

Ion Pressure in Different Regions of the Dayside Auroral Precipitation

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Abstract—The ion pressure in the regions of ionospheric projections of the plasma mantle, polar cusp, low-latitude boundary layer, and the region of structured precipitation of the auroral oval during magnetic calm is studied based on data from the DMSP F6 and F7 low-altitude spacecraft. It is shown that the level of ion pressure in all of these regions does not depend on either the polarity or the value of the B_z component of the IMF. The ion pressure in the mantle varies from 0.02 to 0.06 nPa and does not depend on the magnitude of the solar wind dynamic pressure. The average pressure level is $\langle P_m \rangle = 0.03 \pm 0.01$ nPa. In the cusp area at IMF $B_z > 0$, the ion pressure (P_c) does not depend on the solar wind dynamic pressure (P_{sw}), while the pressure at IMF $B_z < 0$ increases significantly with the increasing in P_{sw} . The average pressure level is $\langle P_c \rangle = 1.0 \pm 0.3$ nPa, which is almost two orders of magnitude higher than that in the mantle. The ion pressure also increases with the solar wind dynamic pressure in both the *LLBL* and the auroral oval precipitation (AOP). The average pressure in the *LLBL* is $\langle P_L \rangle = 0.27 \pm 0.07$ nPa, while in the AOP region its average value is two times lower. The MLT pressure pattern in *LLBL* shows a pronounced increase in the noon sector (~ 11 – 14 MLT), the value of which increases with increasing in the solar wind dynamic pressure. In the AOP region the pressure is distributed over MLT fairly evenly, which results in a significant pressure difference ($\Delta P = P_L - P_A$) in the noon sector between the low-latitude boundary layer and the auroral oval.

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1. INTRODUCTION

Plasma pressure is one of the main parameters that determine the state of the Earth's magnetosphere and the dynamic processes occurring in the magnetosphere-ionosphere system. Suffice it to say that the azimuthal pressure gradients in the plasma sheet are able to maintain longitudinal currents connecting the magnetosphere and the ionosphere (Antonova and Ganushkina, 1997; Troshichev, 2004; Xing et al. 2009). Plasma pressure is determined either in situ with satellites in the magnetospheric plasma or from observations of polar-orbiting, low-altitude satellites. The use of low-altitude satellites, the orbits of which cover virtually the entire high-latitude ionosphere with high spatial and temporal resolutions, is based on the fact that the plasma pressure, temperature, and density remain constant along the geomagnetic field lines (Goertz and Baumjohann, 1991). Thus, the characteristics of the magnetospheric plasma can be obtained via the projecting of ionospheric data into the equatorial plane of the magnetosphere with a magnetic field model.

Precipitation recorded at the heights of the ionosphere within the boundaries of the auroral oval are considered isotropic. The position of the polarward

and equatorward boundaries of the auroral oval in the equatorial plane of the magnetosphere was determined by Antonova et al. (2014) and Kirpichev et al. (2016) with via morphological projection. It was shown that, if the magnetostatic equilibrium condition is assumed to be valid at a low level of magnetic activity ($AL > -200$ nT), the polarward and equatorward boundaries of the nighttime auroral oval are located at geocentric distances of ~ 7 Re and ~ 10 Re, respectively. Based on observations of satellites of the THEMIS project, it was shown earlier that the plasma pressure at geocentric distances of 7–10 Re is almost isotropic and is azimuthally symmetrical (Kirpichev and Antonova, 2011).

The plasma pressure in the plasma sheet is largely determined by the solar-wind dynamic pressure (P_{sw}). In the central part of the plasma sheet at geocentric distances of 10–50 Re, the plasma pressure increases roughly in proportion to the increase in P_{sw} (Tsyganenko and Mukai, 2003). Observations with low-altitude satellites (Vorobjev et al., 2019) have shown that, at all levels of magnetic activity, the plasma pressure at the boundaries of auroral precipitation increases almost linearly with P_{sw} , not only in the area of isotropic precipitation but also in the trapping

region, which is located equatorward of the isotropic boundary (b2i).

In early studies (Fairfield, 1968), it was shown that the projection of the auroral oval boundary along the geomagnetic field lines in the daytime approximately coincides with the magnetosphere boundary. The processes occurring on the daytime magnetopause are intensively studied in order to solve the problem of the transfer of solar-wind energy into the Earth's magnetosphere. The effect of the solar wind dynamic pressure on the state of the daytime magnetosphere was well illustrated by Newell and Meng (1994), who studied the ionospheric projections of various regions of the magnetosphere at low and high P_{sw} levels with data from the DMSP spacecraft. It was shown that the solar wind dynamic pressure dramatically changes the picture of magnetospheric projections. A high dynamic pressure, $\langle P_{sw} \rangle = 6$ nPa, significantly enlarges the longitudinal dimensions of the precipitating regions such as the mantle, polar cusp, and low-latitude boundary layer, and changes the configuration of the auroral oval structured precipitation.

