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Proton Distribution at Low Altitudes in Near-equatorial Latitudes according to Satellite Experiments: The Dynamics of Proton Fluxes

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Abstract—The data obtained on the ACTIVE, SAMPEX, and TIROS-N satellites are used to study the dynamics of low-energy (from tens of keV to several MeV) proton fluxes in the region of the geomagnetic equator ($L < 1.15$) at low altitudes (up to 1000 km). The dependence of the fluxes on the local magnetic time is presented. A number of magnetic disturbances in November–December 1978 are analyzed to illustrate the dependence of the flux on the geomagnetic activity level. The results obtained allow the conclusion that the ring current is one of the main sources of protons at low altitudes in near-equatorial latitudes.

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INTRODUCTION

It is believed today that the double charge exchange mechanism is most responsible for the presence of low-energy protons in the region near the geomagnetic equator [1].

The charge exchange is a two-step process (Fig. 1) beginning with collisions of energetic protons (p) from the outer radiation belt with neutral hydrogen atoms (H) from the exosphere,

$$p^* + H \longrightarrow H^* + p,$$

where the asterisk denotes energetic particles. This process yields a flux of energetic neutral hydrogen atoms, which freely travel in the magnetic field of the Earth. In dense atmosphere, a neutral hydrogen atom may interact with atomic oxygen, which is one of the main atmospheric components,

$$H^* + O \longrightarrow p^* + O^-.$$

The resulting energetic proton is captured by the magnetic field of the Earth.

In early studies [1, 2], it was conceived that the radiation belt is the main source of protons in the near-equatorial region. This means that (i) the proton flux in this region should depend on the level of geomagnetic activity and (ii) the proton flux near the geomagnetic equator should not depend on local magnetic time since the radiation belt is almost symmetric about the magnetic dipole axis.

Later, after the ring current was discovered, its role in the formation of the radiation belt clarified, and its contribution to the dynamics of geomagnetic disturbances assessed, it became clear that the low-energy protons (20–100 keV) largely stem from the ring current, which is asymmetric during the initial phase and occurs in the nightside magnetosphere [3]. The first experimental evidence that the low-altitude proton flux near the geomagnetic equator depends on the local magnetic time was obtained from the *Kosmos-484* satellite. In that experiment [4], protons with energies from 70 to 500 keV were measured. The proton flux was found to be enhanced near the geomagnetic equator in the region of very small L ($L \le 1.15$, including $L \le 1.00$). Proton fluxes in this region were measured only at night local time, ~21 h MLT. The authors of [4] also reported on the detection of protons with energies from

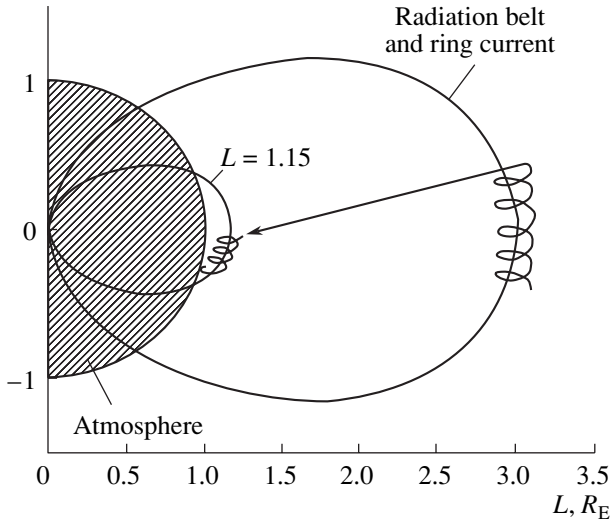

Fig. 1. Scheme of the double charge exchange of the ring current protons, a process resulting in penetration of protons into the near-equatorial region at low altitudes.

1 to 8 MeV from the *Kosmos-378* satellite at 4–7 and 16–19 h local time.

The experiment on board the *Azur* satellite detected an increase in the flux of protons with energies from 0.25 to 1.65 MeV. The measurements took place at about 20 h local time.

A similar dependence of higher energy protons ($E_p > 700$ keV) on the local time was also observed in the experiment on board the SAMPEX satellite [5].

