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Structure of the Latitudinal Profile of Solar Cosmic Rays in the Earth's Magnetosphere during Substorm Activity on October 26–27, 2003

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Abstract—The structure of penetration of solar cosmic rays (SCRs) with energies of 1–100 MeV into the Earth's magnetosphere before a strong magnetic storm of October 29–31, 2003, is studied based on the CORONAS-F satellite data. The effect of north–south asymmetry was observed in the polar caps for more than 12 h, which made it possible to study the dynamics of the boundary between the polar cap (the magnetotail) and the auroral zone (the quasi-trapping region). A previously unknown effect of troughs in the SCR intensity latitudinal profile during the substorm active phases has been detected in the auroral magnetosphere. The mechanism by which troughs are formed owing to the local distortion of the magnetic field line configuration, resulting in radial diffusion of particles from this region, has been proposed.

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1. INTRODUCTION

At the end of October 2003, series of solar flares caused several strong magnetic storms with a sudden commencement (SC) at 0612 UT on October 29, 2003. These storms attracted attention of researchers. Specifically, the large group of native authors published the review [Panasyuk et al., 2004]. This review in particular analyzed the measurements of solar protons on the CORONAS-F polar satellite, compared the SCR fluxes in the magnetosphere with the fluxes in the interplanetary space, and studied the dynamics of the boundary to which 1–50 MeV protons penetrate deep into the magnetosphere. These measurements were analyzed in more detail in [Lazutin et al., 2007], where the effect of SCR trapping into the Earth's proton belt was studied. In the present work, we consider again the CORONAS-F SCR measurements during the previous period (October 26–27, 2003), when unusual troughs in the latitudinal profiles of protons penetrating into the magnetosphere made it possible to determine the specific configuration of the magnetosphere during substorms.

The effect of the magnetospheric configuration on the spatial distribution of particles in the polar cap and in the quasi-trapping region is significant in the region of low energies (1–50 MeV) considered in this work. All observed effects (free penetration into the polar cap along magnetic field lines, asymmetry of the morning and evening boundaries of SCR penetration, and differences in the flux particles measured in the northern and southern polar caps) are related to the global configuration of the magnetosphere and its local features. The character of SCR penetration into the auroral zone on closed field lines is especially variable. It is known that solar protons accumulate and are quasi-trapped, as a result of which the detected particle flux increases in some cases in going from the polar cap into the auroral zone and remains unchanged in other cases (see the review [Pereyaslova, 1982]).

When discussing a new effect (troughs in the SCR intensity latitudinal profile during substorm active phases), we use the SCR measurements as a source of information about the magnetospheric configuration.

2. SCR FLARE AND THE STATE OF THE INTERPLANETARY MEDIUM

The fluxes of SCRs with energies of 1–5 MeV in the interplanetary medium appeared on October 23, when active region 0486 came from behind the eastern solar limb. At 1819 UT on October 26, the X1.2 flare with coordinates of N02W38 occurred in region 0484. Protons with an energy of >165 MeV were generated during this flare (the GOES satellite data). Figure 1 presents the key parameters of the solar wind and the magnetic activity indices. The solar wind velocity was medium (not higher than 600 km/s at a maximum), and the solar wind dynamic pressure only sometimes reached 2 nPa. The IMF B_x component was positive during the considered period; i.e., the Earth was in the same IMF sector. The IMF B_z component, which fluctuated near zero or was positive in the first half of October 26 and in the second half of October 27 but became negative soon after the flare and remained negative during about 13 h (Fig. 1), can be considered

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† Deceased.

