The Substorms Impact on Processes in the Ionosphere and Plasmasphere of the Earth

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Abstract—During magnetospheric substorms in the *F* region of the ionosphere and up to altitudes of ~1000 km, a polarization jet (PJ) is developed. Measurements of energetic ring current ions on the AMPTE/CCE satellite and driftmeter data on the DMSP satellites evidence that the formation of PJ is associated with the injection of energetic ions (10–100 keV) into the inner magnetosphere during substorms. In the region of PJ development, the characteristics of the ionospheric plasma change: the plasma density decreases, sometimes by an order of magnitude, and at the same time, the plasma temperature increases significantly. In addition, simultaneously with the westward plasma drift, upward plasma drift is usually observed. The upward ion flux from the region of PJ development of ~10^9 cm^{-2} s^{-1} is an order of magnitude greater than the average daytime ion flux from the ionosphere to the plasmasphere. Measurements on the MAGION-5 satellite in the plasmasphere on the same *L*-shells, where the polarization jet is recorded in the ionosphere, show an increase in the cold ion density. The density "humps" observed near the plasmapause are apparently formed due to plasma flows from the ionosphere accompanying the formation of the polarization jet. Thus, the consequences of substorms are observed throughout almost the entire magnetosphere.

1. INTRODUCTION

Ideas about magnetospheric substorms initially appeared from the description of auroras, and it was believed that this was a set of phenomena developing in the northern and southern polar regions of the near-Earth space. At the beginning of the satellite era, after the discovery of the Earth's geomagnetic tail (Ness, 1965), it was found that substorms associated with the interaction of disturbed solar wind flows with the Earth's magnetosphere start with processes in the magnetotail and affect areas near the equatorial plane up to distances of 3–5 radii from the center of the Earth (Galeev, 1979). The development of substorms in the magnetotail leads to the injection of energetic ions (20–50 keV) and an increase in the ring current near the Earth (Stephens et al., 2019). The radial electric field arising at the injection boundary is projected into the ionosphere along the magnetic field lines. Thus, the development of a substorm encompasses not only the polar regions of the ionosphere and atmosphere, but also significantly affects the subauroral ionosphere (Deminov, 2008).

The polarization jet (PJ)—fast, up to 3 km/s, westward ion drift at altitudes of the *F* region in the ionosphere—was discovered by Yu.I. Galperin and colleagues based on data from the Cosmos-184 satellite (Galperin et al., 1973, 1974). Such a narrow in lati-

tude, 1–2 degrees, ion drift should be associated with an electric field of 100–130 mV/m directed poleward the pole. In the English-language literature, the term SAID (subauroral ion drift) is most often used for a polarization jet (Spiro et al., 1979). In 2002, J. Foster and coauthors (Foster and Burke, 2002; Foster and Vo, 2002), using data from the DMSP F13 satellite and Millstone Hill incoherent scatter radar, described wider ion drift fluxes (~5° or more) in the ionosphere. The average peak velocity of these fluxes was 0.9 km/s. The authors called this phenomenon SAPS (*subauroral polarization stream*). Such a flow usually does not have sharp boundaries in latitude either on the equatorial or polar side, whereas the polarization jet in most cases has a sharp equatorial boundary. The PJ is considered a special case of SAPS or an area of SAPS near the peak of the westward velocity component (Landry and Anderson, 2018).

The discovery of PJ from satellite measurements contributed to a thorough analysis of data obtained at ground-based ionospheric stations. It was found that additional reflections of *F*3*s* at lower frequencies and at a greater range than regular background traces on ionograms from vertical sounding of the ionosphere, correspond to narrow fast plasma flows near the zenith of the observation station (see (Khalipov et al., 2001; Stepanov et al., 2017) and references therein). After

the appearance of such reflections, the critical frequencies of the background $F2$ layer can sharply decrease within 15−30 min by 2−4 MHz or more; i.e., there is a "break" in frequency, clearly visible on the daily f-graphs of ionospheric data (Stepanov et al., 2016).

Data from ground-based ionospheric stations provide extensive material for studying the conditions for development of the PJ in the ionosphere and its relationship with the development of substorms in the magnetosphere. Simultaneous data obtained on the MAGION-5 satellite in the plasmasphere, at ground-based ionospheric stations, and on DMSP series satellites in the ionosphere make it possible to establish characteristic changes in the thermal plasma parameters both in the ionosphere and plasmasphere that occur during the development of substorms.

