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Solar cosmic rays as a source of the temporary inner radiation belts

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Abstract

Solar protons penetrate into the inner magnetosphere during strong magnetic storms and can be trapped during the recovery of the magnetosphere configuration. Solar proton measurements by the low altitude polar orbiter Coronas-F show several cases of the direct trapping of the 1–5 MeV protons during the magnetic storm recovery phase. Observation over the Brazilian Magnetic Anomaly results in a study of the time history of the temporal solar proton radiation belts. The model presented in this manuscript also explains the occurrence of the fast intensity decrease of the inner belt protons as a result of the magnetosphere reconfiguration and associated intrusion of the quasitrapping region boundary into the inner belt region.

Keywords: Solar cosmic rays; Magnetosphere; Inner radiation belt; Magnetic storm; Penetration boundary

1. Introduction

In addition to stable inner belt, 1–15 MeV proton intensity variations at $L = 2–4$ have been reported in several publications. Bostrom et al. (1970) described both increases and decreases of the protons during and after magnetic storms. Mineev et al. (1983) supposed that solar protons might be an additional source of the inner belt. Several studies have been devoted to the description of the occasional enhanced proton appearance (Hudson et al., 1997; Lorentzen et al., 2002). It was suggested that particles might be resonantly accelerated and injected inward by the E-field pulse induced by impulsive compression of the magnetosphere during the geomagnetic storm Sudden Commencement (SC) (Li et al., Q2 1993; Pavlov et al., 1993; Blake et al., 1992).

Energetic protons measurements by the low altitude polar orbiter Coronas-F can identify special types of the intensity enhancements associated with direct trapping of the 1–5 MeV protons to the inner radiation belt (Lazutin et al., Q3 2007). During extreme magnetic storms in October 2003 the effect of the splitting of MeV solar proton penetration boundary was observed and interpreted as an in situ reflection of the process of the proton trapping into the inner radiation belt. Our study presents a description and temporal and energy features of the double penetration boundary effect, and an explanation of the process of trapping of the solar protons, based on the solar proton measurements during magnetic storms in November 2001 and October 2003.

Coronas-F detectors used in this study measure protons in four differential channels (1–5, 14–26, 26–50 and 50–90 MeV). At an altitude of 500 km field-aligned fluxes of solar protons were measured continuously, while trapped particles may be seen only over the Brazilian Magnetic Anomaly (BMA), and adjacent South-Atlantic region, while on the majority of the trajectories only precipitating particles were recorded.

2. Double penetration boundary effect

2.1. November 24, 2001

Strong magnetic storm with Dst minimum −230 nT was accompanied by solar cosmic ray arrival and penetration deep into the inner magnetosphere. The Dst variation and temporal variations of the solar proton Penetration

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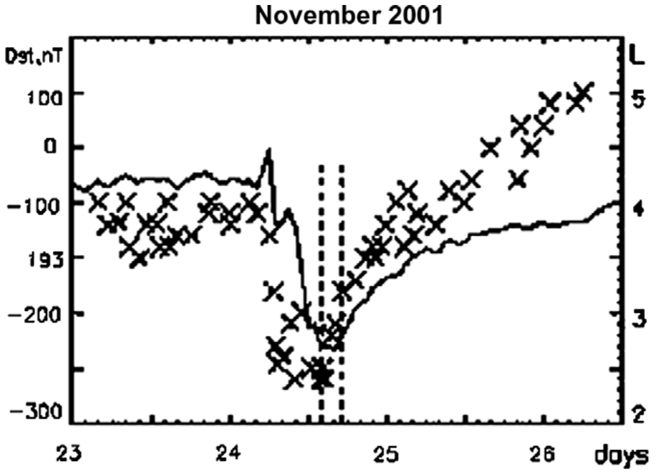

Fig. 1. Penetration boundary dynamics (crosses) and Dst (solid line) during November 24 event. The vertical broken lines denote the moments of the proton radial profiles measurements shown by Fig. 2.