The solar wind velocity varies within relatively small limits; therefore, its kinetic pressure is mainly determined by the plasma density. The characteristics of particles in different daytime precipitation regions respect to the density of the solar wind plasma were studied by Vorobiev and Yagodkina (2006). It was shown that, according to the data of the DMSP F6 and F7 spacecraft, an increase in the solar wind plasma density is accompanied by a significant buildup in the flux of precipitating ions in all regions of daytime precipitation. However, in the zone of structured precipitation of the auroral oval, as well as in the zone of diffuse precipitation, an increase in fluxes is accompanied by a decrease in the average energy of precipitating ions. The daytime plasma pressure at the ionospheric altitude, which is determined by both the fluxes of precipitating particles and their average energy, has not yet been studied.

The close relationship between the behavior of daytime auroras and the B_z component of the IMF was found already in early works (Vorobiev et al., 1976; Horwitz and Akasofu, 1977). It was shown that a B_z decrease (increase) is accompanied by a shift of the auroras to lower (higher) latitudes. A detailed comparison of the IMF variations and aurora positions showed that the response of daytime auroras is delayed by ~ 15 min relative to the corresponding B_z changes in the solar wind in the Earth's orbit (Vorobiev et al., 1976; Sandholt et al., 1983). It was reported (Burch, 1973; Newell et al., 1989 and others) that there is a good correlation between variations in the IMF B_z component and large-scale variations of the polar cusp position.

The goal of this work was to determine the plasma pressure at the ionospheric altitudes in different daytime precipitation regions such as mantle, polar cusp,

low-latitude boundary layer and as the precipitation of the auroral oval. This study will allow us to evaluate the role of plasma pressure in the boundary layers of the magnetosphere and cusp in the pressure balance at the magnetopause. The average pressure values of precipitating ions in different precipitation areas were compared, and the influence of the IMF B_z component and of the dynamic pressure of the solar wind on the level of plasma pressure was studied.

2. DATA USED

Data from the DMSP F6 and F7 spacecraft for the entirety of 1986, a year of quiet Sun at the very beginning of the 22nd solar activity cycle, were used. The satellites had almost circular orbit with an altitude of about 850 km, an orbital inclination of 99° , and an orbital period of ~ 101 min. The fluxes of precipitating particles were measured in an energy range from 32 eV to 30 keV in 20 channels distributed over the range in a logarithmic sequence. To determine the position of the boundaries of auroral precipitations and the time of their registration, we used data from an automated processing system (Newell et al., 1991a) at (<http://civspace.jhuapl.edu>). The satellite data are projected by an automated system along the field lines to an altitude of 110 km.

The pressure created by precipitating ion flux is much higher than the electron pressure, which is less than 15% of the total plasma pressure. The methodology to determine the ion pressure from DMSP data was described earlier (Wing and Newell, 1998). We used a modified version of this technique proposed by Stepanova et al. (2002, 2006), which involves the determination of the average ion fluxes and energies between the adjacent boundaries of different zones of daytime precipitation, and it was further used to calculate the ion pressure. To avoid the interference of processes associated with magnetospheric disturbances, we considered only satellite data collected at a low level of magnetic activity $AL > -200$ nT. The magnetic activity data, as well as the solar wind, plasma, and IMF parameters, were taken from the OMNIWeb site (<http://cdaweb.gsfc.nasa.gov/>). In total, 4460 DMSP F7 satellite passes were recorded in the 0900–1500 MLT sector of the northern and southern hemispheres for $|AL| < 200$ nT; data from the DMSP F6 satellite in the evening and morning sectors were also used.

3. ION PRESSURE IN DIFFERENT PRECIPITATION REGIONS

An area of soft precipitations on the daytime side is created by various particles. To determine the region of the magnetospheric source of various precipitation types, Newell et al. (1991b, 1991c) compared the characteristics of precipitation observed on the DMSP spacecraft with the characteristics of particles at high altitudes. Four different regions were distinguished in

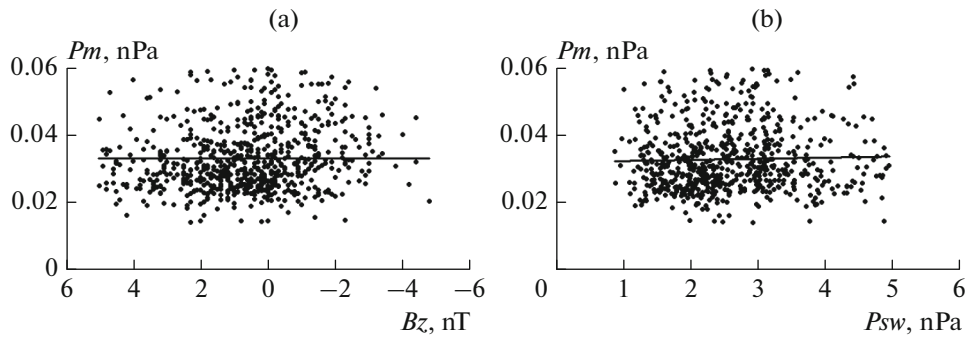


Fig. 1. Ion pressure in the region of mantle precipitation (P_m): (a) at different values of the IMF B_z component; (b) at different values of pressure of the solar wind plasma.

the daytime sector: the plasma mantle, the polar cusp, the low-latitude boundary layer, and the region of structured precipitation of the auroral oval, which is referred to as the conventional boundary plasma sheet (Newell et al., 1991a). The results of the study of the ion pressure in all of these structures are presented below. The influence of the solar wind dynamic pressure and the IMF B_z component on the value of the ion pressure at a low level of magnetic activity was also studied.