In this study, the dependences of the proton flux on the local magnetic time and geomagnetic activity are examined on the basis of data from the following experiments:

(1) On board of the TIROS-N satellite (1978, altitude ~850 km), protons (E = 30–800 keV) in the near-equatorial region were detected by the MEPED telescope (two semiconductor detectors 200 μm thick each) shielded by a magnet deflecting electrons with energies of up to 1.5 MeV [7].

(2) The LICA instrument (a time-of-flight mass spectrometer [4]) on board of the SAMPEX satellite (1993, altitude ~600 km) measured protons with energies >770 keV.

(3) The SPE-1 instrument on board the ACTIVE satellite (1990–1991, altitude 500–2500 km) measured protons with energies from 30 to 550 keV by a single 100-μm-thick semiconductor detector shielded with a magnetic filter deflecting electrons with energies of up to 650 keV [8].

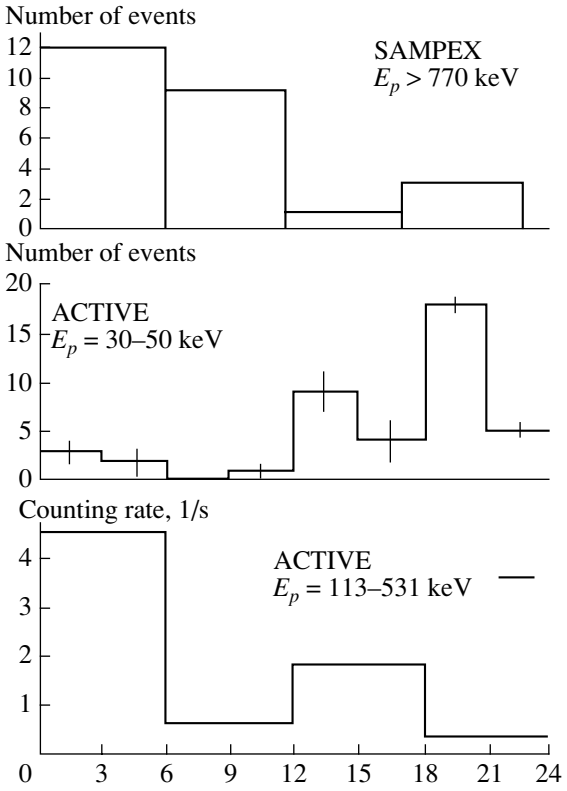

Fig. 2. Proton flux in the near-equatorial region as a function of local magnetic time according to the data from the SAMPEX and ACTIVE satellites.

DEPENDENCE ON LOCAL MAGNETIC TIME

The dependences of the proton flux on the local magnetic time that were found in the experiments on the SAMPEX [4] and ACTIVE [8] satellites are shown in Fig. 2.

According to the ACTIVE data (1990), the proton fluxes in the low-energy channels (30–50 keV) of the detector are enhanced in the afternoon and, especially, evening hours, 18–21 h MLT. By comparison, the fluxes in the morning and day hours are insignificant. The 12-h MLT region is probably the westernmost point to which protons may drift in the ring current at the initial phase of the storm. There is difference in the behavior of fluxes with energies up to ~100 keV and more energetic fluxes, as is evident, for example, from the ACTIVE data in Fig. 2. The fluxes with energies of 100–500 keV (high-energy part of spectrum) have a maximum in the morning sector before 6 h MLT, which agrees with the SAMPEX data, where fluxes observed in the morning are much higher than those in the evening sector. The difference in the behavior of low-energy (below 100 keV) proton fluxes and more energetic particles may be due to the fact that the source of the low-energy component is the ring current, which exists for a quite limited time during a magnetic storm, while more energetic particles are supplied by the radiation belt, which almost always exists. In addition, particle loss strongly depends on their energy because of the different contributions from different loss mechanisms, namely, ionization loss and charge exchange loss.

DEPENDENCE ON GEOMAGNETIC ACTIVITY

The relationship between low-energy proton fluxes near the geomagnetic equator and geomagnetic activity level was first analyzed in [1], where it was found that a strong rise in the low-energy fluxes in the radiation belt $L \approx 3$ and in the low-latitude belt occurs simultaneously. Similar data were obtained by the SAMPEX satellite. In [5], the observed increase in the counting rate of protons with an energy >700 keV is associated with geomagnetic storms. In addition, it was shown that the near-equatorial proton flux is the smallest in the solar minimum periods (1996–1997). The dependence of the proton flux on geomagnetic activity was also studied in [9], where it was shown on the basis of the data from the ACTIVE satellite that this relationship was not as direct and unambiguous as had followed from previous studies.