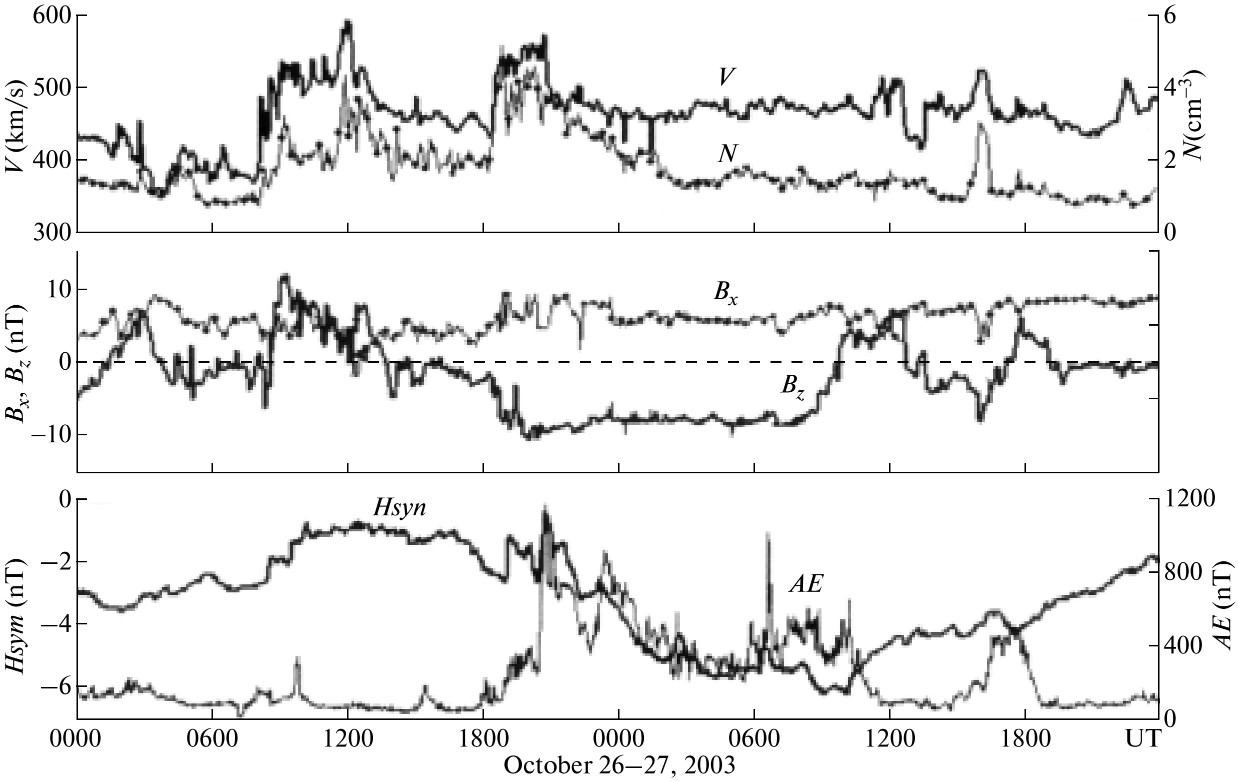

Fig. 1. Situation in the near-Earth interplanetary space and geomagnetic disturbances on October 26–27, 2003. From top to bottom: the solar wind velocity (*V*) and density (*N*), the IMF B_x and B_z components, and the *Hsym* and *AE* indices of geomagnetic disturbance.

the only disturbing factor. As a result, a long interval of substorms lasted from 1900 UT on October 26 to 1000 UT on October 27.

3. SCRS IN THE MAGNETOSPHERE

CORONAS-F measured the proton flux in four energy intervals: 1–5, 16–26, 26–50, and 50–90 MeV. A comparison of the CORONAS-F measurements in the polar caps with the ACE measurements in the interplanetary space (see Fig. 2) indicates that the fluxes identically varied in time and had close values. The fluxes were very anisotropic during an unusually prolonged period (from 2200 UT on October 26 to 1200 UT on October 27). Weak anisotropy of the opposite sign, which was observed up to 2000 UT on October 26 and after 1230 UT on October 27 on the satellite, was related to the satellite orientation conditions in the northern and southern caps.

Figure 3 compares the structures of the SCR proton fluxes on October 27 near midnight in the Northern and Southern hemispheres. Under the conditions of weak flux anisotropy in the interplanetary space (see Fig. 2), the proton fluxes in the polar caps are almost identical. The proton flux in the northern cap is substantially smaller than the flux in the southern cap under the conditions of flux anisotropy in the interplanetary space and negative B_z.

The passes of the satellite in the dusk sectors of the Southern and Northern hemispheres are superposed in Fig. 4. The proton flux in the northern polar cap is lower than in the southern one but increases on closed field lines and becomes equal to the southern flux at $L = 10$–12 (71° of corrected geomagnetic latitude), indicating the beginning of the quasi-trapping region. Here the proton fluxes at the conjugate points become equal. Such a structure of the auroral zone boundaries during substorms corresponds to the results of the classical works on the auroral oval configuration [Starkov and Feldstein, 1967; Starkov, 1994]. The quasi-trapping equatorward boundary reached $L = 4$, where the SCR proton penetration boundary is located at that time. The fact that this boundary shifts to subauroral latitudes during this series of substorms was referred to in the collective work on extreme activity in October 2003 [Panasyuk et al., 2004].

The results of detecting the penetration boundaries (PB) of protons with energies of 1–5 MeV depending on the local time and direction of the IMF vertical component and the boundary between the polar cap (PCB) and the auroral zone (the quasi-trapping region) are summed up in Fig. 5.