3.1. Plasma Mantle

The energy of precipitating ions in the mantle is low and amounts to only a few tens of eV (Newell et al., 1991b). To determine the threshold pressure level detected by F6 and F7 satellites, we examined the E2 channel of an electrostatic analyzer, which measures ion fluxes with an energy of 47 eV (since the E1 32 eV channel sometimes failed). The energy flux threshold of this channel was $F_i = 10^{6.5}$ ($\text{eV cm}^{-2} \text{s}^{-1}$). Rounding these values to 50 eV and 10^7 ($\text{eV cm}^{-2} \text{s}^{-1}$), respectively, we obtain the threshold level of the measured ion pressure $P = 0.001$ nPa. In order to obtain more reliable data, we deliberately increased the threshold values by an order of magnitude to $P = 0.01$ nPa. As a result of this procedure, the number of satellite passes in which precipitations characteristic of the plasma mantle were recorded in the presence of data on the solar-wind plasma and IMF was reduced to 856.

Figure 1 shows the ion pressure in the precipitation of the mantle (P_m) at different values of the IMF B_z component (a) and different kinetic pressures of the solar wind plasma (b). As can be seen from the figure, the pressure in the mantle varies mainly in the range of 0.02 nPa to 0.06 nPa and does not depend on either the IMF polarity or the dynamic pressure of the solar wind. The average pressure level is $\langle P_m \rangle = 0.03 \pm 0.01$ nPa. The significant scattering of P_m values in Fig. 1 may be related to both the B_x and B_y IMF component and the tilt angle of the geomagnetic dipole axis to the solar-wind velocity vector (hemisphere, season, UT time).

3.2. Polar Cusp

In the daytime magnetosphere, there are two regions (one in each hemisphere) in which the geomagnetic field lines are divided into two groups: some close on the side of the magnetosphere facing the Sun, while others extend from the polar cap into the magnetotail. These areas are called daytime polar (magnetic) cusps. One characteristic of the cusp is that the main plasma parameters are extremely similar to those in the transition layer between the magnetopause and the Earth shock wave. This suggests that solar-wind particles penetrate through the cusps into the magnetosphere and precipitate into the atmosphere without significant acceleration.

The energy flux of precipitating ions in the cusp is $F_i > 10^{10}$ ($\text{eV cm}^{-2} \text{s}^{-1}$), and their average energy is $300 \text{ eV} < E_i < 3000 \text{ eV}$ (Newell et al., 1989). The choice of criteria to identify the cusp for an automated data-processing system was discussed (Newell and Meng, 1994). 798 passes with polar cusp precipitation were recorded in the 1200–1500 MLT sector, which is 14% of the total number of satellite passes in this MLT sector (5667). In the presence of data on IMF and solar-wind plasma corresponding to the cusp, 219 passes were recorded at a low level of magnetic activity.

Figure 2 shows the ion pressure determined in the cusp (P_c). Fig. 2a illustrates the ion-pressure levels at different values of the B_z IMF component. As in the case of the plasma mantle, the pressure in the cusp does not depend on either the polarity or the magnitude of the B_z component. The average pressure level in the cusp, $\langle P_c \rangle = 1.0 \pm 0.3$ nPa, is almost two orders of magnitude higher than that in the mantle.

Figures 2b and 2c show the pressure in the cusp as a function of the solar wind dynamic pressure at IMF $B_z > 0$ and at $B_z < 0$, respectively. As can be seen, the plasma pressure in the area of cusp precipitation at positive IMF polarity does not depend on the dynamic pressure of the solar wind, while the pressure at IMF $B_z < 0$ increases significantly with P_{sw} . At a dynamic pressure of 1.5 nPa, the ion pressure was ~ 0.5 nPa and