This relationship between the proton fluxes at low altitudes near the geomagnetic equator with the level of geomagnetic activity and the proton fluxes in the radiation belt, as well as the difference in behavior between

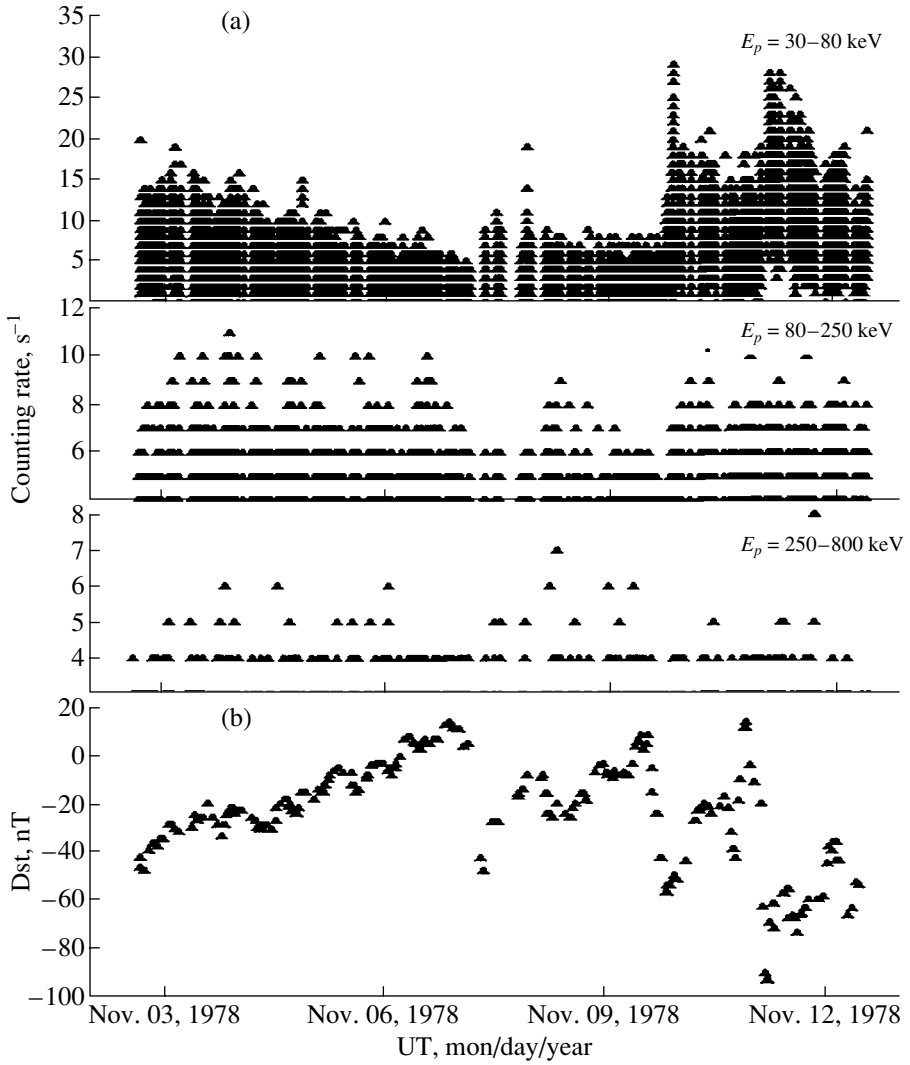

Fig. 3. (a) Proton counting rate in the 30–80, 80–250, and 250–800 keV channels of the MEPED detector on board the TIROS-N satellite as a function of time at $L < 1.15$; (b) geomagnetic disturbance index Dst as a function of time over the same period.

fluxes of low-energy (below 100 keV) and more energetic protons, suggest that the source of the latter is the radiation belt, while the low-energy component comes from the ring current.

Some evidence directly supporting this hypothesis is presented in Fig. 3, which shows the results of counting protons with energies from 30 to 80 keV on the TIROS-N satellite [7] during the period November 2–13, 1978. The proton flux measured at $L < 1.15$ is shown along with the values of the Dst index over the same period of time. At least three strong geomagnetic disturbances can be discerned. It is seen that the changes in the particle flux near the geomagnetic equator follow changes in the Dst index. For example, the proton flux monotonically decreased as the activity decreased in the period from November 3 to 8. During the storms on November 8, 10, and 12, the flux sharply increased and then slowly decreased as the geomagnetic activity index approached the zero value of nondisturbance.