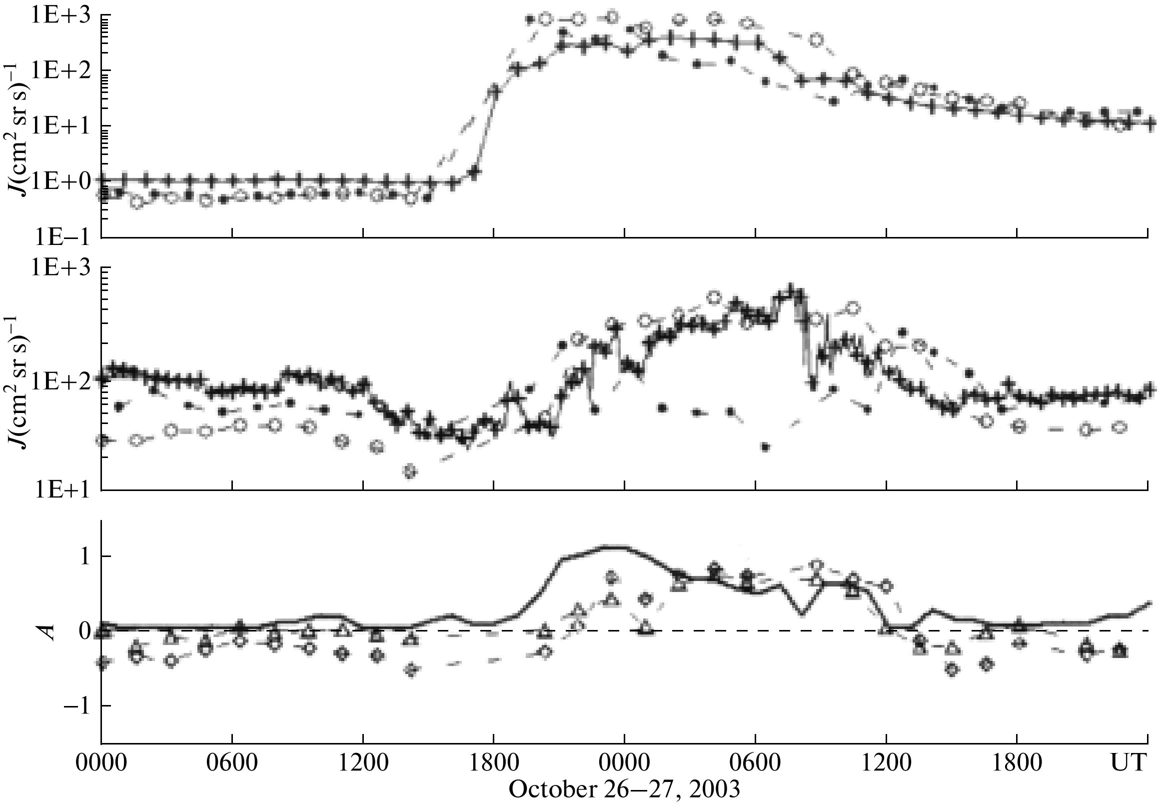

Fig. 2. Fluxes of SCRs on October 26–27, 2003. Upper block: fluxes of 14–26 MeV protons in the southern (circles) and northern (dots) polar caps and >10 MeV protons according to ACE data (a line); middle block: 1–5 MeV protons in the polar caps and 1.06–1.92 MeV protons according to ACE data; lower block: SCR anisotropy, 1–5 MeV (diamonds), 14–26 MeV (triangles), and ACE (a line) protons.

Dotted lines in Fig. 5 show the approximations of the daily variations in these boundaries using the formulas:

$$\mathrm{PB}(B_z \sim 0) = 67.27 - 1.97\cos((\mathrm{MLT} - 22.26) \cdot 15)$$

$$\mathrm{PB}(B_z < 0) = 64.96 - 3.89\cos(\mathrm{MLT} \cdot 15) \qquad (1)$$

$$\mathrm{PCB}(B_z < 0) = 73.68 - 2.26\cos((\mathrm{MLT} - 18.2) \cdot 15).$$

The dependence of PB on the B_z sign is not observed in the noon hours, whereas the transition from $B_z \sim 0$ to $B_z < 0$ in the wide sector from evening to morning results in the displacement of PBs to substantially lower latitudes, which is apparently related to substorm activity.

4. SCRS AND SUBSTORMS ON OCTOBER 26–27, 2003

In the interval of interest, the latitudinal profiles of protons penetrating into the magnetosphere were unusually uneven in latitude and variable in time. The latitudinal profile is usually even in the quiet time and during a magnetic storm, and increases are only sometimes observed in the auroral region. However, the profile pronouncedly changed from pass to pass during the studied period. Short-term decreases in the intensity (troughs in the radial profiles of SCR protons) were especially unusual.

Figures 6a–6d present four examples of such proton radial profiles on October 26–27, 2003.

First of all, it is interesting that the trough amplitude differs depending on the energy: the effect in the 1–5 MeV channel is smaller (Figs. 6a, 6e) than in the higher energy channels or entirely absent (Figs. 6b, 6c). The range of latitudes occupied by the trough is highly variable; it includes the L shells from 6 to 11 and from 5 to 6.5 in the first and last cases, respectively. We observe troughs in the nightside and dayside sectors. The first trough was detected at 1920 UT on October 26; the last trough, at 0845 UT on October 27, which coincides with the beginning and end of the 13-h period during which substorm activity was increased.

It is characteristic that all troughs are detected in the zone of quasi-trapping between PCB and PB. This is evident in Fig. 7, which presents the results of measuring PB of protons with energies of 14–26 MeV in the quiet hours and during the series of substorms, the position of PCB, and the upper and lower latitudes of measured troughs depending on the local time. The approximation curves are as follows:

$$\Lambda\ \mathrm{p}(B_z \geq 0) = 62.94\text{–}0.62\cos((\mathrm{MLT}\text{-}18.6) \cdot 15)$$