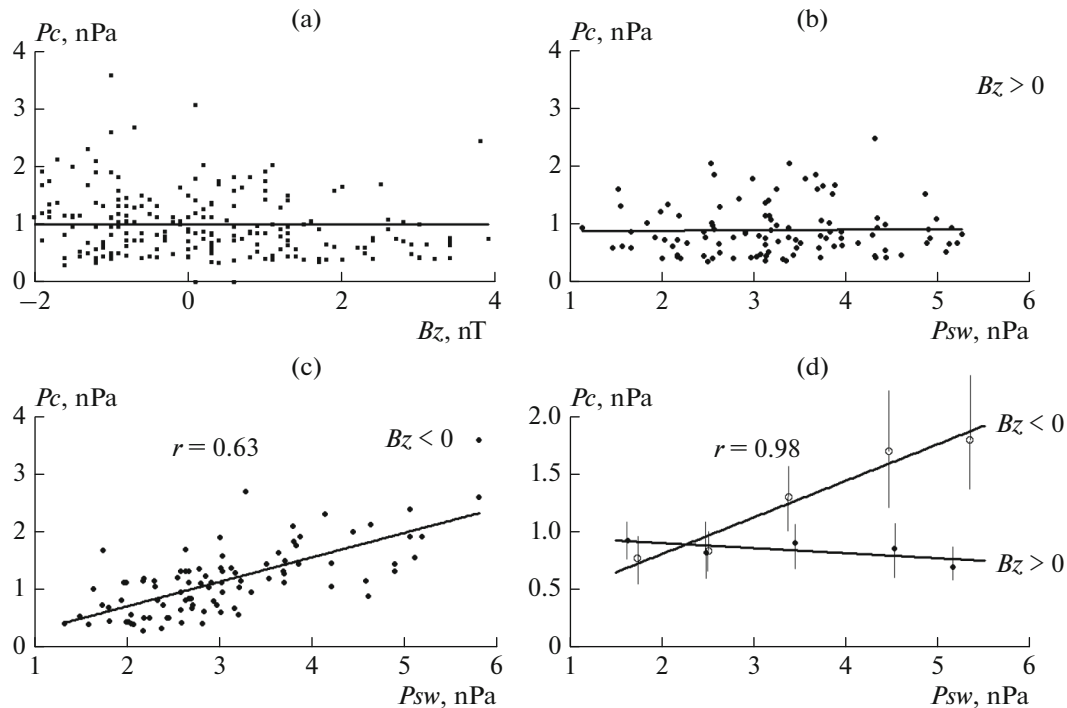


Fig. 2. Ion pressure in the region of cusp precipitation (P_c): (a) at different values of the IMF B_z component; (b, c) with respect to the dynamic pressure of the solar-wind plasma; (b) $B_z > 0$, (c) $B_z < 0$; (d) the same data as in (b) and (c), averaged in each P_{sw} interval by 1 nPa.

at $P_{sw} = 5$ nPa it increases to about ~ 2.0 nPa. The solid lines in Figs. 2a, 2b, and 2c correspond to linear regressions.

Figure 2d shows the dependence of the pressure in the cusp on the solar wind dynamic pressure based on the same data as in Figs. 2b and 2c but averaged over each P_{sw} interval by 1 nPa. This figure, like Fig. 2b, shows that the pressure in the cusp (P_c) at IMF $B_z > 0$ does not depend on the dynamic pressure of the solar wind. At IMF $B_z < 0$, however, the pressure in the cusp increases with P_{sw} , which can be described by the linear equation $P_c (B_z < 0) = 0.32 P_{sw} + 0.18$. The vertical bars show the standard deviation. The correlation coefficient is $r = 0.97$ for the data in Fig. 2d and $r = 0.63$ with the use of all experimental points (Fig. 2c).

3.3. Low-Latitude Boundary Layer (LLBL)

The low-latitude boundary layer (LLBL) is the boundary region of the daytime magnetosphere, in which particles from both the magnetosheath and the magnetosphere are recorded. Accordingly, the energy flux of precipitating ions in the LLBL is approximately an order of magnitude lower than that in the cusp region, and the ion energies are higher and average 3–6 keV. The characteristics of the particles observed in the boundary layer have been described in detail (Haerendel et al., 1978; Newell et al., 1991c).

Figure 3 shows the ion pressure recorded in the LLBL precipitation region. Since the characteristics of the plasma in the boundary layer of the magnetosphere can significantly depend on the angle between the direction towards the Sun and the normal to the magnetopause, a narrower interval of local geomagnetic time, 1100–1300 MLT, was chosen for the research. In this interval, 262 passes of the F7 satellite recorded precipitations of the boundary layer at a low level of magnetic activity and with available data on the parameters of the solar wind and IMF were analyzed.

Figure 3a shows that, as in the plasma mantle and polar cusp, the pressure in the precipitation LLBL (P_L) does not depend on the B_z component of the IMF. The average pressure level is $\langle P_L \rangle = 0.27 \pm 0.07$ nPa, which is significantly higher than in the mantle but about three times lower than that in the cusp.

Figure 3b shows the dependence between the ion pressure in LLBL and the dynamic pressure of the solar wind. As seen in the figure, the ion pressure increases significantly with P_{sw} . The solid line is a linear regression, and the correlation coefficient for all points of the data set is $r = 0.61$. Figure 3c shows the same data as Fig. 3b but averaged over each dynamic pressure interval by 1 nPa. The solid line in the figure corresponds to the equation $P_L = 0.10 P_{sw} + 0.06$ (correlation coefficient $r = 0.90$), which shows an increase in P_L from ~ 0.15 nPa at a solar wind pressure of 1.0 nPa to ~ 0.65 nPa at $P_{sw} = 6.0$ nPa.