The counting rates in higher energy channels (80–250 keV and 250–800 keV) does not show any visible dependence on the geomagnetic activity level.

Thus, one can state that, near the geomagnetic equator, the proton fluxes with energies of tens of keV correlate with the level of geomagnetic activity, while the fluxes of more energetic protons seem to be insensitive to this level.

DISCUSSION

Figure 4 schematically shows the development of a ring current during geomagnetic disturbances [3, 6]. Three storm phases—initial, main, and recovery—are subsequently shown. The ring current and a near-equatorial proton belt are also depicted. The ring current

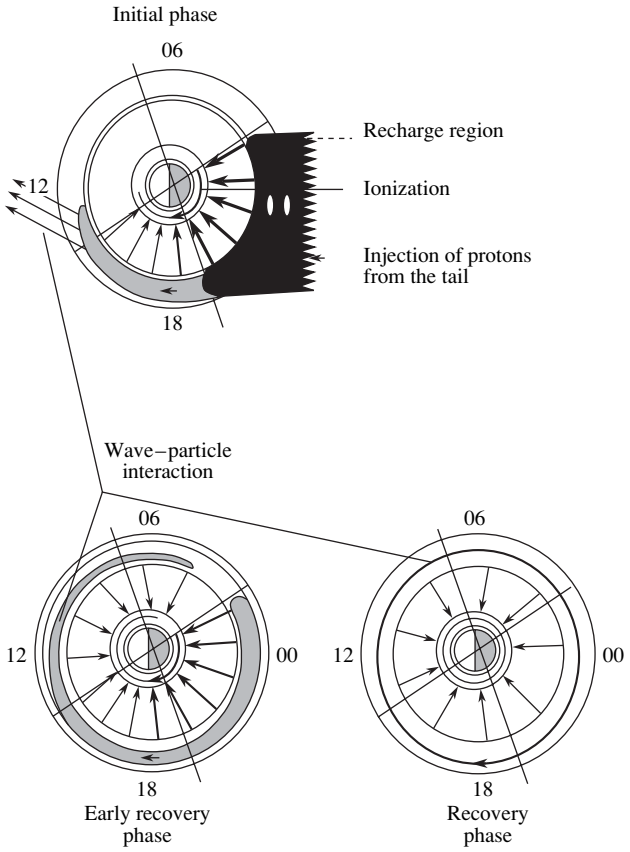

Fig. 4. Development of the ring current during geomagnetic disturbances and formation of the proton belt near the geomagnetic equator.

forms at the initial stage of the storm in the evening and morning sectors of the magnetosphere. Protons with energies of up to ~100 keV from the magnetospheric tail are injected into the belt (at $L \approx 6$) in the midnight sector of local magnetic time. Due to the magnetic field curvature, protons drift eastward, i.e., from the night to the evening sector of the magnitosphere. At the initial phase of the storm, the magnetic field lines in the dayside of magnitosphere are open; therefore, the ring current is asymmetrical. While drifting, the protons change charge with neutral hydrogen atoms of the exosphere. Some of the produced neutrals may be trapped again at low altitudes. In this manner, an asymmetrical proton belt is formed at low altitudes near the geomagnetic equator. As the ring current develops in the evening and day hours of local magnetic time, protons leave the stable trapping region because the drift shells are open. In approximately 1 h, the ring current becomes symmetric. Low-altitude protons near the equator follow the behavior of the ring current and, at a certain time instant, the low-altitude belt near the equator becomes symmetric.

The observed dependences of the near-equatorial proton flux on the local magnetic time and the level of magnetic activity suggest that the ring current is one of the main sources of near-equatorial protons.

CONCLUSIONS

(1) During magnetic disturbances, fluxes of protons with energies below 100 keV are enhanced, while fluxes of more energetic protons remain practically unchanged.

(2) Protons fluxes can be detected mainly in the evening and night hours of local magnetic time.

(3) The ring current is the main source of particles with energies below 100 keV in the near-equatorial region, while more energetic particles come from the radiation belt.

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