"Physics of Auroral Phenomena", Proc. XXIX Annual Seminar, Apatity, pp. 104 - 107, 2006

Polar Geophysical Institute

STUDY OF THE SOLAR PROTON BELTS IN THE INNER MAGNETOSPHERE

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Abstract. In addition to the stable inner proton belt, enhanced flux of the 1-15 MeV protons has been registered from time to time at L=2.5-3.5 after strong magnetic storms.
Our study presents experimental description of the 1-4 MeV solar proton trapping in the inner magnetosphere, based on the particle measurements by low altitude polar orbiter Coronas-F.
We propose explanation of the temporary belts emergence and destruction. Our model does not demand injection and resonant acceleration, it explains appearance and disappearance of solar proton belts (SPB) as a result of the magnetosphere reconfiguration when MeV protons became trapped during the retreat of the solar cosmic ray penetration boundary.

Introduction

Inner proton radiation belt is in general rather a stable formation, but during magnetic storms on L=2-4 rapid intensity variations of 1-15 MeV protons have been reported. Bostrem et al., (1970) observed fast increases and decreases of the proton intensity associated with magnetic storms. Penetration of the solar cosmic rays into the Earth's magnetosphere during magnetic storm of April 3-5? 1979 were studied by Mineev et al, (1983). They suggest that solar protons with energy 0.9-8 MeV may be injected into the inner magnetosphere and can be regarded as a source of the proton radiation belt.
Appearance of the additional proton maximum on L=2-4 were reported by Lorensen et al., (2002). Slocum et al. (2002). Enhanced energetic ions and electrons were registered by CRRES satellite in the inner magnetosphere several minutes after the sudden commencement (SC) of the March 24, 1991 magnetic storm {Blake et al., 1992). 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 SC (Li et al., 1993, Pavlov et al., 1993).
During extreme magnetic storms of October-November 2003 new effect named "double solar proton penetration boundary" was found using Coronas-F satellite data. New model of direct low energy proton trapping into the inner magnetosphere was introduced (Lazutin et al, 2006). During magnetosphere reconfiguration when penetration boundary (PB) of high energy protons shifts away from the Earth, part of 1-5 MeV solar protons and alpha particles remained on the old boundary and became trapped. Temporal, energetic and spatial characteristics if the solar pronon belts were described.
Our paper presents the analysis of the Coronas-F proton measurements during the two November 2001 magnetic storms. The effects observed during October 2003 events are confirmed and some new features of the direct MeV proton trapping are presented.

Observations

Coronas-F was launched in 2001 to the polar orbit at the altitude of 500 km. SINP particle detector MKL had four proton differential channels (1-5, 14-26, 26-50 and 50-90 MeV). At the altitude of 500 km trapped particles could 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. It is necessary to outline that intensity and latitudinal profiles depend on the trajectory

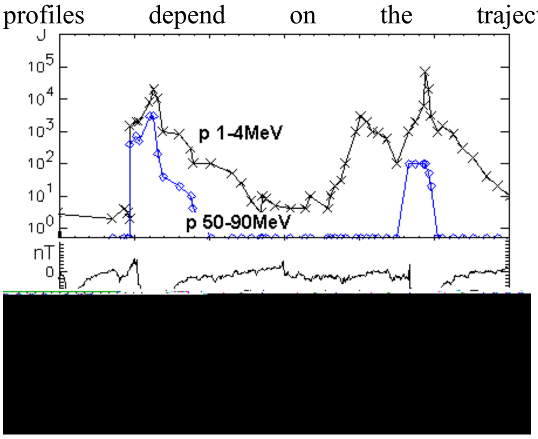

Fig.1. General features of the November 2001 events: 1-4 Mev and 50-90 MeV time profiles measured in the polar cap and Dst-index.

position relative to the center of the anomaly, creating a relatively large uncertainity of the considered parameters.
The discussed effects were recorded only in 1-5 MeV channel proton data, which we will refer to below as MeV protons for short.
Figure 1 presents general features of the November 2001 events: 1-4 Mev time plot measured in the polar cap and Dst-index. Two strong magnetic storms were registered with SC at 0152UT, November 6 and 0556UT, November 24. Both storms can be classified as strong with Dst equal to -277nT and 213nT respectively.