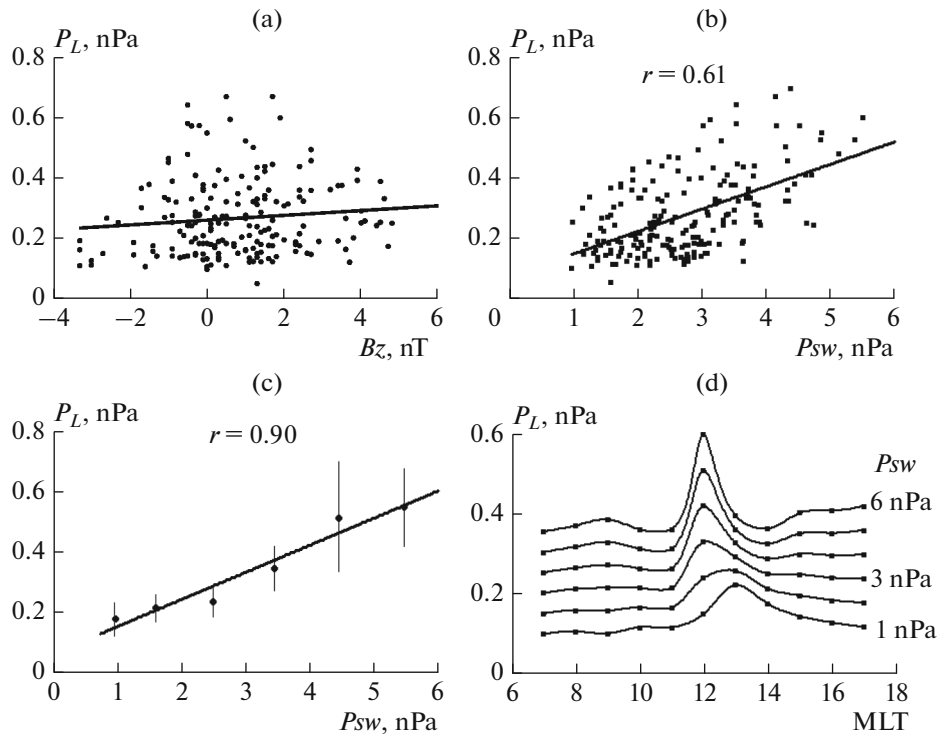


Fig. 3. Ion pressure in the *LLBL* (P_L) precipitation region: (a) at different values of the IMF B_z component; (b) with respect to the dynamic pressure of the solar wind; (c) the same data as in b, averaged over 1 nPa P_{sw} intervals; (d) pressure distribution over MLT at different P_{sw} levels (from 1.0 nPa to 6.0 nPa).

Figure 3d illustrates the pressure distribution in the precipitation of the boundary layer over MLT at different levels of the solar-wind dynamic pressure (from 1.0 to 6.0 nPa). The points on the plots correspond to the regressions obtained for all MLT sectors shown in the figure. The data at 1200 MLT corresponds to the regression equation for the 1100–1300 MLT sector. Similar linear equations $P_L = P_L(P_{sw})$ were obtained for all 2-h MLT intervals with a shift of 1 h in the eastern and western directions (1200–1400, 1300–1500...1200–1000, 1100–0900 MLT, etc.).

Figure 3d demonstrates a pronounced local increase in the ion pressure with an increase in P_{sw} in the midday sector. At $P_{sw} = 6$ nPa, the P_L peak is approximately twice the pressure level in the adjacent MLT sectors, which is significantly higher than the standard deviation typical for our data sets.

3.4. Auroral Oval Precipitation (AOP) Region

The term auroral oval precipitation (AOP) was introduced by Starkov et al. (2002). In the daytime sector, this region spatially coincides with precipitation of the *BPS* (boundary plasma sheet) type in Newell et al. (1991a). The need for a new term was dictated in this case by the need to avoid the direct comparison of the precipitation area recorded at the ionospheric altitude with any magnetospheric domain. On the one

hand, it is not clear what the term “boundary plasma sheet” means in relation to the daytime magnetosphere. On the other hand, no unambiguous interpretation of the relationship between the daytime sector of the auroral oval and any of its magnetospheric sources has been achieved.

Large fluxes of soft (<1 keV), structured precipitation are characteristic of the AOP region. Rayed auroral arcs are observed here, as well as short-lived (1–2 min) rayed forms and separated rays at a low level of magnetic activity. In general, the precipitation characteristics in the daytime AOP region are similar to those of the polar part of the nighttime auroral oval.

Figure 4 illustrates the main results obtained in the study of ion pressure (P_A) in the AOP region. Note that, as in all of the precipitation regions considered above, the pressure in the AOP does not depend on either the polarity or the magnitude of the IMF B_z component (not shown). Figure 4a presents a data array showing the distribution of P_A with respect to the dynamic pressure of the solar wind in the 1100–1300 MLT sector. Precipitations characteristic of AOP were recorded in 577 satellite passes in this sector at a low level of magnetic activity. Figure 4a indicates a certain tendency towards an increase in ion pressure with the dynamic pressure of the solar wind. The solid line in the figure corresponds to the linear regression with the correlation coefficient over the entire data set, $r = 0.58$. The aver-