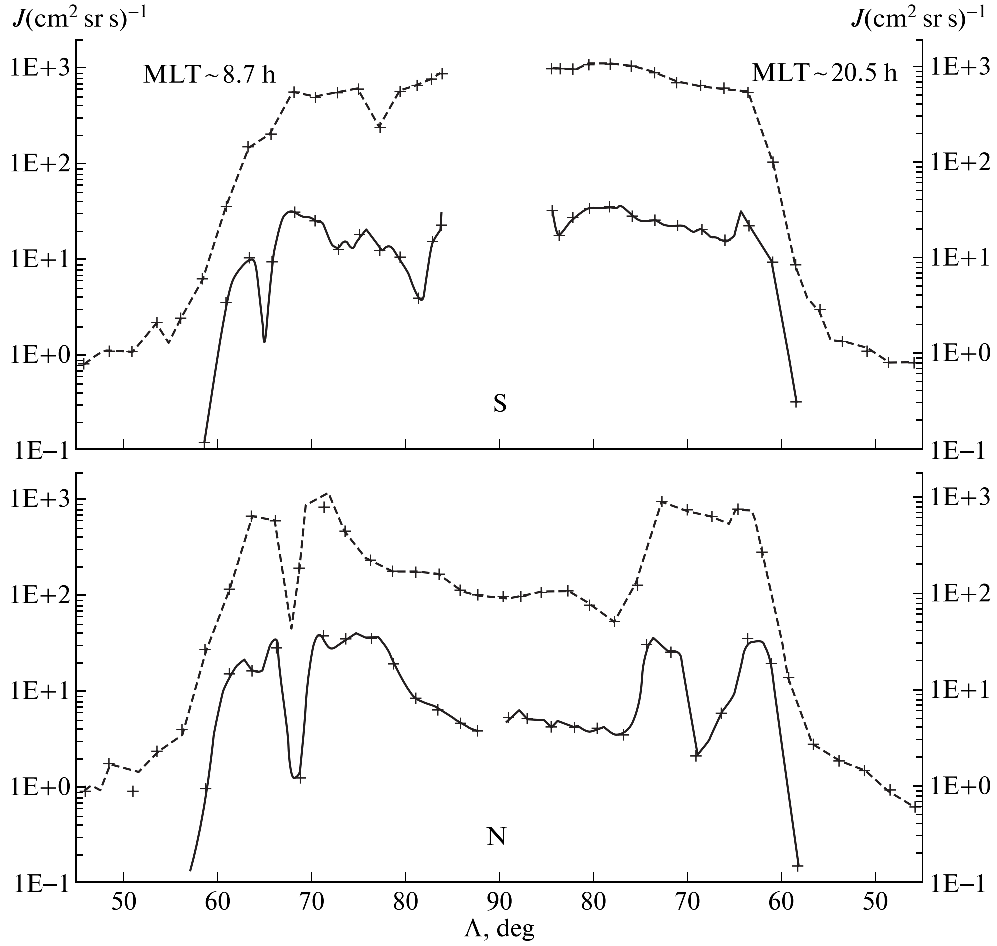

Fig. 3. Protons with energies of 1–5 MeV (dots) and 14–26 MeV on October 27 in the northern (upper block) and southern polar caps.

$$\Lambda\ \mathrm{p}(B_z < 0) = 61.86–0.8\cos((\mathrm{MLT}\text{-}18.9) \cdot 15)$$

$$\Lambda\ \mathrm{p(pos1)} = 66.19–1.23\cos((\mathrm{MLT}\text{-}22.37) \cdot 15) \quad (2)$$

$$\Lambda\ \mathrm{p(pos2)} = 69.47–2.18\cos(\mathrm{MLT} \cdot 15–23.7)$$

$$\Lambda\ \mathrm{pc}(B_z < 0) = 75.8–3.87\cos((\mathrm{MLT}\text{-}21.2) \cdot 15).$$

It is clear that the B_z sign reversal under the conditions of a low solar wind pressure results only in an insignificant displacement of proton PB by ~1° in latitude at all local times.

The consideration of the latitudinal profiles from pass to pass indicates that the number of differently located troughs with different depths is approximately the same as the number of more or less even latitudinal profiles. What can cause such rapid and short-term troughs in the intensity of particles that seemingly penetrated deep into the magnetosphere and were trapped? To answer this question, we considered the auroral zone magnetograms, which most comprehensively reflect the local features in the development of substorm activity.

Figure 8 presents the magnetogram of the *H* component at Lovozero observatory, where vertical bars mark the passes with the most distinct and deep troughs, and horizontal bars mark the pass times when the proton profile was even in latitude. Three of five passes with troughs (except the first and the last passes) coincide with the peaks of bay-like disturbances, i.e., with the maximum of the substorm active phase. The first pass coincides with a positive disturbance of the magnetic field: Lovozero is located in the evening sector at that time west of the Harang discontinuity, and we most probably fall on the substorm active phase in this case too. Finally, the last (fifth) pass took place when the observatory was already in the dawn sector, and bay-like disturbances were indistinct. However, the magnetic field *H* component does not increase in this case either when the magnetic field, which is recovered after the next active phase, is interrupted at the instant of interest, and this interruption results from the next baylike disturbance. Thus, all five troughs indicate that the substorm active phase is the cause of such a deep decrease in the intensity of 1–50

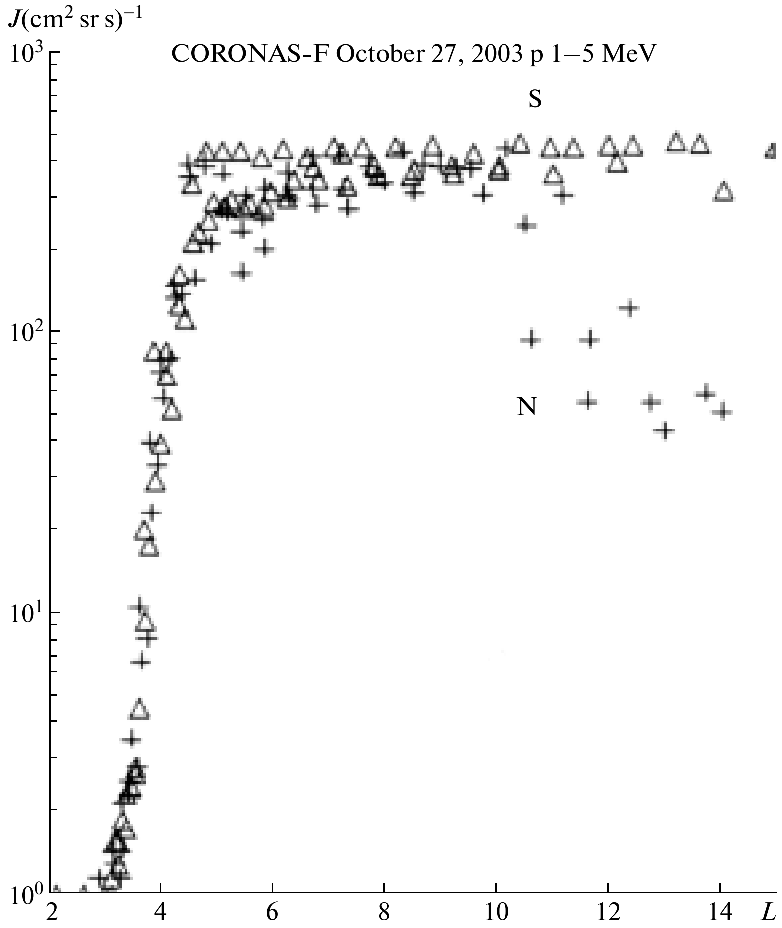

Fig. 4. Superposition of the latitudinal profiles of the solar proton intensity in the Northern and Southern hemispheres.

