions $n_{H^+}(L)$ were measured, which are shown in Fig. 8a. Unfortunately, measurements in the postmidnight sector were found to be fragmentary owing to insufficient telemetric support of the experiment and, therefore, distributions $n_{H^+}(L)$ measured in the postmidnight sector during the considered interval are not given here, but only the plasmapause positions are shown. In Fig. 8b as in Figs. 2b and 5b, the changes of the K_p index and the D_{st} variations are shown for the same interval. The times of the *Probe* passes through the plasmasphere are marked by thick lines on the time axis.

The geomagnetic activity in the beginning of the considered period was characterized by a slow increase. It was replaced by a magnetic storm of class II (according to the classification proposed in [13, 14]), which began at 17:30 UT and lasted to the end of the considered interval (see Fig. 8b).

From the first 3 distributions $n_{H^+}(L)$ measured under conditions of increasing magnetic activity, a practically stable plasmapause position and some decrease of the H^+ ion density inside the plasmasphere can be seen. The fourth distribution measured during the phase of storm growth shows the plasmapause displacement to the Earth and, simultaneously with it, an increase of the H^+ ion density inside the plasmasphere. During the sub-

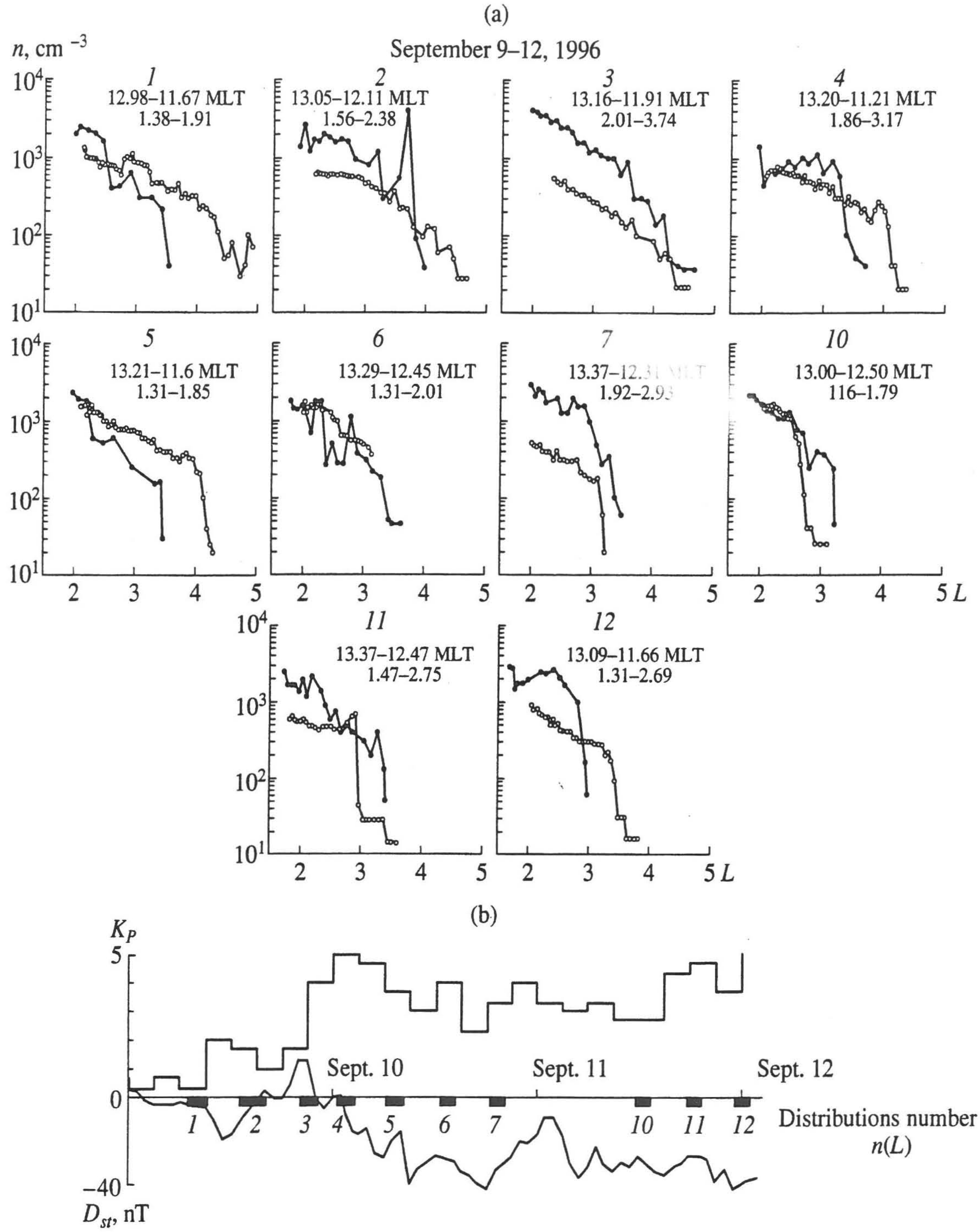

Fig. 5. (a) Postmidnight and daytime distributions $n_{H^+}(L)$ measured during 12 consecutive passages of the *Probe* through the plasmasphere in the period of September 9–12, 1996 (distributions are numbered from 1 to 7 and from 10 to 12). Night distributions $n_{H^+}(L)$ are shown by points and daytime distributions by open circles; (b) plot of the D_{st} variation in the period of September 9–12, 1996. On the time axis, time intervals of the *Probe* passes through the plasmasphere are marked by thick dashes.