Boundary (PB) are shown by Fig. 1. The penetration boundary position was defined as the background level (approximately 1/100 from the intensity maximum). Two vertical broken lines show the time of latitudinal PB profiles presented by Fig. 2.

The first profile of the 1 MeV protons is shown by the solid line at the time of the Dst minimum. It has a double-boundary structure. The outer boundary reproduces the current penetration boundary position; it coincides with the penetration boundary measured by 14–26 MeV and higher proton channels (shown by broken line). The inner profile was recorded by the 1 MeV proton channel alone. We suppose that the penetration boundary was there some time before and 1 MeV protons became trapped during PB retreat and associated dipolarization of the Earth's magnetosphere. For the protons with higher energy, reconfiguration process was too slow as compared with particle magnetic drift and effectiveness of the tapping was too small to be registered by the Coronas-F detectors. Measurements during the nearest flight over BMA shown at the second profile were taken during early recovery phase and show 1–5 MeV protons trapped in the additional inner belt with maximum at an L value of 2.3. The intensity and position of the penetration boundary differs from the previously trapped belt on November 6, 2001.

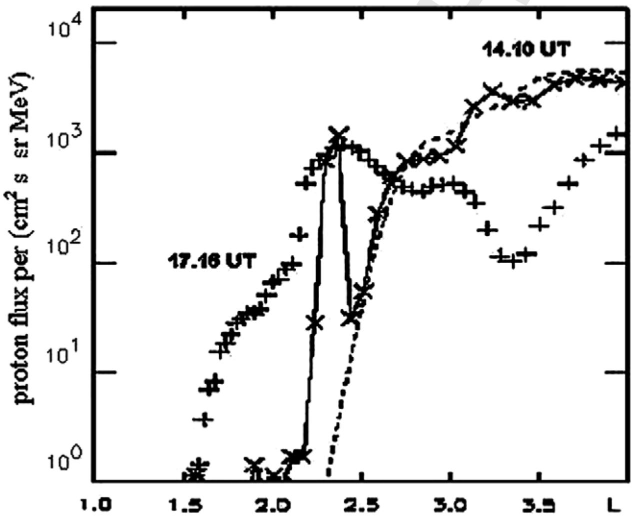

Fig. 2. November 24, 2001, double penetration boundary of 1–5 MeV protons (solid lines) and 14–26 MeV proton penetration boundary (broken line). The nearest 1–5 MeV L-profile over the Brazilian Magnetic Anomaly (BMA) is shown by triangles.

The second smaller maximum was recorded at an L value of 3.0. We cannot insist that this maximum was created by solar protons, because at 500 km altitude enhanced low-energy proton fluxes were registered occasionally at $L = 3–4$ by Coronas-F without Solar Cosmic Ray (SCR) events. Precipitation from the proton belt due to the pitch-angle diffusion might cause such increases of the proton flux near the loss cone. On the other hand, during the strong magnetosphere distortion at the main storm phase the inner proton belt might be essentially degraded. Free penetration of the energetic solar protons from interplanetary space must be accompanied by near-free escape of the previously trapped protons. Therefore, the "old" proton flux at $L = 3$ might be small and the maximum in Fig. 2 can be of solar proton origin.

2.2. *October 30–31, 2003*

During the chain of the October 2003 extreme superstorms the Penetration Boundary (PB) approached even closer to the Earth than in November 2001. The closest to the Earth position of the penetration boundary was observed during the evening of the October 30, 2003. The penetration boundary intensity profiles of four proton energy channels usually coincide without notable differences, but several exceptions from this rule were observed during this retreat. The position of the penetration boundary was easy to follow by the measurements by the three high energy channels (14–90 MeV). At the same time low-energy protons have double-boundary structure.