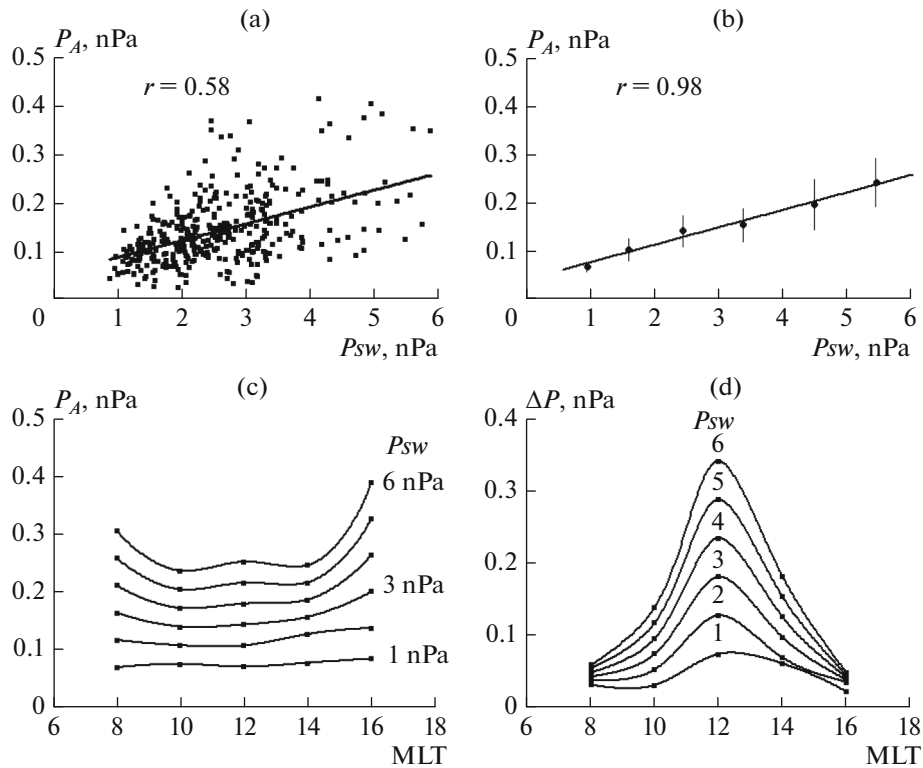


Fig. 4. Ion pressure in the AOP region (P_A): (a) at different values of the solar wind dynamic pressure; (b) the same data as in a, averaged over 1 nPa P_{sw} intervals; (c) pressure distribution over MLT at different P_{sw} levels; (d) MLT distribution of the pressure difference between the LLBL and AOP regions.

age value of the ion pressure, $\langle P_A \rangle = 0.14 \pm 0.03$ nPa, is ~ 0.5 of the pressure level in the LLBL precipitation. Figure 4b shows the same data as in Fig. 4a, but averaged over each P_{sw} interval by 1 nPa. The solid line in this figure corresponds to the equation $P_A = 0.036 P_{sw} + 0.030$ with a correlation coefficient of $r = 0.98$. In accordance with this equation, the ion pressure in the AOP region increases approximately by a factor of four from ~ 0.08 nPa to ~ 0.25 nPa when P_{sw} changes from 1.0 to 6.0 nPa.

Figure 4c shows the distribution of AOP pressure over MLT for different levels of the solar wind dynamic pressure. The plots are linear regressions obtained for averaged data in each of the 2-h intervals of the 0700–1700 MLT sector. The values obtained in each interval are referred to the center of the corresponding 2-h MLT interval. The figure shows that P_A is distributed fairly evenly in the midday sector and increases slightly towards the evening and morning MLT hours at high P_{sw} levels. In the noon sector, there are no distinct features found earlier in the area of LLBL precipitation. Figure 4d presents the difference in ion pressure between the LLBL and AOP regions ($\Delta P = P_L - P_A$). The figure shows that the difference in pressure between the precipitation of the boundary layer and the precipitation of the auroral oval in the midday sector increases significantly with

the solar-wind dynamic pressure. At $P_{sw} = 6$ nPa, the pressure difference not only reaches the pressure level in the AOP region but even exceeds it.

Figure 5 shows a comparison of the ion pressure in the noon sector (Fig. 4b) of the AOP region with the pressure at the polar edge of the auroral oval in the pre-midnight sector (2100–2400 MLT) at different levels of the solar-wind dynamic pressure. The solid and dashed lines in the figure correspond to the regression for the midday and midnight sectors, respectively. The vertical bars show the standard deviations. Since the pressure is determined by the average energies and energy fluxes of precipitating particles, Fig. 5 indicates that the characteristics of auroral particles (protons) precipitating in the noon sector of the AOP are similar at a low level of magnetic activity to the characteristics of the precipitation at the polar edge of the AOP region in the midnight sector.

4. RESULTS AND DISCUSSION

Data from the DMSP F6 and F7 spacecraft were used to study the ion pressure in the daytime sector in the regions of ionospheric projections of the plasma mantle, polar cusp, LLBL, and the region of structured AOP. The influence of the IMF B_z component and the dynamic pressure of the solar wind (P_{sw}) on

the plasma pressure in various regions of precipitation at a low level of magnetic activity ($AL > -200$ nT) was studied.

The main results obtained via statistical analysis can be formulated as follows.

1. The ion pressure in the mantle region varies mainly in the range from 0.02 nPa to 0.06 nPa and does not depend on either the IMF polarity or the solar-wind dynamic pressure. The average pressure level is $\langle P_m \rangle = 0.03 \pm 0.01$ nPa.