sequent 24 h, when the level of geomagnetic activity remained rather high ($D_{st} < -60$), the value of the density $n_{H^+}(L)$ inside the plasmasphere remained at an enhanced level, and the plasmapause position changed from $L = 2.7$, recorded during the 5th passes, to $L = 2.1$ during the 8th passes. Later, during the phase of recovery, a decrease of density inside the plasmasphere occurred, and, together with it, there was an increase in the geocentric distance of the plasmapause.

Figure 9a shows the dynamics of the position of the daytime and postmidnight plasmapause in the period of June 8–10, 1997; the time dependence of the normalized H^+ ion density inside the plasmasphere (at $L = 2.25$) is shown in Fig. 9b. Changes in the K_p index and D_{st} variations over the same period are shown in Fig. 9c.

From Fig. 9a it can be seen that, as on September 4–5, 1996 (see Fig. 2a), the plasmapause displacement to the Earth in the postmidnight and daytime sectors of the

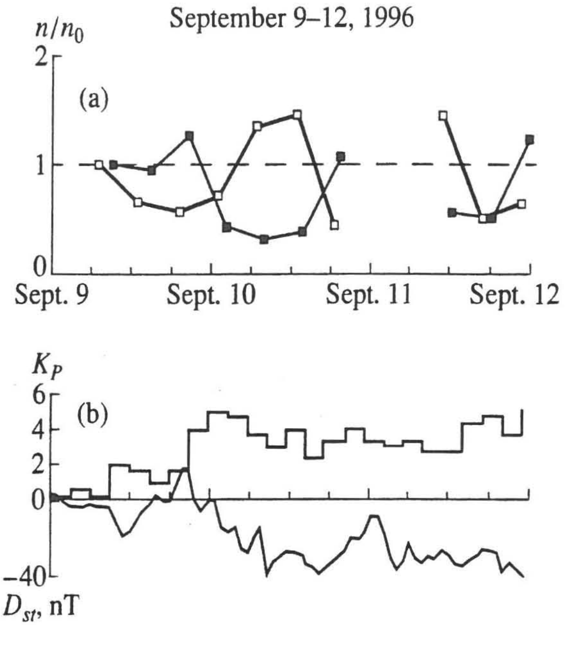

Fig. 6. (a) Normalized variations of the density in the plasmasphere at $L = 2.4$ in the postmidnight (black squares) and daytime (empty squares) sectors in the period of September 9–12, 1996. Each plot is normalized by the value of the density measured during the 1st *Probe* pass; (b) the K_p indexes and D_{st} variations for the same period.

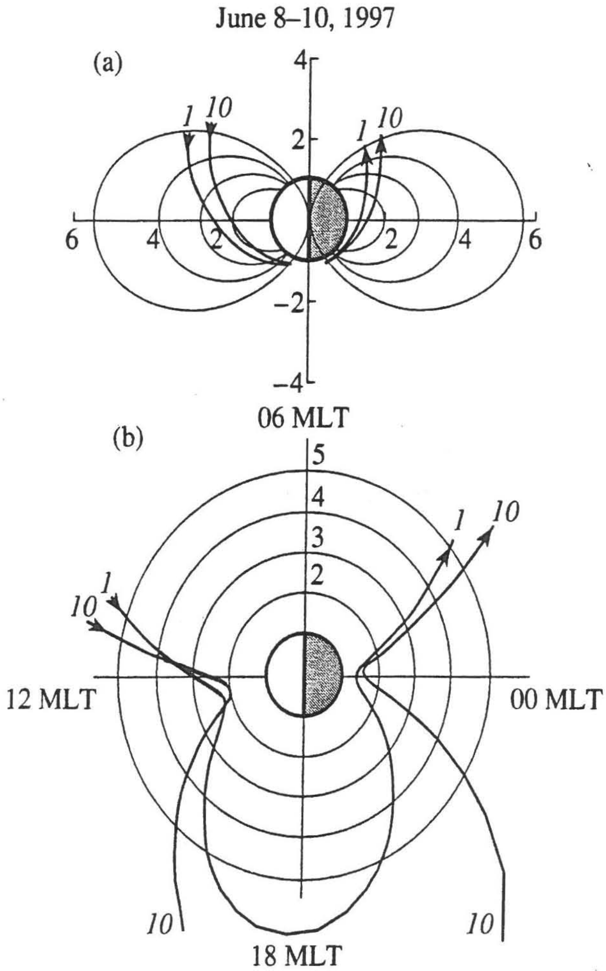

Fig. 7. Projection of the 1st and 10th orbits of the *Auroral Probe* in the period of June 8–10, 1997. Notation and coordinates are the same as in Fig. 1.

plasmasphere began simultaneously and proceeded approximately with equal rates, but the daytime plasmapause reached the minimum geocentric distance ~10–12 h later than the postmidnight one.