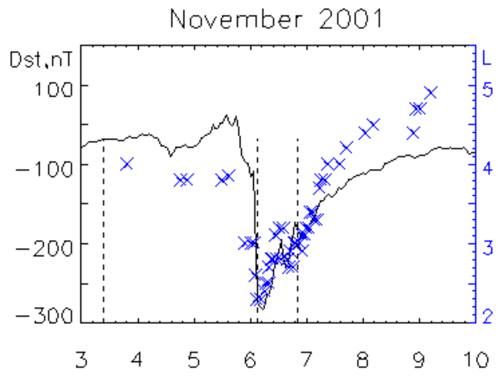

Fig.2. Penetration boundary dynamics and Dst-index during November 6 event. Vertical broken lines show the moments of measurements of the proton radial profiles shown in fig.3.

The auroral activity was also high with maximum of 3-hours Kp-index equal to 8.7 and 8.3. A detailed description of these storms was made by Kuznetsov et al., (2005).
Solar protons in 1-90 MeV energy range penetrate deep inside the inner magnetosphere creating a favorable condition for the direct trapping of the Mev protons.

<u>**November 6, 2001 event**</u> Figure 2 shows Dst-index also the penetration boundary dynamics during November 6 magnetic storm.
PB L-values were taken at the background level of the 1-5 MeV protons counting rate as

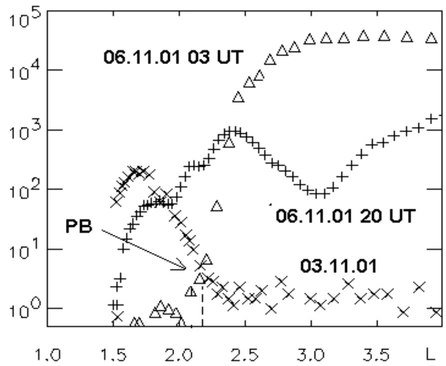

Fig.3. Three MevV proton profiles: over BMA before the event, during the innermost PB position and during the subsequent fight over BMA during magnetic storm recovery.

illustrated by the dotted line in Figure 3. Only four points per orbit (90 minutes) are available, more detailed PB dynamics during the intervals when Coronas-F was away from the PB region remain unknown. One can see a relatively good correlation of the PB position with Dst, especially after the Dst minimum, when solar protons penetrate L< 2.5. Figure 3 presents three MeV proton latitudinal profiles measured at times indicated in fig 2 by the vertical broken lines. The first measurement was taken before the storm on 03.11.01 when Coronas-F was over BMA. Only the stable inner radiation belt was measured with the maximum at L=1.7.

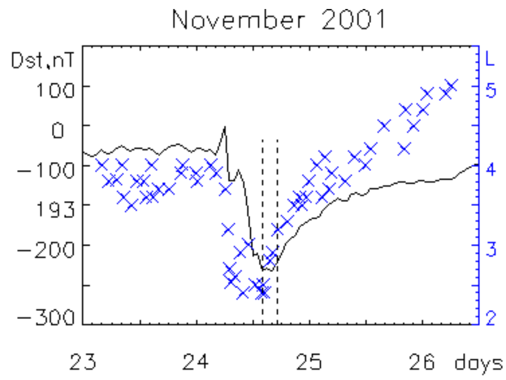

Fig .4. The same as fig.2 for November 24 event.

The next profile was the first one after the SC at the beginning of the storm main phase when PB was measured at the position closest to the Earth.
Measurements during the third profile were taken over the BMA at the beginning of the recovery phase. The penetration boundary moved away from the Earth, but essential flux of the MeV protons remained in the inner belt with maximum at L=2.5. Similar profiles with decreasing intensity were recorded during the BMA crossings on the days, that followed, until the next magnetic storm.