MeV protons. The passes without evident troughs, on the contrary, fall on the periods of a decrease in substorm activity and the phases of recovery or growth of the next substorm (these phases combine with each other in the chain of substorms). Since substorms are accompanied by local short-term distortions of the magnetic field configuration in the auroral magnetosphere, this should be the cause of the detected effect.

5. DISCUSSION AND CONCLUSIONS

In this section, we first consider the problem of SCR troughs and then resume the dynamics of SCR PBs and structural boundaries of the magnetosphere.

5.1. Substorm Troughs of SCRs

Substorm activity in the auroral zone is observed almost every day. It is unclear why the effect of troughs was not detected previously. What is the uniqueness of the situation observed on October 26–27, 2003? The case is that substorm activity should be accompanied by the appearance of increased solar proton fluxes near the Earth. In addition, a magnetic storm should not occur at that time. During magnetic storms (especially strong), the character of penetration of 1–100 MeV SCRs into the Earth's magnetosphere considerably changes, and it is still unclear how. As a result, an even latitudinal profile is formed and PBs of protons with energies of 1–50 MeV often coincide with one another [Lazutin et al., 2006]. Substorm activity is as a rule absent in the interval of arrival of the SCR flux caused by a flare and the onset of a magnetic storm. The search for events with troughs during the operation of CORONAL-F from 2001 to 2005 does not show new events. Indeed, low activity was observed before all storms, and substorms were absent. In this sense the measurements performed in October 2003, when large SCR fluxes were observed during substorm activity in the absence of a magnetic storm, were unique.

As a hypothesis explaining the effect of troughs during substorms of October 26–27, 2003, we can assume that field lines crossing the trough latitudes are stretched in the equator region (see Fig. 9). High-energy SCRs are not retained on such field lines and will be ejected onto adjacent field lines located at smaller and larger distances from the Earth. A back-

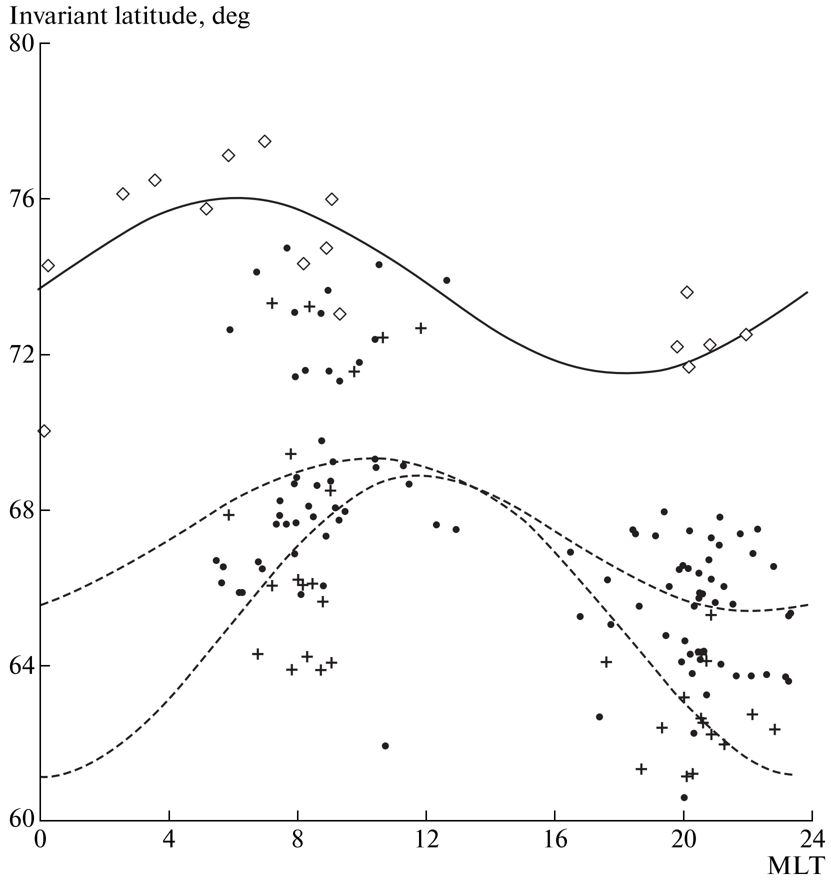

Fig. 5. Penetration boundaries of 1–5 MeV protons at $B_z \sim 0$ (dots) and $B_z < 0$ (crosses) and PCB at $B_z < 0$ (diamonds).

ward flux from quasi-dipole field lines to stretched ones will be much lower; thus, the corresponding flux tubes will carry a decreased flux during the entire magnetic drift.

The formation of thin current sheets and the corresponding stretching of field lines are usually related to the magnetotail. However, such a local situation is also quite possible in the region of closed field lines in the auroral magnetosphere.

Considerable fluxes of newly accelerated electrons and ions with energies from several to several hundreds of kiloelectronvolts appear here during intensification substorms (mostly near the equator), which results in the appearance of the azimuthal current and stretching of field lines. Both phenomena were repeatedly observed [Lazutin, 2007]. Based on the CRRES satellite measurement during substorms in the equator region, Kozelova and Kozelov [2003] calculated the substorm wedge, corresponding to the particle and magnetic field measurements, and the magnetic field line configuration. The calculation results indicate that local stretched field lines similar to those shown in Fig. 9 appear in the quasi-trapping region.