2. The pressure in the cusp region does not depend on the value of the IMF B_z component. The average pressure level is $\langle P_C \rangle = 1.0 \pm 0.3$ nPa, which is almost two orders of magnitude higher than that in the mantle. At positive IMF polarity, the pressure in the region of cusp precipitation does not depend on the solar wind dynamic pressure, while the pressure at $B_z < 0$ increases significantly with P_{sw} .

3. As in the plasma mantle and in the polar cusp, the pressure in the *LLBL* precipitation region does not depend on the level of the vertical IMF component; however, it increases significantly with dynamic pressure from ~ 0.15 nPa at $P_{sw} = 1.0$ nPa to ~ 0.65 nPa at $P_{sw} = 6.0$ nPa. The average pressure level is $\langle P_L \rangle = 0.27 \pm 0.07$ nPa.

4. The pressure distribution in the *LLBL* precipitation over MLT reflects a pronounced local maximum in the noon sector (~ 11 – 14 MLT), where the pressure increases along with P_{sw} . At $P_{sw} = 6$ nPa, the P_L peak is approximately twice as high as the pressure level in the adjacent MLT sectors.

5. The pressure in the *AOP* region, as in all the of the precipitation areas considered above, does not depend on the IMF B_z component but increases significantly with P_{sw} . The average pressure here is ~ 0.5 of the pressure level in the *LLBL* precipitation.

6. The pressure in the *AOP* region is distributed quite evenly over the noon hours of the local geomagnetic time; therefore, a significant pressure difference between the *LLBL* and *AOP* regions in the ~ 10 – 14 MLT sector is observed. At $P_{sw} \sim 4$ – 6 nPa, the pressure difference ($\Delta P = P_L - P_A$) is comparable to the pressure level in the *AOP* region.

7. At a low level of magnetic activity, $|AL| < 200$ nT, the characteristics of auroral ions (protons) precipitating in the noon sector of the *AOP* are similar to the characteristics of precipitations at the polar edge of the *AOP* in the midnight sector.

The plasma mantle, cusp, and low-latitude boundary layer are located directly near the magnetopause, the outer boundary of the magnetosphere. From the moment the magnetopause was identified, this region was defined as a current sheet in which the total pressure balance is maintained. However, there have been relatively few experimental studies of the conditions of such a balance, despite the presence of simultaneous observations from several satellites, due to the high

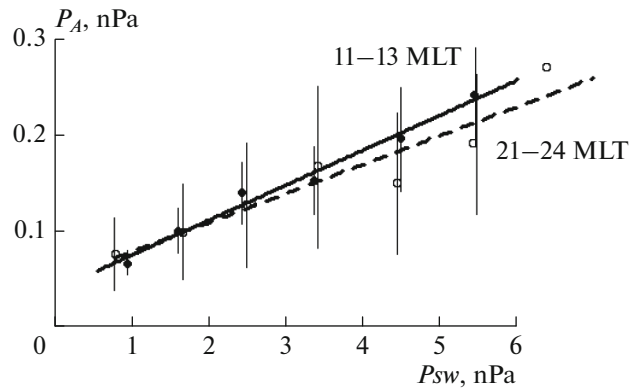


Fig. 5. Ion pressures in the noon sector (solid line) of the *AOP* and at the polarward edge of the auroral oval in the midnight sector (dashed line) with respect to the dynamic pressure of the solar wind.

turbulence in the magnetosheath (Panov et al., 2008). The results of the statistical analysis of the pressure in the boundary layers and the cusp obtained in this work are thus extremely useful for an understanding of the mechanisms of magnetopause formation and a describing of its dynamics.

It can be noted that the use of commonly used concepts of the role of magnetic reconnection in the formation of the cusp and boundary layers is rather complicated (e.g., Haerendel et al., 1978; Gosling et al., 1991). The magnetopause is in constant motion, and its position at each point is determined by the local pressure balance. The models of pulsed penetration of the magnetosphere by magnetosheath plasma considered by Lemaire (1977) and Roth (1992), conversely, have not had a satisfactory theoretical foundation. A high level of turbulence in the magnetosheath (Rossolenko et al., 2007; Rossolenko et al., 2008) leads to significant differences in the magnitude and direction of the magnetic field at different points of the magnetopause, which is the crucial parameter in reconnection theories. Abrupt magnetopause jumps are triggered by abrupt changes in currents inside the magnetosphere (Pulinets et al., 2016). When the magnetopause moves outward, part of the magnetosheath plasma falls inside the magnetosphere. Such dynamic processes, however, have been little studied so far.

Magnetopause crossings were studied during quiet periods under stable conditions in the solar wind, when the magnetopause moved slowly. The imbalance in magnetopause pressure during these events is very small, e.g., the pressure imbalance recorded during a TEMIS satellite flight described by Znatkova et al. (2011) did not exceed 3%. It should be noted that the freezing-in condition is not applicable in the description of slow plasma motion and the observation of the pressure balance condition (Artsimovich and Sagdeev, 1979). Therefore, this study does not consider the pro-

cesses described in the framework of reconnection theory under local disturbances of magnetic freezing.