Fig. 3 shows penetration boundary crossings in the south-evening sector at 2330 UT and 0110 UT, on October 31. The intensity profiles along the penetration boundary of the 50–90 MeV protons are shown by dotted lines and the penetration boundary of 1–5 MeV protons is illustrated by solid lines. The counting rates of both energy channels are normalized so as to coincide in the polar cap. One can see that 1–5 MeV channel has double-boundary structure: during the first part of the satellite flight toward high latitudes the intensity increase follows the old, closer to the Earth boundary. Then after the interval of the decrease, the counting rate again begins to increase along the new boundary, which coincides with the boundary of energetic protons. A similar double boundary was observed in other sectors, both during the flight toward the lower latitudes and back; therefore it is not the result of some temporal variations.

As a reasonable explanation of this effect we again suppose that part of the 1–5 MeV protons remained trapped

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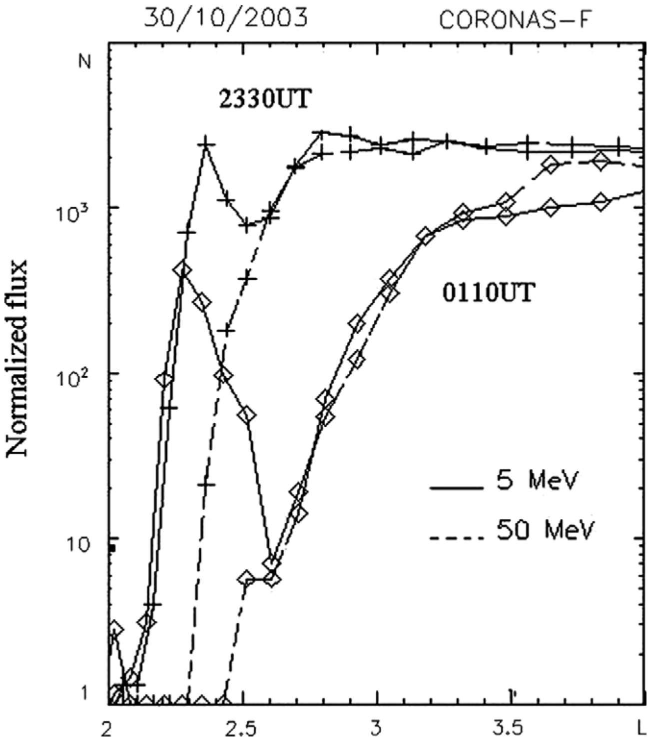

Fig. 3. Double boundary effect of 1–5 MeV protons during the magnetic storm recovery phase, 30–31 October, 2003. The dotted lines indicate the penetration boundary of the 50–90 MeV protons. The solid lines indicate the penetration boundary of 1–5 MeV protons.

during fast retreat of the penetration boundary. Their drift trajectories which were open previously in a quasitrapping region became closed, thus creating new solar proton belt.

Fig. 4 presents the dynamics of the penetration boundaries during the double boundary interval. The outer boundaries of all energies from 1–5 to 50–90 coincide and move away from the Earth while the inner boundary of 1–5 MeV for the several hours remain stable and slightly moves earthward until 01 UT on 31 October. (This earthward motion with additional acceleration of a freshly trapped protons was more pronounced during July 2004 magnetic storm analyzed by Kuznetsov et al. (2008).)

The intensity of the protons at the inner boundary decreased rapidly approximately ten times during an hour. The fast decrease of the observed proton flux does not mean the decay of the entire solar proton belt. It only indicates the disappearance of the proton flux in the loss cone, while magnetic field lines recover to a more dipolar shape. During this time the rate of the pitch-angle diffusion on field line curvature decreases sharply and particles remain stable trapped, sometimes for many days as we will see below.