From variations of normalized values of ion density $n_{H^+}(L)$ at $L = 2.25$ shown in Fig. 9b, it is easily seen that, under quiet geomagnetic conditions, even a rather small increase in the level of geomagnetic activity leads to a quite noticeable (up to 50%) decrease in the H^+ ion density inside the plasmasphere in the daytime sector. With the development of a geomagnetic storm (according to the accepted classification, it refers to the class II type), a decrease in the density was replaced by its increase, and by 11:40 UT the H^+ ion density increased by a factor of 4 in comparison with its minimum value measured during the 3rd *Probe* passes through the plasmasphere (see Figs. 8a and 9b). At the end of the phase of recovery, the ion density n_{H^+} returned to its initial value.

The time dependence of the value of the density (also normalized to its first value) obtained in a magnetically quiet period on March 20–22, 1997, is shown in Fig. 10a. In Fig. 10b, variations of the K_p index and D_{st} variations for the same period are shown. From Figs. 10a and 10b it is seen that in the magnetically quiet period on March 20–22, 1997, the value of the density inside the plasmasphere, practically, did not vary with time, and one can find some growth of the density only with the beginning of an increase in the level of geomagnetic activity.

3. DISCUSSION OF RESULTS

The experimental results presented in the previous section will be considered, mainly, from the point of view of obtaining data about variations of the cold plasma density inside the plasmasphere during geomagnetic disturbances and for refinement of the mechanism of propagation of the plasmapause response to the geomagnetic disturbances from the night sector into the daytime.

Before considering the experimental data, we expound the present views on the mutual connections between the ionosphere and the plasmasphere, which will be used by us to interpret the results of measurements made on the *Auroral Probe*.

The plasmasphere is an area of the magnetosphere supported by the ionosphere and containing cold plasma of ionospheric origin. This plasma fills in geomagnetic field tubes, and as a result, around the Earth an area is formed that contains cold plasma and is bounded by the plasmapause on the outside. On the inside, the plasmasphere physically is not bounded. However, in some cases, it is considered conventionally that the inner boundary of the plasmasphere lies at an altitude of 2000 km, in others cases, the area where the ionospheric plasma becomes collisional is considered as an inner boundary. In any case, for interpretation of