This article examines the relationship between phenomena that occur in the magnetosphere, plasmasphere, and ionosphere during development of substorms.

2. FORMATION OF A POLARIZATION JET DURING THE INJECTION OF ENERGETIC PARTICLES INTO THE INNER MAGNETOSPHERE

A number of studies examining possible mechanisms of PJ formation in the ionosphere took into account the electric field that arises in the magnetosphere during substorms near the midnight meridian upon the injection of energetic ions of the plasma sheet and the ring current's approach towards the Earth (Smiddy et al., 1977; Southwood and Wolf, 1978). This electric field is mapped to the ionosphere along magnetic field lines and results in westerly plasma drift. Near the equatorial plane, energetic ions also drift westward, and over time, the PJ develops in the ionosphere in the evening sector. However, a single generally accepted mechanism describing PJ development not yet been elaborated.

Khalipov et al. (2003, 2016a) presented experimental evidences on the relationship between PJ formation at ionospheric heights and the injection of ions with energies of several tens of kiloelectronvolts into the inner magnetosphere during substorms. Near the injection region in the near-midnight sector of magnetic local time ions without dispersion are observed on geostationary satellites, and in the evening sector, ions with dispersion in the form of "nose structures" were detected. In the cited articles, only cases of PJ and energetic ions recorded within 3 h after an isolated AE burst were considered (Geomagnetic Data Service (kyoto-u.ac.jp)), so that, on the one hand, it was possible to easily associate these phenomena with a specific substorm and, on the other hand, to avoid considering nose structures corotating with the Earth.

In Fig. 1, another example is considered, indicating the relationship between the formation of the ion injection boundary and the PJ in the ionosphere. This figure shows the results of measurements of hydrogen, oxygen and helium ion fluxes near the equatorial plane of the Earth's magnetosphere on the AMPTE/CCE satellite with the CHEM instrument on October 3−4, 1987 (Index of /AMPTE/summary_images/summary_image_files (jhuapl.edu)), (Gloeckler et al., 1985). Along the ordinate axis the ion energy is shown in kiloelectronvolts per unit charge; along the abscissa axis − time UT, the value of the McIlwain parameter L (distance from the center of the Earth to the magnetic field line at the equator in Earth radii), local time (LT), and magnetic latitude (MLAT) of the measurement location are given. The vertical dashed line marks the boundary of ion injections into the inner magnetosphere. This boundary was observed at 1115 UT, 2330 LT (local time hereinafter is given in hours) on the magnetic shell $L \approx 3.2$. At the Yakutsk ground-based ionospheric station ($L = 3.0$) a polarization jet was detected 1 h later at 1215 UT, 2125 LT. It is known that on the shell $L \approx 3$, within an hour, the PJ shifts to the west, i.e., to earlier LT hours, on average, by 3 h LT (Khalipov et al., 2003). In the case shown in Fig. 1, in 1 h, the PJ could have moved by 0205 LT and also drop to a slightly lower L-shell. Both recording at the deep L-shell of the plasma sheet ion injection boundary and the observation of the PJ in the ionosphere are associated with development of a substorm. The isolated burst of the AE-index (Fig. 1, top graph) occurred at 1030 UT on October 3, 1987, 45 min before detection of the ion injection boundary in the near-midnight sector and 1 h 45 min before formation of the PJ above the Yakutsk station in the late evening sector.

It should be noted that ions of the plasma sheet injected into the inner magnetosphere drift around the Earth, forming a ring current, and thus the ion injection boundary is simultaneously the inner boundary of the near-Earth ring current.

Khalipov et al. (2016a), using significant statistical material, showed that the invariant latitude (or the McIlwain parameter L) of the injection boundary of ions with energy of about 50 keV depends on the AE-index, which characterizes the substorm intensity, and this dependence coincides with the dependence of the position of the equatorial boundary of the PJ also on the AE-index. Figure 2 reproduces the final figure from the cited work and demonstrates the coincidence of the dependencies. The dependence of the invariant latitude (Λ_{eq}) of the equatorial boundary of the PJ on the magnitude of the AE burst is approximated by a linear function, shown as a solid line in Fig. 2:

$$\Lambda_{eq} = -0.0079AE + 64.0. \qquad (1)$$

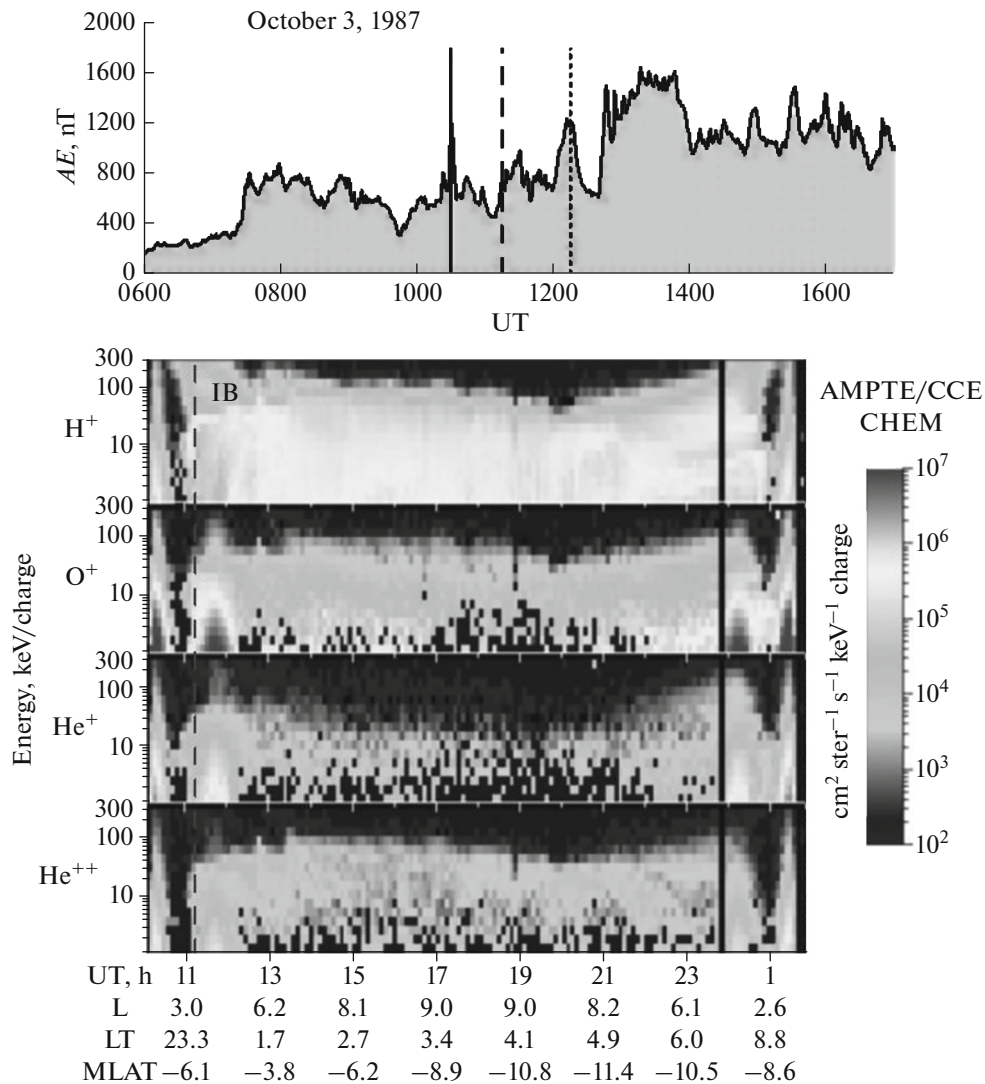The dotted line in Fig. 2 shows a linear function that approximates the dependence of the invariant latitude

Fig. 1. Bottom: Energy–time spectrograms for various ions recorded by CHEM instrument on AMPTE/CCE satellite on October 3–4, 1987. The dashed line indicate the ion injection boundary (IB). Top: Change in *AE*-index with time. Solid line marks the *AE* burst. The dashed line is the time of the injection boundary detection, the dotted line is the time of the PJ detection at the Yakutsk station.

of the inner boundary of the ring current (Λ_b) on the *AE* burst magnitude:

$$\Lambda_b = -0.0072 AE + 63.2. \qquad (2)$$

Relations (1) and (2) are very close, the determination coefficients are 0.79 and 0.68, respectively, and this evidences on the identity of the inner boundary of the ring current (or the energetic ion injection boundary) and the equatorial boundary of the PJ; their formation occurs on the same *L*-shells at the same local time, albeit at different geomagnetic latitudes. Thus, it was reliably established that PJ formation is associated with energetic ion penetration into the inner magnetosphere during substorms.