3. Solar proton belts observed over the Brazilian Magnetic Anomaly

3.1. November 6, 2001

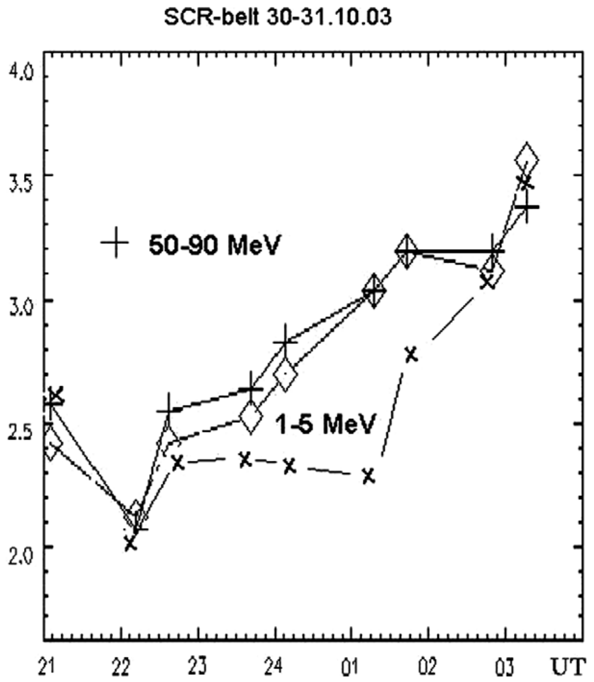

Fig. 4. Dynamics of the inner (triangles) and the outer PB positions (crosses and diamonds for 1–5 and 50–90 MeV accordingly) during double boundary event.

During the November 6, 2001 magnetic storm and solar cosmic ray event double boundary effect was not registered, but the effect of the 1–4 MeV proton trapping was clearly seen starting from the storm recovery phase. The trajectory of the Coronas-F placed the satellite at about 500 km altitude and most of the flight time was below the radiation belts with the exception of the Brazilian and South Atlantic anomaly. Here we could observe the radial profile of the inner radiation belts and study their transformation. Fig. 5 shows the Dst variation and the penetration boundary motion during this event and Fig. 6 shows the three proton latitudinal profiles measured at times shown at Fig. 5 by dotted lines.

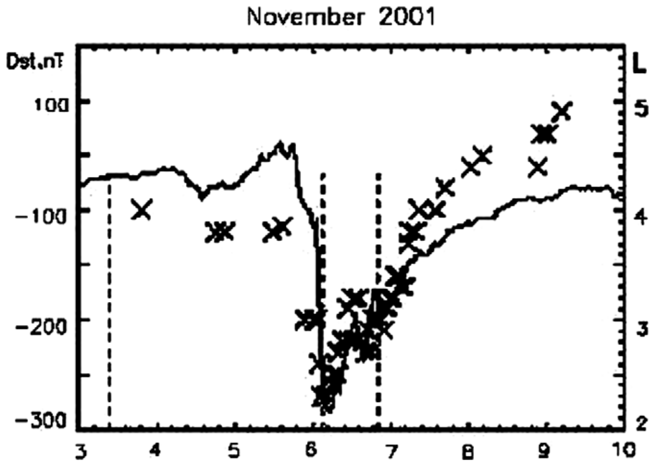

Fig. 5. Penetration boundary dynamics (crosses) and Dst (solid line) during November 6, 2001 event. The vertical broken lines denote the moments of the proton radial profiles.

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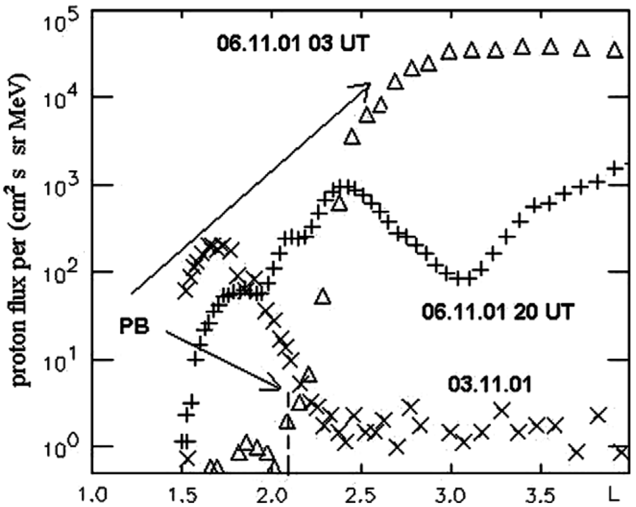