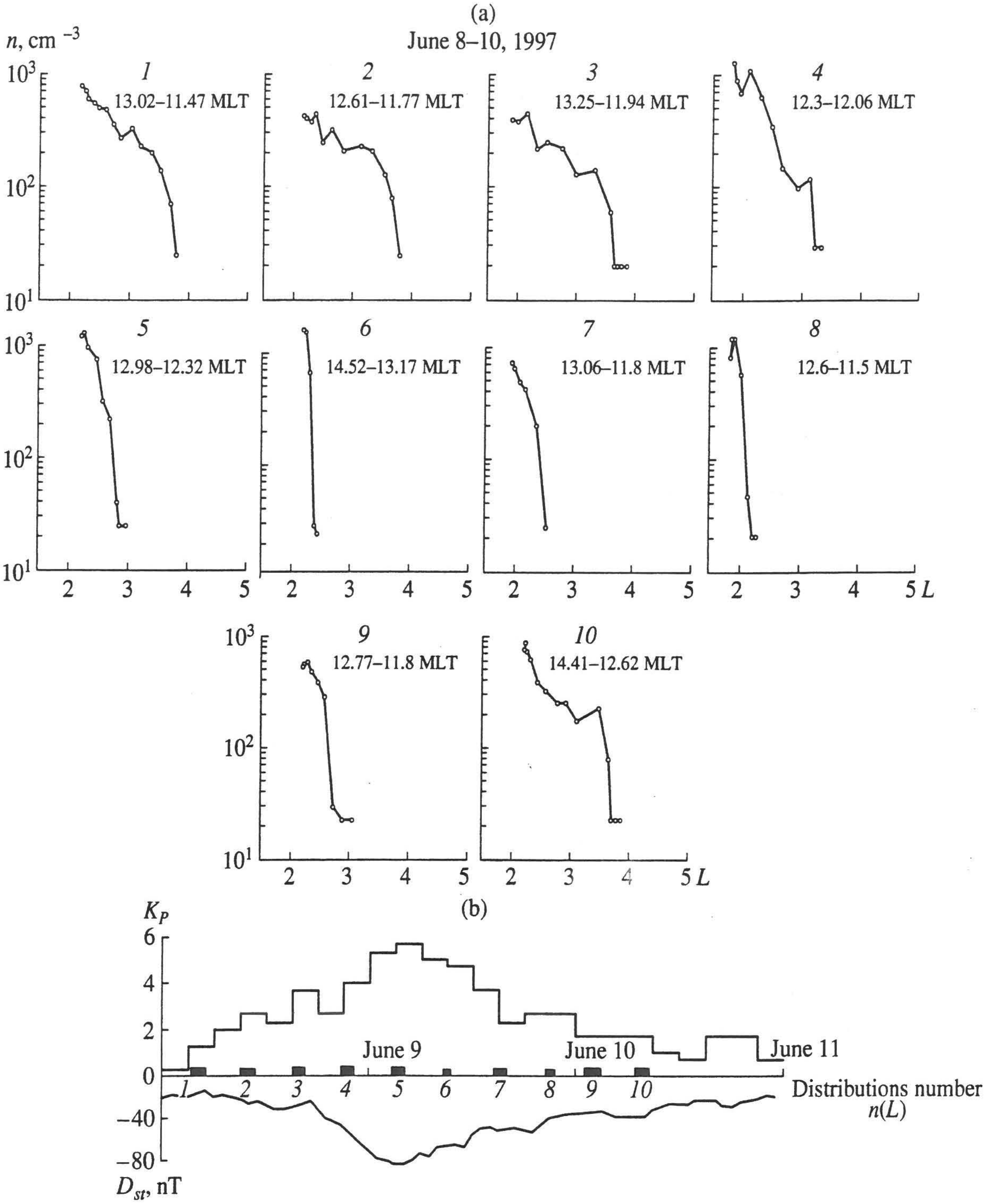

Fig. 8. (a) Daytime distributions $n_{H^+}(L)$ measured during 10 consecutive passages of the *Probe* through the plasmasphere in the period of June 9–10, 1997; (b) plot of the D_{st} variations in the period of June 8–10, 1997. On the time axis, the time intervals of the *Probe* passes through the plasmasphere are marked by thick dashes.

the obtained experimental data, it is important that there is no insurmountable barrier for the existence of exchange flows of cold plasma of ionospheric origin from the plasmasphere into the ionosphere and back.

It is known that, in quiet periods in the light time of day, flows of ionospheric plasma are mainly directed from the ionosphere into the plasmasphere, filling in the plasmasphere; in the dark time, the flows are directed from the plasmasphere into the ionosphere, being one of the factors supporting the existence of a night ionosphere.

According to available estimations, the value of the daytime fluxes is 3×10^8 cm^{-2} s^{-1}; the corresponding night value is 1.5×10^8 cm^{-2} s^{-1} (see, for example, [18, 19]). In [19], it was suggested that night fluxes from the plasmasphere into the ionosphere increase

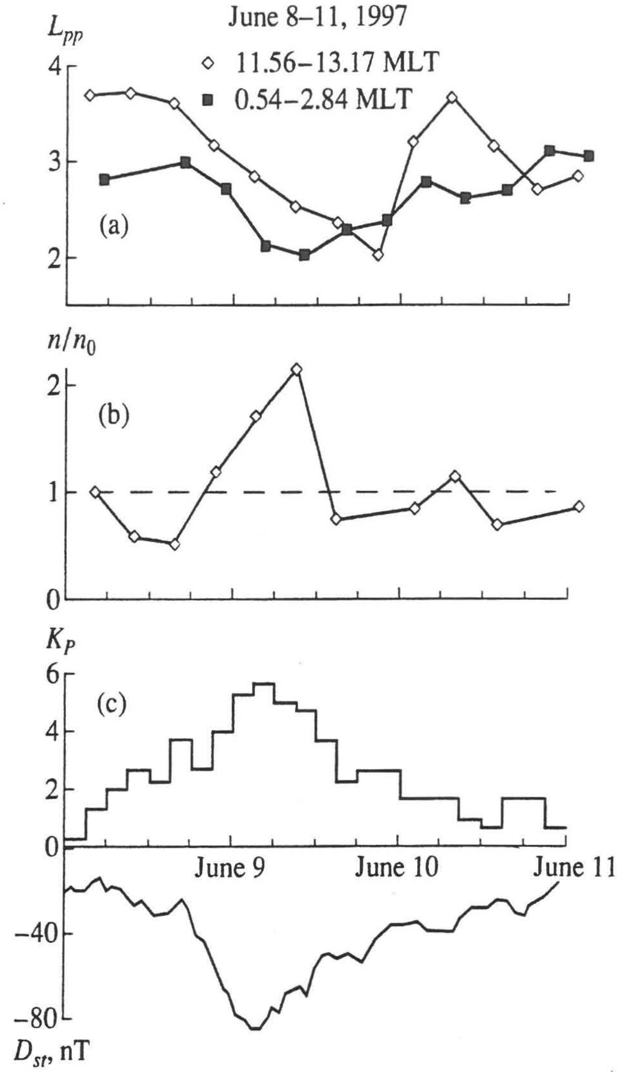

Fig. 9. (a) Dynamics of the plasmapause in the daytime sector in the period of June 8–10, 1997; (b) normalized variations of density in the plasmasphere at $L = 2.2$ in the daytime sector. The plot is normalized to the value of the density measured during the 1st *Probe* passes in the period of June 8–10, 1997; (c) the K_p indexes and D_{st} variations in the period of June 8–10, 1997.

during substorms, so that the plasma density in the ionosphere grows. The same author reported on his recording of backward plasma flows *from* the daytime plasmasphere *into* the ionosphere during a storm, which, in the author's opinion, can represent the important aspect of ionosphere–plasmasphere relations.