<u>**November 24, 2001 event**</u> Figure 4 illustrates a magnetic storm development and PB dynamics during 24.11.01 magnetic storm. In this case PB approached the Earth immediately after the SC, much before the Dst minimum. Vertical broken lines indicate the time of two Coronas-F latitudinal crossings presented in fig. 5. The first profile of the MeV proton shown by the solid line belongs to the time of Dst minimum. It has a double boundary structure, similar to the double boundary effects measured during October 29-31, 2003 magnetic storm and is

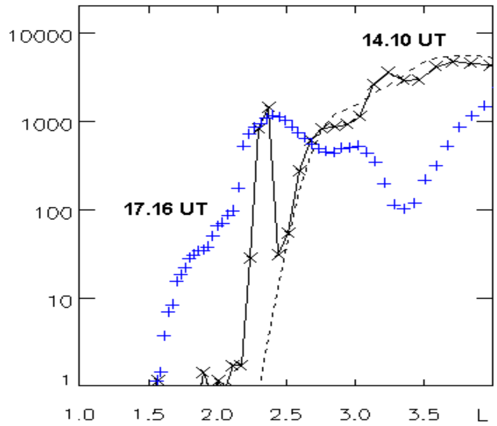

Fig.5. November 24 1-4 MeV proton latitudinal profiles

discussed in detail in (Lazutin et al, 2006). The outer boundary reproduces the current PB position, it is confirmed by the coincidence with the PB measured by three other proton channels. The profile of 14-26 MeV protons is shown by broken line. It closely coincides with the outer MeV profile, while the inner profile was recorded by MeV proton channel alone.

Measurements during the nearest flight over BMA were taken during the early recovery phase and revealed MeV protons trapped in the additional inner belt with maximum at L=2.3.

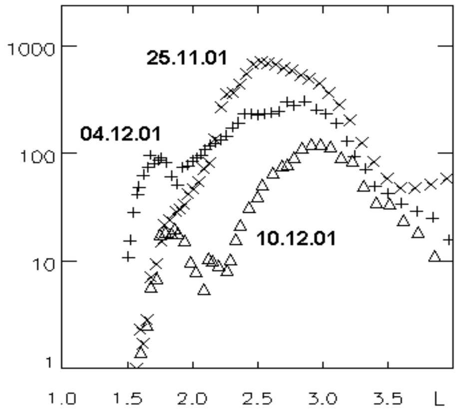

Fig.6. Three Coronas-F flights over BMA illustrate the intensity decay and outward shift of the maximum position.

By the intensity and position it differs from the previously trapped belt on November 6, 2001.

The second smaller maximum was recorded at L=3.0. We cannot insist, that this maximum was created by solar protons, because at 500 km altitude low-energy proton fluxed were registered occasionally at L= 3-4 without SCR events as a result of the precipitation from the proton belt due to the pith-angle diffusion {Vakulov et al, 1976). On the other hand, during the strong magnetosphere distortion at the main storm phase inner proton belt at the outer side of PB might be essentially degraded. The free penetration of the energetic solar protons from the interplanetary space must be accompanied by near-free escape of the previously trapped protons. Therefore, the L=3 maximum in fig 5 might be as well of solar proton origin.

The solar proton belt 500 km level intensity created on November 24 does not remain at the same level. Figure 6 presents three MeV proton profiles measured over BMA at 25.11.01, 04.12.01 and 10.12.01. Along with the decrease of the intensity the proton maximum shifted from L=2.3 to L=3.0. If we remember that at the beginning two maxima were registered at L 2.3 and 3.0, it is possible also to suppose that 2.3 maximum disappeared faster while 3.0 maximum resists to diffusion more effectively.

Discussion

Low altitude satellites regularly registered the inner proton belt only over Brazil Magnetic Anomaly centered around L=1.4-1.8. The enhanced MeV proton fluxes were registered at L=2-4 only occasionally. Two types of these events can be identified by their location and origin. The first type with maximum at L from 3 to 4 , described by (Vakulov et al., 1976, Mineev et al,. 1973) may be explained by the pitch angle diffusion on the waves with harmonics close to the proton cyclotron frequency from the inner belt which for Ep=1 MeV has the broad maximum at L=3-4.

Proton flux in the L range from 2 to 2.7 during four years of the Coronas-F measurements was registered only after strong magnetic storms and only when large fluxes of the SCR were present in the magnetosphere.