Fig. 6. Proton profiles vs L for three different times: (1) proton profile over the BMA before the magnetic storm, 3 November, 2001. (2) PB position during the main storm phase, 03 UT 6 November, 2001. (3) Proton profile over the BMA during magnetic storm recovery, the same day, 20 UT.

First profile was measured for the three days before the magnetic storm and before the arrival of the solar protons from the associated solar flare. During this initial interval that established the initial profiles (indicated by the triangles composing line 1 in Fig. 6), only the stable inner radiation belt with maximum at $L = 1.6$ was observed. The next latitudinal profile was taken right at the maximum of the Dst and closest approach of the penetration boundary to the Earth. During this event the background level boundary position was at $L = 2.2$, while if we define the penetration boundary position as 0.5 of the polar cap value, then it will be at an L value of 2.7 as indicated by the arrows in Fig. 6.

The third profile shown in Fig. 6 (line 3 indicated by the crosses) was the nearest after the previous one measured over the Brazilian Magnetic Anomaly (BMA). One can see that the penetration boundary was shifted to $L = 3.2$–3.7, leaving behind enhanced flux of 1–5 MeV protons with maximum at $L = 2.4$, which was there all the subsequent BMA crossings until the next magnetic storm which occurred on November 24, 2001.

3.2. Intensity variations

After the initial arrivals of the enhanced 1–5 MeV proton flux on November 6 and November 24, 2001 similar profiles with the same maximum position were observed during all satellite passages over the BMA with subsequent flux intensity decreases as can be ascertained by examination of Figs. 2 and 6. Fig. 7 presents a temporal diagram of the solar proton belt (or more correctly solar proton inclusion to the inner proton belt) trapped during November 6 and November 24 magnetic storms.

The decrease of the 1–5 MeV proton flux at the 500 km altitude does not mean total disappearance of the additional proton population. For such conclusion we need measurements near the equatorial plane. It is quite possible that pitch-angle diffusion or other type of particle losses are more effective in a small pitch-angle range leaving trapped particles at the enhanced level for a long interval.

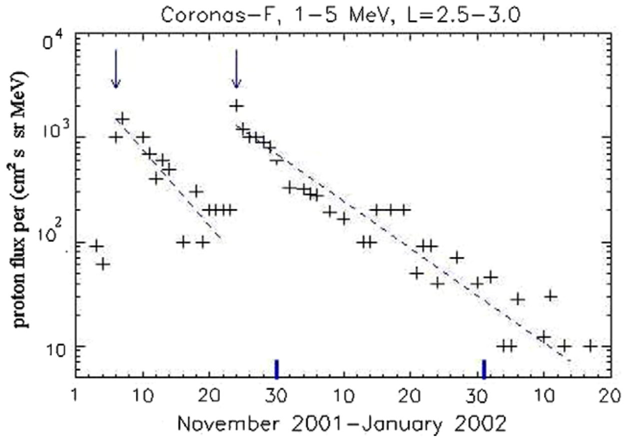

Fig. 7. Decay of the solar proton belts intensity, measured by Coronas-F over the BMA during November 2001–January 2002. The intervals of the solar proton trapping are indicated by the arrows.

Fig. 8 shows the temporal variations of proton flux at the maximum of the additional belt measured over BMA during November–December 2003. During the first 20 days until November 20 the maximum intensity and position remain at the same level. But after the next severe magnetic storm the maximum shifts closer to the Earth and a steady decrease of the intensity maximum occurred. There were no solar cosmic rays registered during this storm and therefore additional belts from these particles were not been created.