On the other hand, it is known that geomagnetic storms cause essential changes in many parameters of the ionosphere. In this case, as was noted in [17], the response of the ionosphere to geomagnetic disturbances is very complex and unpredictable. For example, according to [20], during an ionospheric storm, a double increase of the total number of electrons in a magnetic field tube (the positive phase of an ionospheric storm) was observed, whereas other investigations [21, 22] indicate that during ionospheric storms resulting from geomagnetic disturbances in the ionosphere, in a number of cases, a decrease in the plasma density was observed, whose value reached a factor of 2 (the negative phase of ionospheric storm). It has also been noted that the positive phase of the storm, which was recorded in the extensive range of latitudes, began in the night hemisphere and then corotated with the Earth to the illuminated side. The authors of [23] suggest that fluxes of plasma from the plasmasphere, which have increased during the geomagnetic storm, are the reason for the increasing density in the night ionosphere.

Thus, based on the above-mentioned data, in interpreting the results obtained on the *Auroral Probe*, we assume that the H^+ ion density in the night sector of the plasmasphere does not experience the immediate influence of the ionosphere, but the plasma density in the night plasmasphere can noticeably decrease due to increasing fluxes of cold ions into the ionosphere during geomagnetic disturbances. On the contrary, the value of the cold plasma density in the daytime plasmasphere is closely connected both with changes of the electron density at the ionospheric level and with changes of the altitude of the maximum of the F2 layer during geomagnetic storms.

Now, we consider in more detail the response of the H^+ ion density in the postmidnight and daytime sectors inside the plasmasphere under changing levels of a geomagnetic disturbance. As is seen from Fig. 3b, where variations of the H^+ ion density inside the plasmasphere at $L = 2.4$ measured in the period of September 4–5, 1996, are shown, the H^+ ion density in the postmidnight sector of the plasmasphere is rather stable, its changes do not exceed 20% from the initial value. It is also seen that the development of a weak substorm had no effect on the level of plasma density inside the plasmasphere, from which it is possible to reach a conclusion on small changes of plasma flows from the postmidnight plasmasphere into the ionosphere in comparison with flows characteristic for quiet periods. The level of density inside the daytime plasmasphere, which seemed to be stable during the quiet period, grew by ~40% in ~7 h after the beginning of a geomagnetic storm. A considerable decrease of the density in the daytime sector of the plasmasphere, accompanied only by a small approach of the plasmasphere to the Earth (0.3L), was recorded 12 h after the night plasmapause was found at $L = 2.2$ during the fourth *Auroral Probe* passes through the plasmasphere. It is not improbable that such a response of the plasmasphere (a sharp approach of the night plasmapause to the Earth and a considerable decrease in the cold plasma density in ~12 h in the daytime plasmasphere at a rather stable position of the plasmapause) may be characteristic for weak substorms.

The dynamics of the plasmapause in the night and daytime sectors of the plasmasphere in the period of September 9–11, 1996, was considered in [24]; therefore, here, only variations of the cold plasma density inside the plasmasphere at $L = 2.4$ are presented (see Fig. 6a). From Fig. 6b, where the plots of the D_{st} variations and the K_p index are shown for the same period, it is seen that the geomagnetic activity during the considered interval was higher than in the period of September 4–5, 1996 ($K_{p\max} = 5.3$, $D_{st\max} = 39$).

As is seen from Fig. 6a, the night H^+ ion densities in the postmidnight sector shown by full squares indicate a well-pronounced fourfold decrease in the period of 01:00–18:00 UT on September 10, 1996. We believe that this stable and deep decrease in the cold plasma density in the plasmasphere, whose duration exceeded 18 h, is determined by a rapid plasma escape into the ionosphere under the action of a moderate geomagnetic storm that began at ~21:00 UT on September 9, 1996. We suggest also that the decreased H^+ ion density relative to its initial level recorded after ~13:00 UT on September 11, 1996, results from a moderate storm that began at ~05:00 UT the same day.