M. I. Pudovkin assumed (private communication) that several such local stretched structures can exist and they collapse by turn during the substorm poleward expansion. Such an assumption is confirmed by a fine structure of auroras during the substorm active phase [Kornilova et al., 1990]. The existence of a double structure is also confirmed by the trough shape during certain passes, specifically, during the pass shown in Fig. 6a.

Since a decrease in the intensity of trapped particles can be related to not only radial diffusion but also pitch-angle diffusion into the loss cone, we should estimate the possibility of this effect maintaining the detected value of a decrease in the intensity during a trough in the regime of strong diffusion. The estimation formulas describing the motion of energetic particles in the region of SCR penetration have the following form. The Larmor radius is

$$\rho = K\sqrt{E}/B, \tag{3}$$

where $K = 3.37 \times 10^3$ km for electrons and 1.4×10^5 km for protons; E, B, and ρ are measured in megaelectronvolts, nanoteslas, and kilometers, respectively. The period of particle drift around the Earth (in seconds) is

$$\tau_3 = 2640/EL. \tag{4}$$

The period of proton fluctuations along a field line (in seconds), if E is measured in megaelectronvolts, is

$$\tau_2 = 2.2L/\sqrt{E}. \quad (5)$$

The lifetime of particles owing to pitch-angle diffusion (in seconds) is

$$\tau_1 = \tau_2 B/2B_{eq} = 1.1L^4/\sqrt{E}. \quad (6)$$

According to these formulas, the lifetime of protons with energies of 1, 14, and 20 MeV is 40, 10, and 6 min, respectively; and the drift period is 350, 25, and 8 s, respectively. Consequently, during the period of auroral intensification (5–10 min), the flux of protons with energies of 15 and 40 MeV can decrease by a factor of *e*, provided that this flux remains in the regime of strong diffusion during this period. However, the longitudinal extension of the substorm active region is only 10–15°; i.e., the duration of strong diffusion being a factor of 10–20 as short as the drift period since the regime of pitch angle diffusion changes toward a decrease in diffusion at an exit from the active region with a distorted configuration of the magnetic field. Thus, an escape of particles into the atmosphere does not maintain the observed trough effects.

We should only assume that radial diffusion operates in such cases.

Such structures are certainly very transient: one episode of intensification lasts from one to several minutes; however, one jump is sufficient for protons to escape onto adjacent field lines at considerable changes in the pitch angle.

The dependence of the trough depth on the particle energy indicates that our hypothesis is correct. Figures 6a and 6b demonstrate that the trough depth is smaller in the 1–5 MeV channel since protons with such energies have smaller Larmor radii and, consequently, do not leave the leading magnetic field line so easily.

5.2. SCRs and Structural Boundaries of the Magnetosphere

In addition to the conclusion on the short-term localized feature in the magnetospheric configuration, the analyzed data allow us also to make certain assumptions about the global structure of the magnetosphere.

Solar protons with low energies (1–100 MeV) readily respond to the magnetic field structure and its changes and are consequently carriers of corresponding information. The measurements of electrons and protons with energies reaching several tens of kiloelectronvolts, performed onboard low-orbiting satellites, are widely used to determine the boundaries of magnetospheric domains (see, e.g., [Feldstein and Galperin, 1996] and references therein). However, these techniques have a certain disadvantage that follows from the fact that particles with the indicated energies actively participate in the processes of disturbance of the outer magnetosphere and are affected by these processes. Therefore, the boundaries of precipitating fluxes reflect not only the structure of the magnetosphere but also disturbances observed at these boundaries.