The plasma mantle is adjacent to the magnetopause mainly on the flanks of the magnetosphere. The pressure in the plasma mantle is much lower than the pressure of the magnetic field in the lobes of the magnetotail. Thus, the pressure balance in the magnetopause is maintained almost completely by the magnetic field created by the currents in the magnetotail.

In the cusp region, the magnetosheath plasma directly penetrates the magnetosphere down to the ionospheric altitudes; the pressure in the region is approximately isotropic due to the high level of turbulence. In the cusp near the magnetopause, the magnetic field is insignificant, and the pressure balance at the magnetopause from the side of the magnetosphere is maintained mainly due to plasma pressure. The dynamic pressure from the magnetosheath side makes a large contribution, which is determined by the solar-wind dynamic pressure. Analysis of the magnetopause pressure balance requires the determination of the normal to the magnetopause. However, when the plasma pressure is close to isotropic, the pressure is constant along the magnetic field line. In the present study, $P_c (B_z < 0) = 0.32 P_{sw} + 0.18$, which gives an angle of $\sim 56^\circ$ between the direction of the normal to the magnetopause and the solar wind. This value roughly corresponds to that reported by Panov et al (2008). Thus, this estimate confirms the dominant contribution of the plasma pressure in the cusp to the pressure balance at the magnetopause.

At IMF $B_z > 0$, the cusp in the region of the magnetopause and at the heights of the ionosphere is recorded at the highest latitudes, where there is practically no dependence of the pressure on the solar wind dynamic pressure. The average level of ion pressure at $B_z > 0$ is 0.9 nPa for all studied events, while $\langle P_c \rangle = 1.2$ nPa for negative IMF polarity.

The plasma pressure in the equatorial plane was determined based on data from the THEMIS mission (Kirpichev and Antonova, 2011; Antonova et al., 2013, 2014) without *LLBL* as a separate unit. Therefore, the plasma pressure in *LLBL* determined in this work is so far the only result of the kind. The pressure values obtained as a function of the solar-wind dynamic pressure confirm the crucial role of the Earth's dipole in the pressure balance in the equatorial plane under the magnetopause. However, it should be noted that the magnetopause pressure balance on the magnetospheric flanks in the equatorial plane (Antonova et al., 2018, Fig. 2) is mostly provided by the plasma pressure.

Comparison of the ion pressure in the *LLBL* and *AOP* precipitation regions yielded an interesting result. The pressure difference between these areas (Fig. 4d) may indicate the presence of significant radial gradients, a "trough" of plasma pressure in the noon sector of the magnetosphere. Ionospheric observations indicate that, from the magnetopause towards the Earth, a

sufficiently high pressure in the *LLBL* region can first rapidly decrease to the pressure level in the region of *AOP* projection and then experience a smooth increase as the distance to the Earth decreases. The radial scale of such pressure variations can be roughly estimated from the width of the *LLBL* and *AOP* precipitation regions (1° latitude corresponds to ~ 1 Re), which is $\sim 2^\circ$ latitude each at $B_z > 0$ (Vorobjev et al., 2013, Fig. 7). However, this effect requires a more careful analysis that takes into account the strong distortion of the magnetic field near the magnetopause.

6. CONCLUSION

The ion pressure in the regions of ionospheric projections of the plasma mantle, polar cusp, low-latitude boundary layer (*LLBL*), and the region of structured *AOP* was studied based on data from F6 and F7 low-altitude spacecraft. The spacecraft data for the entirety of 1986, a year of quiet Sun at the very beginning of the 22nd cycle of solar activity, were considered. The pressure levels of precipitating particles in different precipitation regions were compared; the influence of the IMF B_z component and the solar-wind dynamic pressure on the plasma pressure level was studied. It was found that the level of ion pressure in all of the studied precipitation regions does not depend on either the polarity or the value of the IMF B_z component. The pressure in the mantle region varies in the range from 0.02 to 0.06 nPa and does not depend on the solar-wind dynamic pressure. The average pressure is $\langle P_m \rangle = 0.03 \pm 0.01$ nPa. In the cusp region, the ion pressure does not depend on the solar-wind dynamic pressure at IMF $B_z > 0$, while it increases significantly with P_{sw} at IMF $B_z < 0$. The average pressure level is $\langle P_c \rangle = 1.0 \pm 0.3$ nPa, which is almost two orders of magnitude higher than that in the mantle. The pressure in the *LLBL* precipitation increases significantly with the dynamic pressure, which may be due to the increased efficiency of plasma penetration from the magnetosheath on the geomagnetic field lines. The average pressure level in *LLBL* is $\langle P_L \rangle = 0.27 \pm 0.07$ nPa. The pressure distribution in the *LLBL* along the MLT e shows a pronounced local increase in the noon sector (~ 11 – 14 MLT), which magnitude increases significantly with an increase in P_{sw} . The pressure in the *AOP* region also increases with P_{sw} and averages ~ 0.5 of the pressure in the *LLBL* precipitations. In the *AOP* region, the pressure is distributed over MLT fairly evenly, which results in a significant pressure difference ($\Delta P = P_L - P_A$) between the *LLBL* and *AOP* regions in the midday sector.

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