Variations of the cold plasma density inside the plasmasphere in the daytime sector according to results of measurements on September 9–11, 1996, present a more complex pattern. From ~06:00 UT on September 9 to ~02:00 UT on September 10, 1996, during some increase of the geomagnetic disturbance, a stable decrease of the value of the density in the daytime plasmasphere recorded during 3 passages of the *Probe* was observed. The decrease of density was replaced by its threefold growth from 21:00 UT on September 9 to 14:00 UT on September 10. In the beginning of this period, the value of the K_p index grew sharply from 1.7 up to 5.3, while $-8 > D_{st} > -10$ nT. The increased value of the density was supported for more than 6 h, after that it decreased again. This decrease of the density inside the daytime plasmasphere can be connected with a short-time quiet geomagnetic situation, which occurred at 21:00–24:00 UT on September 10.

Now, we refer to Fig. 9b, where variations of the H^+ ion density inside the plasmasphere at $L = 2.2$ in the daytime sector are shown during the development of the storm on June 8–10, 1997. From Fig. 9b one can see that during a slow increase of the D_{st} variations, 03:00–15:00 UT on June 8, 1997, the density n_{H^+} at $L = 2.2$ decreased by a factor of ~2. At 17:30 UT, after the beginning of the storm, the density began to increase and at 09:00 UT on June 9, 1997, its value had grown by a factor of 4 in comparison with the level reached in the period of 03:00–15:00 UT. After 6 h the density had decreased to a value close to the initial level and varied around it up to the end of the interval under consideration.

The results of measurements presented in this paper allow us to conclude that, in the course of monitoring the plasmasphere, reliable experimental data about dynamics of the H^+ ion density inside the plasmasphere in the postmidnight and noon sectors were obtained in

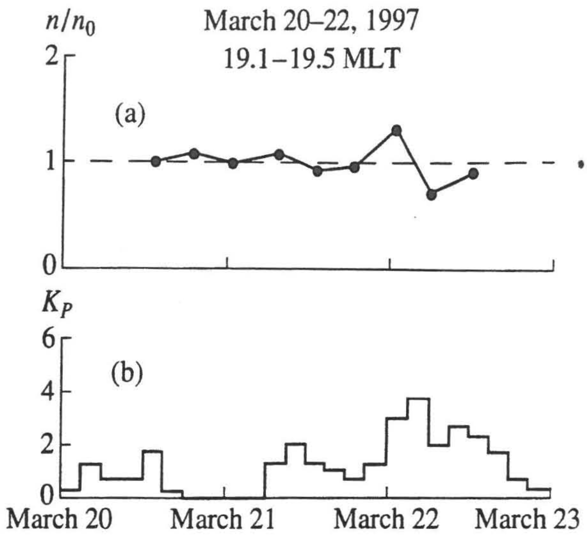

Fig. 10. (a) Normalized variations of density in the plasmasphere at $L = 2.4$ in the evening sector in the period of March 20–22, 1997. The plot is normalized to the value of the density measured at $L = 2.4$ at ~12:00 UT on June 8, 1997; (b) variations of the K_p indexes in the period of March 20–22, 1997.

the course of the development of geomagnetic disturbances with low and moderate intensity for the first time. In the night sector deep in the plasmasphere, a considerable decrease of the H^+ ion density was recorded, which seems to result from the increase of fluxes of cold plasma from the plasmasphere into the ionosphere during geomagnetic storms. In [12], an increase of electron fluxes from the night plasmasphere into the ionosphere was reported. In the daytime sector in the course of a low-intensity substorm on September 5, 1996, a considerable decrease of the H^+ ion density in 12 h after a sharp decrease in the geocentric distance of the plasmapause in the postmidnight sector was observed (see Figs. 2a, 3b). In the course of the development of substorms of class II in the daytime sector, at first, a double decrease of the H^+ ion density was observed, which changed to an increase with a growing geomagnetic disturbance. At present, we cannot unambiguously name the reason for such variations of the H^+ ion density in the daytime sector inside the plasmasphere; however, we believe that the indicated variations are directly connected with the negative and positive phases of ionospheric storms (i.e., with a decrease and increase of the electron density in the ionosphere and, probably, with increasing h_mF2). In turn, ionospheric storms result from a serial chain of ionospheric processes initiated by geomagnetic storms.

A sufficient, though not complete, understanding of exchange processes between the plasmasphere and the ionosphere initiated by geomagnetic storms can be reached only as a result of coordinated simultaneous investigations of the plasmasphere and the ionosphere on the background of geomagnetic disturbances.

As for the propagation of the plasmasphere deformation resulting from geomagnetic disturbances, there are different points of view [16, 25, 26]. In [26], the mechanism of separation of cold plasma elements from the plasmasphere and/or the formation of plasmaspheric tail-like structures are observed. According to [26], at the initial stage such plasma structures are formed under the effect of a substorm in the prenoon sector of the plasmasphere. Later, these structures move into the postnoon or dusk sector, where plasma bulges can be separated from the plasmasphere. The results of measurements presented in this paper refer to the postmidnight and daytime sectors and, hence, do not allow us to compare them with the model [26]. The experimental data obtained on the *Auroral Probe*, probably, will be compared with the model [26] later.