In addition, coincidence of the PJ equatorial boundary and the ion injection boundary, as well as, almost simultaneous observations of the PJ and ion injection boundary in the near-midnight sector of the magnetosphere shown in a number of examples (Fig. 1, (Khalipov et al., 2003, 2016a)), indicate that the electric field arising in the magnetosphere does not have time to be neutralized by the thermal plasma of the plasmasphere and is very quickly transmitted to ionospheric heights.

3. FORMATION OF A POLARIZATION JET IN THE SUBSTORM EXPANSION PHASE

The initial analysis of PJ development in the ionosphere according to data from the DE-2 satellite (Dynamics Explorer–2) showed that the minimum delay time for the occurrence of the PJ with respect to
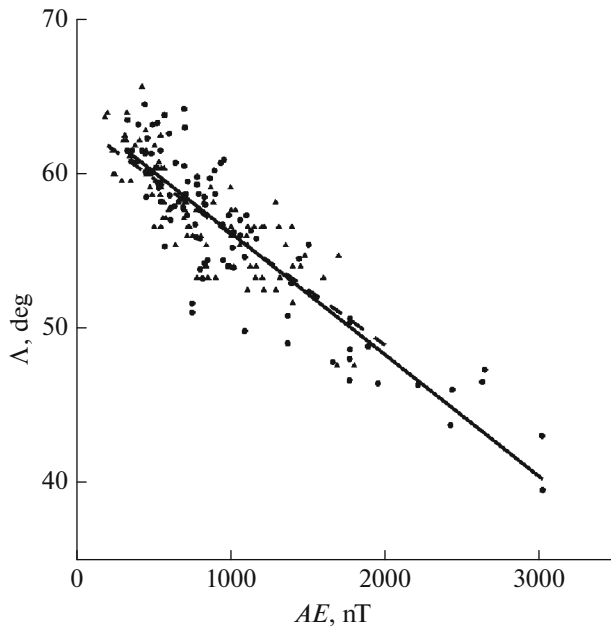
Fig. 2. Dependence of the equatorial boundary of the PJ (dots) and the inner boundary of the ring current (triangles) on the burst magnitude of substorm activity in *AE*. The corresponding fitting lines, solid and dotted, are described in the text.

Fig. 3. Dependence of the time of PJ occurrence at the Yakutsk and Podkamennaya Tunguska stations on the time of substorm beginning (burst in *AE*-index). These times coincide on the dotted lines. Solid lines show linear approximations. Local midnights in Yakutsk and Podkamennaya Tunguska is marked with dash-dotted lines.

the beginning of the *AE*-burst is 30 min; thus, the PJ forms during the recovery phase of the substorm (Anderson et al., 1993). However, detailed analysis of data from ground-based ionospheric stations in Yakutsk ($L = 3.0$, MLT = UT + 9) and Podkamennaya Tunguska ($L = 3.0$, MLT = UT + 7) (Khalipov et al., 2001; Stepanov et al., 2008) showed that the minimum delay in the occurrence of the PJ with respect to the onset of substorm development can be less than 10 min (Fig. 3). Such events are observed when, at the time of substorm onset, the station is located near the midnight meridian. This happens quite rarely even with continuous observations at ground-based ionospheric stations, especially such coincidences of the measurement location and a substorm onset are difficult to "catch" during satellite observations.

Figure 3 considers events for which the delay time for the PJ appearance above stations relative to the onset of the substorm expansion does not exceed 3 h. It was empirically established that at the Yakutsk and Podkamennaya Tunguska stations, which are located at the magnetic shell $L \approx 3$, the PJ is usually observed at $AE \geq 500$ nT. Therefore, isolated bursts of $AE \geq 500$ nT were considered. Figure 3 also shows the number of considered events (N) and correlation coefficients (R) of the approximating lines: $UT_{PJ} = 0.81 UT_{AE} + 3.5$ for Yakutsk station and $UT_{PJ} = 0.82 UT_{AE} + 3.7$ for Podkamennaya Tunguska station.