4. Discussion and conclusions

1. During the main phase of the strong magnetic storms the boundary of 1–100 MeV solar proton free penetration into the inner magnetosphere may reach $L = 2.2$–

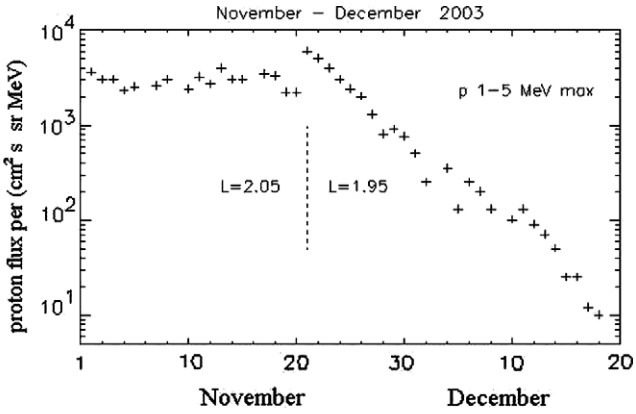

Fig. 8. Temporal variations of the intensity of solar proton belt created during October 30–31 magnetic storm recovery phase.

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2.5. As a result, previously trapped particles from higher L may escape from the radiation belt, which explain particle flux dropouts observed after some magnetic storms.

2. As a result of the fast retreat of the penetration boundary during magnetic storm recovery phase, solar protons with energy 1–5 MeV might be trapped, creating temporary solar cosmic ray belts on $L = 2$–3 or providing additional flux to the previously existed population. This trapping action is observed as a double boundary effect in the Coronas-F measurements. Further solar proton belt evolution was observed during satellite passages over the Brazilian Magnetic Anomaly.
3. During double boundary development earthward shift of the inner boundary was registered presumably due to the $\mathbf{E} \times \mathbf{B}$ drift due to the induced electric field.
4. Energy spectrum of the protons in solar proton belts decreases steeply from 5 to 10 MeV. Protons and alpha particles with $E > 4$ MeV were recorded only occasionally and with a small intensity. The efficiency of the trapping depends on the relation of the particle magnetic drift velocity and the rate of the magnetosphere reconfiguration. Typical time of the magnetosphere reconstruction equals several minutes. Magnetic drift periods for 1 MeV and 50 MeV protons at $L = 3$ are about 15 min and 20 s, respectively. Fast drifting energetic protons will trace the latest position of the penetration boundary while the "old" low-energy protons will be transferred to the closed drift orbits and recently arrived ones will follow latest penetration boundary position.
5. After the trapping, the flux of precipitation protons inside the loss cone decrease exponentially as $N = N_0\exp(-kt)$, where $t = 1.15$ h. Outside the loss cone, at the altitude of 500 km over BMA the enhanced proton flux may sometimes remain at the stable level for two decades (1–20 November, 2003), but more often field aligned particles gradually disappear in 15–30 days presumably due to the pitch-angle diffusion.
6. The closest recorded position of the penetration boundary was at an L value of 2.2; at this close distance the inner belt part at $L < 2$ will be conserved during extreme magnetic storms.
7. Inspection of the BMA profiles for extended intervals from September 2001 to May 2005 shows that the enhanced proton flux with maximum intensity at L values between 1.9 and 2.7 arrived only after strong magnetic storms that occur during solar cosmic ray events. At L values between 3 and 4 the enhanced proton fluxes were observed during intervals without magnetic storms. Separate investigation of these phenomena will be presented elsewhere.

The proposed mechanism of the direct trapping of the solar protons during magnetic storms does not contradict the sudden commencement induced injection model; it is totally different process. They differ by the energy range of the involved particles: while direct trapping affects 1–5 MeV particles, the sudden commencement injection is effective for the particles with energy above 15 MeV (Pavlov et al., 1993). Described creation of solar cosmic ray belts and erosion of previously existed trapped particles might be important for the space weather radiation models.

Acknowledgements

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