The authors of [16, 25], using the methods of statistical analysis, have found that changes of the plasmapause position in the daytime sector connected with a changing level of geomagnetic disturbance are observed, as a rule, ~12 h (or slightly more) later than in the night sector at different levels of geomagnetic disturbance (for $0 < K_p < 6$). Based on this result, the authors of [16, 25] have concluded that a decrease in the plasmasphere dimensions, beginning in the night sector, propagates to the daytime sector with an angular velocity close to the velocity of cold plasma corotation around the Earth. The dynamics of the plasmapause in the night and daytime sectors by the data obtained on the *Auroral Probe* during several concrete geomagnetic storms was considered in [24, 27], and it was found that during strong geomagnetic storms the plasmapause displacement toward the Earth in the night, morning, and daytime sectors of the MLT, as a rule, began practically simultaneously or, in any case, during a time interval essentially smaller than the time necessary for the transport of a field tube with plasma from the night sector into the daytime sector with the velocity of corotation. At the same time, from Figs. 3a and 9a, where the plasmapause position is shown for September 4–5, 1996, and June 8–9, 1997, respectively, it is seen that the daytime plasmapause reaches a minimum distance from the Earth 12 h later than the night plasmapause. The experimental results presented here obtained on the *Auroral Probe* in the course of the development of the indicated magnetic substorms, on the one hand, confirm conclusions from [6, 25] on the basis of statistical analysis about the transfer of "plasmasphere deformation" occurring as a result of a geomagnetic storm from the night sector into the daytime sector with a velocity of corotation. On the other hand, they testify to a simultaneous beginning of the process of displacement of the plasmapause to the Earth in the night and daytime sectors, which is determined by growing large-scale electric and magnetic fields in the magnetosphere.

CONCLUSION

For the first time, experimental data have been obtained about variations of the H^+ ion density deep in the plasmasphere before and during the development of several geomagnetic substorms in the postmidnight and daytime sectors of the plasmasphere.

It was found that, in the postmidnight sector, the development of a moderate substorm was accompanied by a considerable decrease in the H^+ ion density inside the plasmasphere at $L = 2.2$. It returned to the initial level after the termination of the substorm. This fact seems to testify to a large cold plasma escape from the plasmasphere into the ionosphere in the course of the development of the substorm in the night hours.

In the daytime sector at the initial phase of the substorm, a double decrease of the H^+ ion density was observed that was replaced then by its fourfold increase. The character of variations of the H^+ ion density in the daytime sector of the plasmasphere seems to be connected with variations of the parameters of the underlying ionosphere. The decrease of the H^+ ion density at the initial phase of a substorm can be caused by the development of the negative phase of an ionospheric storm. At the same time rare cases are known when, in the daytime during a substorm, electron fluxes from the plasmasphere into the ionosphere were observed. The increase of the H^+ ion density seems to be connected with an increase of fluxes of the ionospheric plasma into the plasmasphere after a change of the negative phase of the ionospheric storm to the positive phase.

By contrast with the model of propagation of a plasmasphere deformation during a magnetic substorm from the night sector into the daytime sector with the velocity of corotation proposed in [16, 25], a practically simultaneous beginning of the plasmapause displacement to the Earth in the night and daytime sectors is found. It was also found that the plasmapause displacement to the Earth in the daytime sector lasts for 10–12 h once the night plasmapause begins to move away from the Earth. The last fact seems to be explained by the arrival of magnetic field tubes with plasma of decreased density after a magnetic substorm from the nightside to the daytime side as a result of corotation.

ACKNOWLEDGMENTS

We would like to thank G.L. Gdalevich for attention to this work and useful discussions, and S.A. Pulinets and V.D. Ozerov for useful discussions.

REFERENCES

1. Binsack, J.H., Plasmapause Observation with the M.I.T. Experiment on *IMP2*, *J. Geophys. Res.*, 1967, vol. 72, pp. 231–237.
2. Carpenter, D.L., Relation between the Dawn Minimum in the Equatorial Radius of the Plasmapause and D_{st}, K_p

and Local K at Byrd Station, *J. Geophys. Res.*, 1967, vol. 72, pp. 969–971.