The dependence of the PJ occurrence time over stations on the onset time of the substorm expansion is
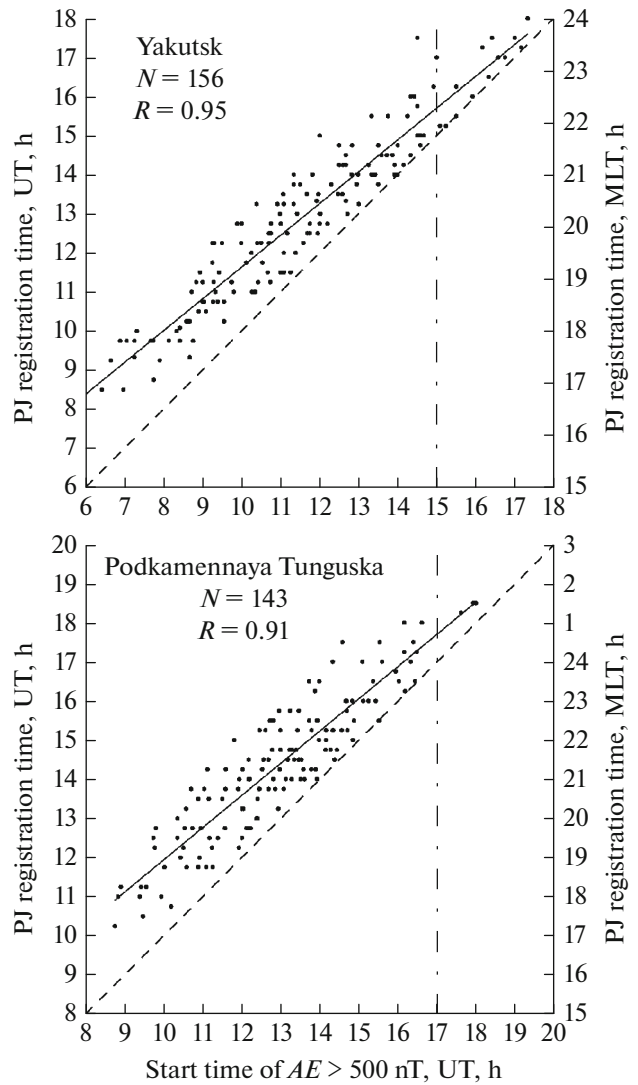
described by almost identical linear functions with high correlation coefficients $R > 0.9$, which additionally indicates a close connection between the occurrence of PJ and bursts of substorm activity. The obtained empirical dependence can be used to estimate the time of PJ appearance after the onset of a substorm. On average, in the near-midnight sector, the PJ occurs 30 min after the start of the *AE* burst, and this, more or less, corresponds to the satellite data (Anderson et al., 1993); however, the number of events with a shorter delay is significant, and, therefore, in some cases, the PJ develops in the expansion phase of the substorm.

Apparently, the main factor in the PJ appearance is the penetration of energetic ions into the near magne-

tosphere during substorms, and the start of PJ development is associated with the time of ion injection. The mechanism describing the appearance and development of PJ must necessarily take into account the injection of energetic ions during substorms.

4. CHARACTERISTICS OF IONOSPHERIC PLASMA AND UPWARD PLASMA FLOWS IN THE REGION OF POLARIZATION JET DEVELOPMENT

PJ formation in the ionosphere during the development of magnetospheric substorms leads to changes in the plasma characteristics. In the PJ formation region, the plasma density is reduced, sometimes by an order of magnitude, while at the same time the plasma temperature significantly increases (Anderson et al., 1991; Moffett et al., 1998; Roger et al., 1992; Stepanov et al., 2011). Good examples of observing PJ in the F-layer of the ionosphere on the DE-2 satellite are given in (Anderson et al., 1991). Figure 1 in this study showes that significant westward plasma drift is accompanied not only by a dip in the plasma density and a rise in its temperature, but also by significant upward movement of the plasma. Apparently, the first observations of large fluxes of oxygen ions upward from the PJ development region were described earlier by Yeh and Foster (1990). The authors analyzed data from the incoherent scatter radar at Millstone Hill and found ions flowing upward at extremely high velocities, sometimes exceeding 3 km/s at at an altitude of 1000 km. Upward fluxes were observed simultaneously with the detection of rapid westward ion drift during a strong magnetic storm on February 8, 1986, at an invariant latitude of 57° around 1800 MLT. The ion temperature in this region was elevated, exceeding 4000 K. (The usual ion temperature at these heights is 1000−2000 K). According to the authors' estimates, the upward flux of oxygen ions was $\geq 3 \times 10^9$ cm^{-2} s^{-1}.