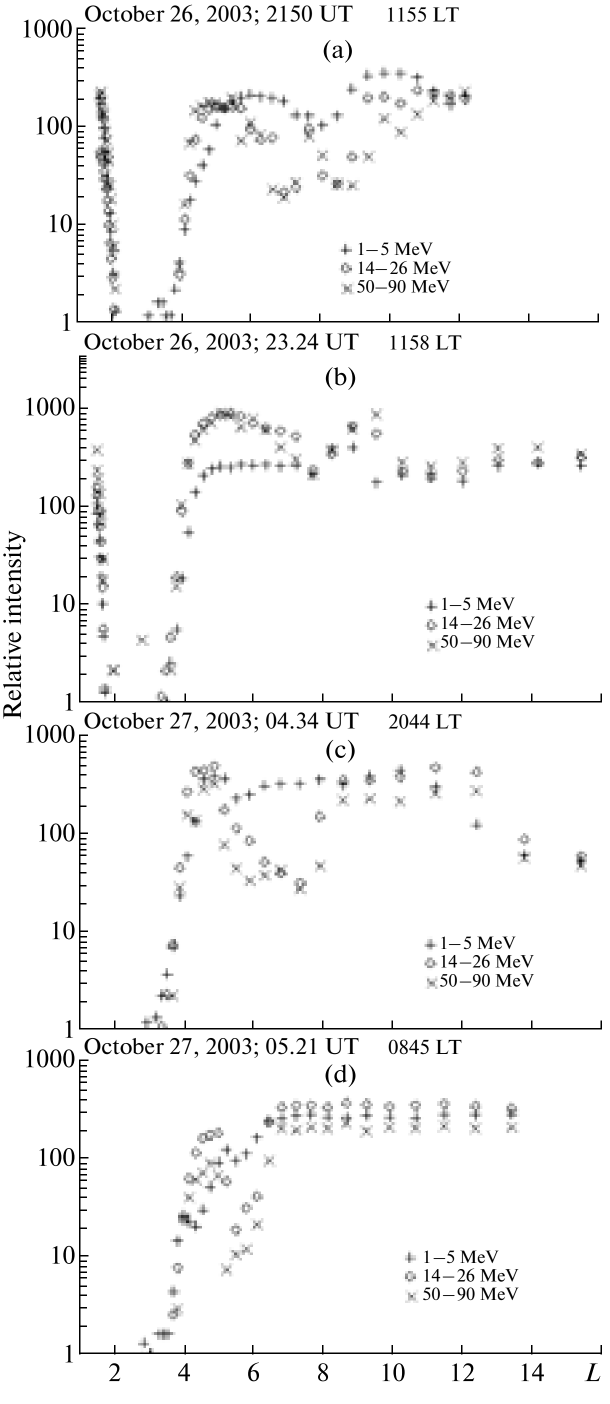

Fig. 6. (a)–(d) Examples of solar proton latitudinal profiles according to measurements in the 1–5, 14–26, and 50–90 MeV spectrometer channels during substorm activity on October 26–27, 2003.

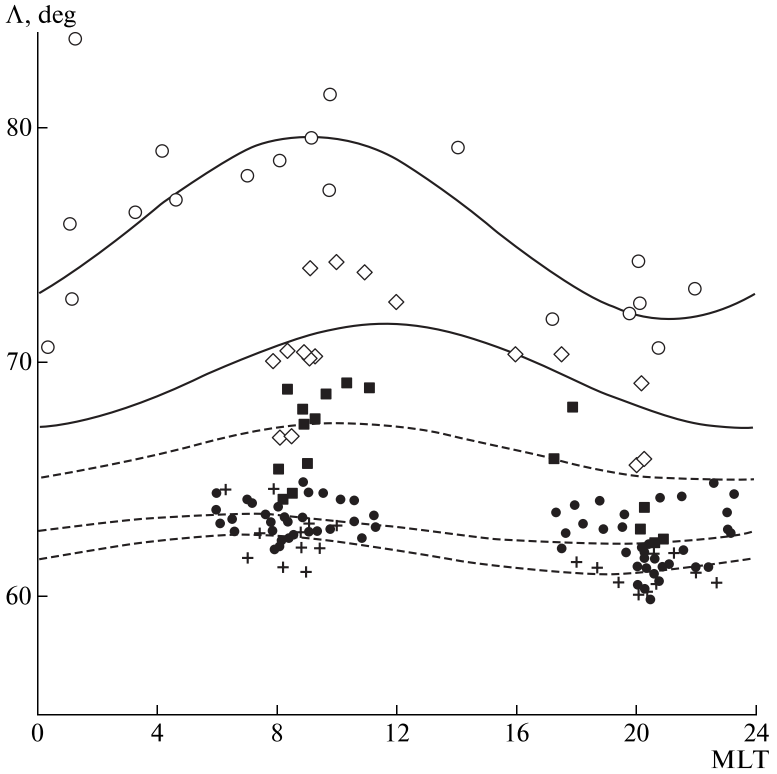

Fig. 7. Boundaries of proton troughs in the 14–26 MeV channel relative to PCB (circles) and proton PB at $B_z \geq 0$ (circles) and $B_z < 0$ (crosses). Low-latitude (squares) and high-latitude (diamonds) trough boundaries.

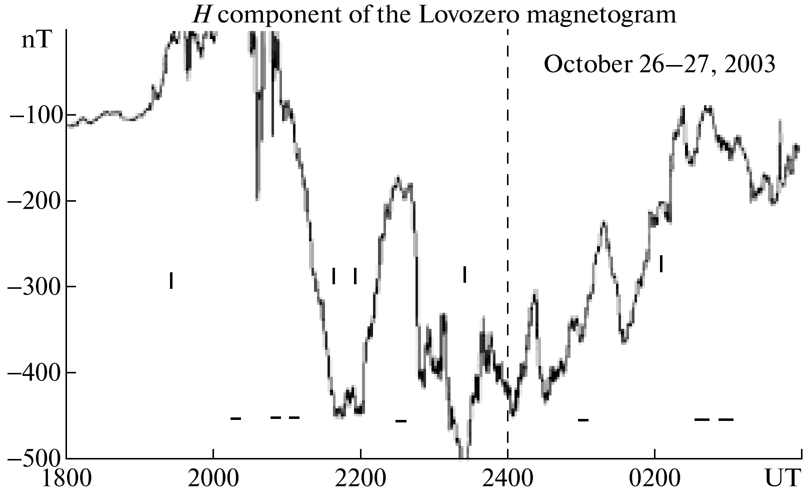

Fig. 8. *H* component of the magnetogram at Lovozero Observatory. The profiles with (vertical bars) and without (horizontal bars) SCR troughs.

Solar protons do not affect magnetospheric disturbances and are resistant to effects, responding only to the magnetic field configuration.