Although the stable trapped 1 MeV proton flux at L=2.5 might be large enough to provide particle precipitation into the loss cone, the above mentioned appearance of MeV protons exclusively after strong magnetic storms with SCR effect strongly suggests that these temporary belts are created by solar protons.

Therefore, now there are two known types of the events or mechanisms, which results in the trapping of solar cosmic rays in the inner magnetosphere. One is the resonant particle injection by induced electric field impulse of the SC, registered during March 24, 1991 magnetic storm. The SC amplitude must be extremely high (>100nT) to create unconfused effect, therefore such events are rare.

The resonant injection mechanism is not efficient for the low energy protons (Ep < 15 MeV) which magnetic drift period is large compared with the duration of the SC pulse.

The second mechanism described in the present paper presumes direct trapping and only the low energy part of the SCR spectra, less than 4-10 MeV.

Solar particles are on open drift orbits behind the PB and if the recovery of previously compressed magnetosphere is fast compared with the particle drift period, then a part of this particle will remain on the closed trapped orbits. For example at L=3 magnetic drift of the 50 MeV and 1 MeV protons equals approximately 20s and 15 minutes. Geostationary satellites transit after the magnetosphere compression from the solar wind back to the magnetosphere lasts 5-10 minutes, and therefore 1 MeV proton belt may be created, while 15-100 MeV protons will not be trapped. The SPB must be destroyed during the next magnetosphere compression if the PB reach this belt position, opening particle trajectories.

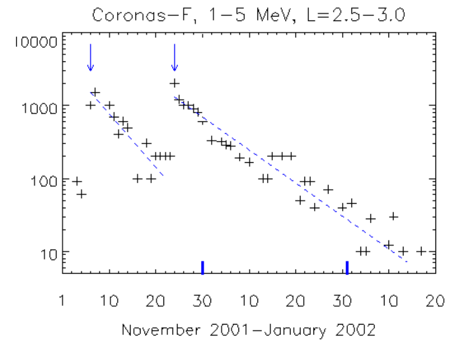

Fig.7. Decay of the solar proton belts intensity, measured by Coronas-F over BNA during November 2001-January 2002 flights.

A detailed analysis of the October 2003 data and November 2001 events presented here shows that in all those cases the penetration boundary reached low latitude sufficient for the direct trapping of the MeV protons into the closed drift orbits after the fast retreat of the PB boundary.

Figure 7 presents joint plot of the solar proton belts temporal evolution. The proton intensity decreased tenfold approximately 15 days after the November 6 event and 24 days after the November 24 ones. Coronas-F measurements supplied information only of particles with pitch angles close to the loss cone. We have no information on the associated intensity variation of the trapped particle, therefore it will be incorrect to conclude, that the decrease of the measured proton flux means disappearance of the solar proton belt. Most probable it means a decrease of the particle flux of relatively small pitch angles and gradual recovery of the equilibrium PAD with a large intensity gradient along the magnetic field line which is typical for the stable MeV proton belt.

Indeed, the solar cosmic rays penetrating into the inner magnetosphere must have an isotropic PAD. When they become trapped, they change undisturbed inner belt protons PAD especially near the loss cone. The fast decrease of this flux might be the result of the pitch angle diffusion on the ion-cyclotron waves for example generated by the ring current protons.

Conclusion

Dynamics of the solar proton penetration boundary during the two November 2001 magnetic storms have been investigated. The measurements of the 1-90 MeV solar protons on board Coronas-F satellite show that the penetration boundary approached the Earth as close as L=2.2-2.5.

It was found that 1-4 MeV solar protons became trapped and were registered at L=2.3-2.5 during the satellite flights over the BMA after magnetic storm.

A tenfold decrease of the proton flux at 500 km altitude was registered in 15-25 days.

The observed effects are sufficiently explained by the model of the direct solar proton trapping into the inner radiation belt during the recovery of the magnetosphere configuration and outward shifts of the proton penetration boundary.

Acknowledgements. This study was partly supported by the grant № 06-05-64225 of the Russian foundation for Basic Research.

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