3. Bezrukikh, V.V., The Results of Charged Particle Flux Measurements onboard *Electron-2* and *Electron-4* Satellites, *Kosm. Issled.*, 1970, vol. 8, pp. 271–277.
4. Chappell, C.R., Harris, K.K., and Sharp, G.W., A Study of the Influence of Magnetic Activity on the Location of the Plasmapause as Measured by *OGO-5*, *J. Geophys. Res.*, 1970, vol. 75, pp. 50–56.
5. Carpenter, D.L. and Anderson, R.R., An ISEE\Whistler Model of Equatorial Electron Density in the Magnetosphere, *J. Geophys. Res.*, 1992, vol. 97, pp. 1097–1108.
6. Chappell, C.R., Recent Satellite Measurements of the Morphology and Dynamics of the Plasmasphere, *Rev. Geophys. Space Phys.*, 1972, vol. 10, pp. 951–979.
7. Gringauz, K.I. and Bezrukikh, V.V., Asymmetry of the Earth's Plasmasphere in the Direction Noon–Midnight from the *PROGNOZ-1* and *PROGNOZ-2* Data, *J. Atmos. Terr. Phys.*, 1976, vol. 38, pp. 1071–1076.
8. Gringauz, K.I. and Lemaire, J., *The Earth's Plasmasphere*, Cambridge: Cambridge Univ. Press, 1988, p. 312.
9. Carpenter, D.L., New Experimental Evidence of the Effect of Magnetic Storms on the Magnetosphere, *J. Geophys. Res.*, 1962, vol. 67, pp. 135–145.
10. Park, G.P., A Morphological Study of Substorm-associated Disturbances in Ionosphere, *J. Geophys. Res.*, 1973, vol. 79, pp. 2821–2827.
11. Carpenter, D.L. and Park, G.O., On What Ionosphere Workers Should Know about Plasmasphere-Plasmapause, *Rev. Geophys. Space Phys.*, 1974, vol. 11, pp. 133–154.
12. Park, C.G., Whistler Observations of the Interchange of Ionization between the Ionosphere and Protonosphere, *J. Geophys. Res.*, 1970, vol. 75, pp. 4249–4260.
13. Gallagher, D.L., Craven, P.D., and Comfort, R.H., An Empirical Model of the Earth's Plasmasphere, *Adv. Space Res.*, 1988, vol. 8, pp. 15–24.
14. Galperin, Y.I., Soloviev, V.S., Torkar, K., *et al.*, Predicting Plasmaspheric Radial Density Profiles, *J. Geophys. Res.*, 1997, vol. 102, pp. 2079–2091.
15. Gringauz, K.I. and Lemaire, J., *The Earth's Plasmasphere*, Cambridge: Cambridge Univ. Press, 1998, p. 188.
16. Kamide, Y., Sun, W., and Akasofu, S.-I., The Average Ionospheric Electrodynamics for the Different Substorm Phases, *J. Geophys. Res.*, 1996, vol. 101, pp. 99–109.
17. Gonzales, W.D., Joselyn, J.A., Kamide, Y., *et al.*, What Is the Geomagnetic Storm?, *J. Geophys. Res.*, 1994, vol. 90, pp. 5771–5792.
18. Afonin, V.V., Bezrukikh, V.V., Gringauz, K.I., *et al.*, Observations of the Cold Ion Fluxes from the Plasmasphere into the Ionosphere at Middle Latitudes at Night, *Kosm. Issled.*, 1984, vol. 22, pp. 884–888.
19. Park, G.P., Westward Electric Fields as the Cause of Night-Time Enhancement in Electron Densities in the Midlatitude F Region, *J. Geophys. Res.*, 1971, vol. 75, pp. 4249–4260.
20. Ho, C.M., Mannucci, A.J., Sparks, L., *et al.*, Ionospheric Total Electron Content Perturbations by the GPS Global Network during Two Northern Hemisphere Winter Storms, *J. Geophys. Res.*, 1998, vol. 103, pp. 26409–26420.
21. Yeh, K.C., Ma, S.Y., and Lin, K.H., Global Ionospheric Effects of the October 1989 Geomagnetic Storm, *J. Geophys. Res.*, 1994, vol. 99, pp. 6201–6218.
22. Szuszczewich, E.P., Lester, M., Wilkinson, P., *et al.*, A Comparative Study of Global Ionospheric Responses to Intense Magnetic Storm Conditions, *J. Geophys. Res.*, 1998, vol. 103, pp. 11665–11684.
23. Oliver, W.L. and Hagan, M.E., Simulation of a Gravity Wave over the Middle and Upper Atmosphere Radar, *J. Geophys. Res.*, 1991, vol. 96, pp. 9793–9800.
24. Bezrukikh, V.V., Kotova, G.A., Lezhen, L.A., *et al.*, Dynamics of the Plasmasphere and Plasmapause under the Action of Intense Geomagnetic Storms, *J. Atmos. Sol. Terr. Phys.*, 2000, vol. 62.
25. Decreau, P.M.F., Lemaire, J., Chappel, C.R., and Waite, J.H., Nightside Plasmapause Positions Observed by DE-1 as a Function of Geomagnetic Indices: Comparison with Whistler Observations and Model Calculations, *Adv. Space Res.*, 1986, vol. 6, pp. 209–214.
26. Lemaire, J., The Formation of Plasmaspheric Tails, *Phys. Chem. Earth*, 2000, vol. 25, pp. 9–18.
27. Bezrukikh, V.V., Kotova, G.A., Lezhen, L.A., *et al.*, Plasmapause Dynamics during Magnetic Storms as Observed by the Auroral Probe/Alpha-3 Experiment, *Phys. Chem. Earth*, 2000, vol. 25, pp. 19–22.