The CORONAS-F low-altitude satellite detects precipitating particles at an altitude of 500 km in all orbits except several passes over the Brazilian Magnetic Anomaly. Particles should escape into the loss cone in the regime of strong pitch angle diffusion so that the flux of precipitating protons would be equal to that of quasi-trapped particles, which is in turn equal

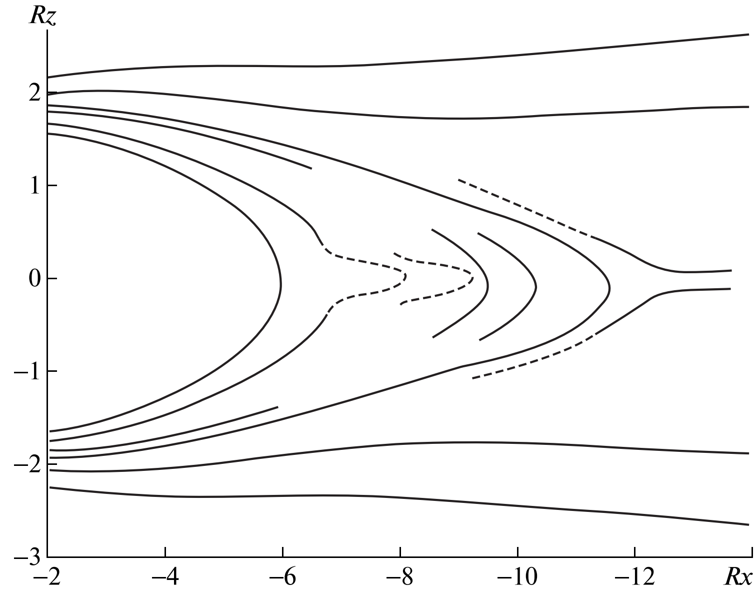

Fig. 9. Possible structure of magnetic field lines in midnight sector during substorm intensification.

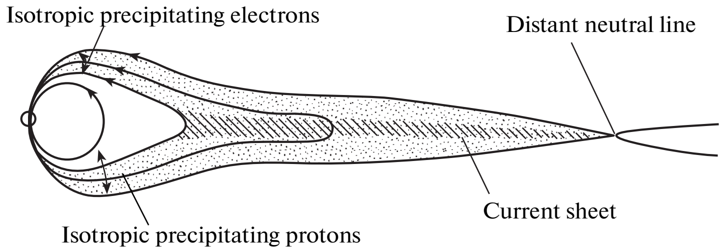

Fig. 10. Structure of quasi-trapping region from [Yahnin et al., 1997].

to the flux in the interplanetary space. Pitch angle diffusion can maintain such an escape because the curvature of field lines is insignificant when the ratio of the particle Larmor radius (ρ) to the curvature radius of field lines (R_c) (the so-called parameter of adiabaticity) is larger than the critical value (0.1–0.2). These estimations were made when particle fluxes were modeled [Sergeev and Tsyganenko, 1982; Kuznetsov and Yushkov, 2002; Andersen et al., 1997; Young et al., 2008].

The region of nonadiabaticity is located between SCR PB and the outer boundary of the quasi-trapping region (the auroral zone) with the magnetotail (the polar cap).

A comparison of the PB position at different IMF B_z signs (see above) indicates that PB on the nightside at $B_z < 0$ is located at substantially lower latitudes than at $B_z \sim 0$, and these boundaries are almost coincident on the dayside. This conclusion agrees with the model calculations of the adiabaticity boundary owing to the field line curvature [Kuznetsov and Yushkov, 2002], which predict that protons move nonadiabatically under quiet conditions at latitudes higher than ~65° on the nightside. On the dayside the proton nonadiabaticity boundary reaches ~70°. Under the conditions of a low solar wind pressure at $B_z < 0$, the nightside proton PB shifts to ~61°, and the dayside boundary of the adiabatic motion remains unchanged.

The position of the boundary of the quasi-trapping region with the magnetotail, determined above based on the boundary of SCR north–south asymmetry (Fig. 7), corresponds to the position of the poleward boundary of the auroral oval with the polar cap (see above) found by Starkov and Feldstein [1967]. However, the low-altitude satellite and auroras give information only about the projection of magnetospheric domains onto the ionosphere. It is insufficiently clear where this boundary field line extends in the plane of the magnetic equator. In our opinion argued in [Lazutin, 2004], this line does not extend deep into the magnetotail and is quasidipole. Figure 10 taken from [Yahnin et al., 1997], where the poleward boundary of the quasi-trapping region of high-energy particles is projected deep into the magnetotail, reflects an alternative (rather popular) opinion. Our measurements indicate that such a configuration of the boundaries is improbable. It is easy to show that SCR protons are not kept in retained a trap. According to direct measurements, the magnetic field vertical component in the magnetotail is ~2 nT; from expression (3) we find that the Larmor radius for protons with an energy of 1 MeV is about 20 R_e, whereas the field line curvature radius in the equator region is about 2–4 R_e. It is quite evident that quasi-trapping will be absent here. In other words, the action of the Lorentz force will be insignificant for protons moving from the mirror point into the magnetotail along such a line, and the particle will continue moving in the previous direction. In essence, fluxes with different intensities in the northern and southern magnetotail lobes do not mix during the effect of north–south SCR asymmetry described above owing to insignificant deviation in the vertical direction. The outer boundary of quasi-trapping should be located on a more dipole field line that is closer to the Earth (~10 R_e during a quiet period), where B_z is no smaller than 20 nT and the Larmor radius is not more than several Earth radii.

The second important conclusion following from the described measurements is that the region of substorm activity (and, consequently, active auroras, acceleration and escape of auroral particles, etc.) is within the zone of quasi-trapping rather than in the structure similar to those shown in Fig. 10 stretching into the magnetotail. To understand the mechanism by which magnetospheric substorms originate, it is of primary importance to correctly select the geometry of magnetospheric domains.

ACKNOWLEDGMENTS

I started this study in close collaboration with Sergei Nikolaevich Kuznetsov. Before his tragic death, we had time to report the first results [Kuznetsov and Lazutin, 2007]. Then, the work was not continued for two years. However, I nevertheless considered that it is necessary to accomplish this work in memory of my departed friend.

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