Later, based on satellite and ground-based data, it was shown that the PJ development is always accompanied by significant upward plasma flows from the ionosphere (Wang and Luhr, 2013; Khalipov et al, 2016b; Stepanov et al., 2019). According to Doppler data from ground-based ionosondes, during substorms, significant plasma flows are observed with velocities of up to 150−180 m/s along the magnetic field from the F-layer of the ionosphere. According to data from drift meters on DMSP series satellites, in the upper ionosphere at heights of ~850 km, simultaneously with the westward plasma drift, vertical drift velocities reached 1.5−2.0 km/s. The maxima of westward and upward flows do not always coincide, but in the narrow latitudinal interval in which the PJ exists, vertical flows are also recorded (Stepanov et al., 2019).

5. FORMATION OF DENSITY DISTRIBUTION INHOMOGENEITIES IN THE PLASMASPHERE

The observed upward plasma flows from the PJ development region in the ionosphere are possibly associated with density distribution inhomogeneities in the outer regions of the plasmasphere and the plasmasphere boundary layer (Kotova et al., 2023).

To analyze the thermal plasma characteristics in the Earth's plasmasphere, it is convenient to use data from the Czech MAGION-5 subsatellite of the INTERBALL project, since measurements on this subsatellite were carried out using a PL-48 wide-angle thermal ion analyzer with very good time resolution, and the energy spectrum of protons (<25 eV) was measured within 0.4 s every 8 s. MAGION-5 was launched together with the main apparatus INTERBALL-2 in August 1996 into a near-Earth orbit with an inclination of ~65° and an orbital period around the Earth of about 6 h. Unfortunately, a day after the launch, communication with the subsatellite was lost, but almost 2 years later it was restored. The boom on which the PL-48 wide-angle thermal ion analyzer was installed also did not open immediately, so data was obtained from August 1999 to July 2001.

When calculating the plasma parameters from the measured energy spectra, it was assumed that the particles were distributed according to Maxwell's law, but taking into account partial screening by the potential of the spacecraft. The data processing technique is described in detail by Kotova et al. (2014).

To analyze ionospheric drifts and plasma characteristics in the ionosphere, data from the SSIES equipment complex (DMSP SSIES INSTRUMENT CHARACTERISTICS (bc.edu))installed on DMSP satellites (List Madrigal experiments (openmadrigal.org)) were used.

Figure 4 shows the proton density profiles obtained on the MAGION-5 satellite on September 28, 2000; October 30, 2000; and November 27, 2000 as functions of the invariant latitude (Λ). Below them in this figure are the ion velocities and electron density in the upper ionosphere at a height of about 850 km, measured on the F15 and F12 satellites. The vertical dashed line marks the maximum velocity of westward ion drift in the ionosphere, which corresponds to the satellite crossing the PJ. The bottom panels show the changes in the AE-index during the corresponding measurement periods on the satellites.

The left panels of Fig. 4 show measurements taken on September 28, 2000. In the plasmasphere, the density gradually decreases towards the outer L-shells, although some inhomogeneities were also observed for $L < 3$. Before the plasmapause ($L \approx 4.3$) in the post-midnight sector, a region of increased plasma density is seen at $58° < \Lambda < 61°$. 8.5 hours earlier in the evening sector of the upper ionosphere in the Northern Hemisphere, a classical PJ was recorded on the
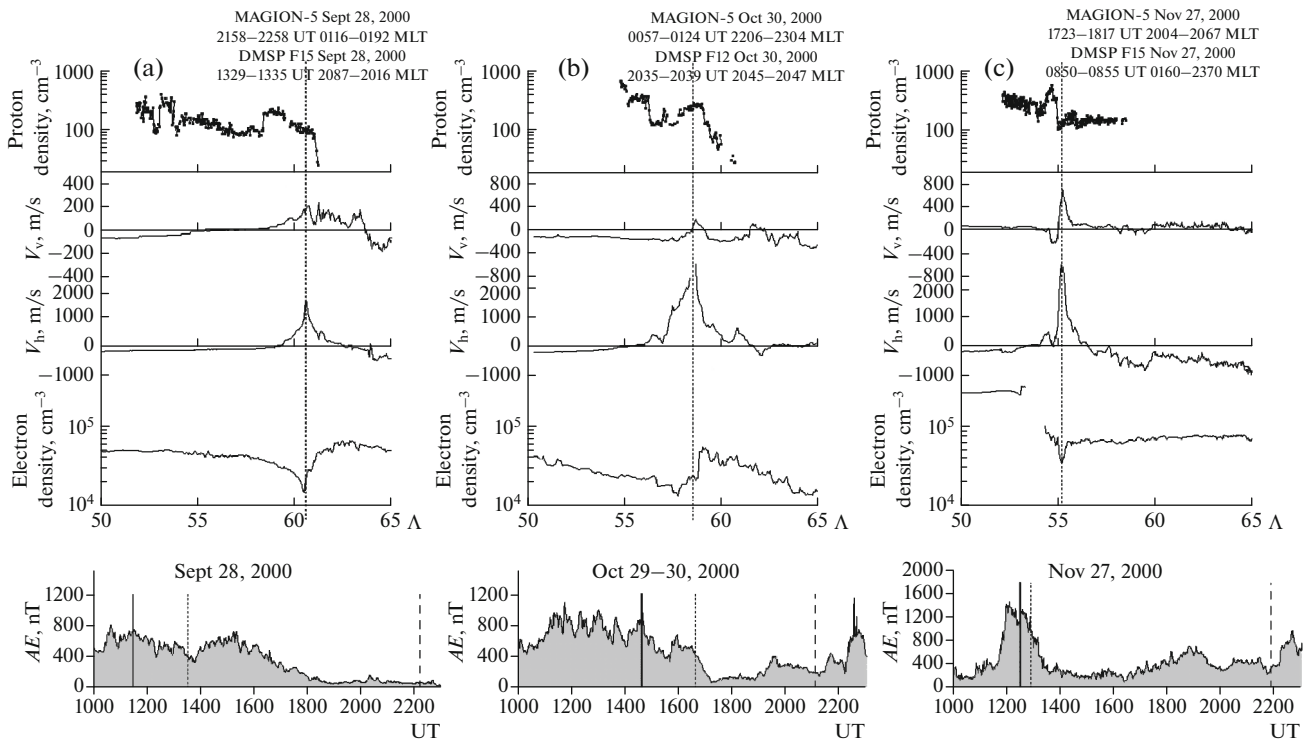
Fig. 4. Examples of density increases in the outer plasmasphere (a, c) or in the plasmasphere boundary layer (b) and associated observations of PJ in the upper ionosphere. From top to bottom, dependences on invariant latitude in degrees (Λ) are shown: variations in proton density along the orbit of MAGION-5 satellite, ion drift velocities in vertical (V_h) and horizontal (V_v) directions, and electron density according to data from the DMSP F15 and F12 satellites. The dotted line marks the maximum westward velocities.. Bottom panels show variations in the *AE*-index for the corresponding days. Dashed and dotted lines indicate measurement times on the MAGION-5 and DMSP satellites, respectively. Solid lines show *AE* peaks responsible for PJ formation.

same *L*-shell,. The maximum velocity of westward ionospheric plasma drift was $V_h \sim 1500$ m/s; in the direction from the Earth, $V_v \sim 200$ m/s; at the same time, a dip in the plasma density was observed.

The middle panels of Fig. 4 show that in the plasmasphere, the ion density on average decreased quite sharply, as usually happens in the boundary layer of the plasmasphere (Kotova et al., 2018). The satellite crossed the plasmapause at $\Lambda \sim 55°$ ($L = 3.04$). However, at the invariant latitude of ~58°–59.5°, the density is significantly increased ("hump"), and at the same latitude in the ionosphere 4.5 h before the observations on MAGION-5, the DMSP F12 satellite recorded the PJ with the maximum westward drift velocity $V_h \sim 3000$ m/s and low upward drift speed $V_v \sim 200$ m/s. During recording of this PJ, the density in the ionosphere was reduced. On October 29, 2000, from approximately 1500 UT, a number of bursts in the *AE*-index were observed, the last of them at 1835 UT, apparently caused the PJ formation, which 2 h later at 2037 UT was detected in the evening sector of the ionosphere.

The right panels of Fig. 4 show data obtained on November 27, 2000. In the region of invariant latitudes 54° < Λ < 55° in the plasmasphere, the density is increased by three to five times with respect to neighboring regions. With an accuracy to 0.5° at the same invariant latitude, 8.5 h before the detection of this region in the plasmasphere, the DMSP F15 ionospheric satellite crossed the region of development of the classical PJ ($V_h \sim 2800$ m/s, $V_v \sim 600$ m/s, dip in electron density) in the near-midnight sector of local time in the Southern Hemisphere. About 20 min before detection of the PJ, the burst in the *AE*-index indicated the development of a substorm in the magnetosphere.

It can be seen that all of the above cases of observation of thermal plasma density "humps" in the outer plasmasphere or in the region of the plasmasphere boundary layer were accompanied by PJ detection several hours earlier at the same *L*-shells in the ionosphere.

To reliably calculate the trajectory and time of plasma element movement from the ionosphere to the magnetosphere, careful complex theoretical calculations are needed that take into account ion charge exchange, particle collisions, wave interactions, etc. Rough estimates of the delay time of the magnetospheric plasma response to changes in the ionosphere associated with the development of PJ were made by Kotova et al. (2023). The distance along the magnetic

field line at $L \sim 3-4$ between the location of PJ detection and the measurement region in the plasmasphere in the dipole magnetic field approximation is about 3 Earth radii. Assuming that the plasma drifts along the field line at a velocity of ≤ 1 km/s, we can suggest that the delay time is 5.5 h, which corresponds in order of magnitude to the observations in Fig. 4.

The magnetic local time (MLT) of measurements in the plasmasphere and ionosphere also differs. On September 28, 2000, this difference is apparently maximum and amounts to more than 4 h, while on October 29−30, it is less than 2 h. Kotova et al. (2023) consider two more examples of coupled measurements in the ionosphere and plasmasphere, on February 12 and November 12, 2000, in which the data were obtained at close local times. Shifts in MLT are associated with two oppositely directed plasma movements. On the one hand, the high westward velocity of the ionospheric plasma in the PJ band should lead to a significant shift of the plasma to the west during the time from the DMSP observations to the MAGION-5 measurements. On the other hand, during this time, the Earth, together with the ionosphere and plasmasphere, is rotating eastward under the satellite's orbit. The linear velocity of plasma corotation at the height of the MAGION-5 satellite ($\sim 13\,500$ km) is ~ 1500 m/s, i.e., comparable to the plasma velocity in the PJ. Depending on the actual relationship between these velocities, local MLT may be the same or different.

6. CONCLUSIONS

It is known that the development of substorms in the Earth's magnetosphere is associated with the interaction of solar wind fluxes with the Earth's magnetosphere, when the dynamic pressure in the solar wind increases and/or when the sign of the interplanetary magnetic field component directed along the Earth's magnetic dipole changes from north to south. The development of substorms in the magnetotail leads to injection of energetic ions (20−50 keV) into the near magnetosphere and an increase in the ring current near the Earth.

Experimental data have shown that the formation of a polarization jet in the ionosphere is associated with the development of substorms in the magnetosphere. The equatorial boundary of the polarization jet band is physically related to the inner injection boundary of energetic ions approaching the Earth during substorms. These boundaries are formed at the same L-shells.

In turn, PJ development is associated with changes in the characteristics of the plasma in the ionosphere. In the PJ formation region, the plasma density is reduced, sometimes by an order of magnitude, and at the same time, the plasma temperature is significantly increased. In addition, simultaneously with the plasma drift to the west, upward plasma drift is commonly observed.

The Earth's plasmasphere is essentially a continuation of the ionosphere to high altitudes (Lemaire and Gringauz, 1998; Kotova, 2007). It is believed that the plasmasphere begins at a height of (≥ 1000 km), where hydrogen ions replace oxygen ions and become the main plasma component. On average, in the daytime plasma flows upward from the ionosphere to the plasmasphere, ion fluxes are $\sim 10^8$ cm^{-2} s^{-1}, and at night, plasma flows downward from the plasmasphere to the ionosphere. There are many theoretical models that consider the processes of depletion and refilling of the plasmasphere based on hydrodynamics and kinetics (see (Krinberg and Tashchilin, 1984; Lemaire and Gringauz, 1998; Khazanov, 2011; Kitamura et al., 2021), etc.). During PJ development, the ion flux from the ionosphere can be estimated as follows. For an electron density in the upper ionosphere $\sim 5 \times 10^4$ cm^{-3} and upward velocities ~ 400 m/s, the upward electron flux from the PJ development region is $\sim 2 \times 10^9$ cm^{-2} s^{-1}, and this value is an order of magnitude greater than the average daytime ion flux from the ionosphere to the plasmasphere. This local upward plasma flow leads to a change in the characteristics of the plasma in the plasmasphere and the appearance of limited zones of increased plasma density. Despite the fact that the PJ develops only during substorms and in a limited space region, such flux cannot be ignored when constructing ionosphere−plasmasphere interaction models.

Thus, the consequences of substorms are observed throughout nearly the entire magnetosphere and await theoretical description.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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