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 low altitude polar orbiter Coronas-F reveal several cases of the direct trapping of the 1-4 MeV protons during magnetic storm recovery phase. Observation over Brazilian Magnetic Anomaly allow to study time history of the temporal solar proton radiation belts. Presented model also explains the occurrence of the fast intensity decrease of the inner belt protons as a result of the magnetosphere reconfiguration and associated solar cosmic ray penetration boundary intrusion into the inner belt region

1. Introduction

In addition to stable inner belt, 1-15 MeV proton intensity variationsat L=2-4 were reported in several publications. Bostrem 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, Slocum 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 SC [Li et al., 1993, Pavlov et al., 1993, Blake et al., 2002].

Energetic protons measurements by low altitude polar orbiter Coronas-F allows to identify special type of the intensity enhancements associated with direct trapping of the 1-4 MeV protons to the inner radiation belt [Lazutin et al., 2006]. Inspection of the proton measurements over the Brazilian Magnetic Anomaly from September 2001 to June 2005 revealed strong tendency that enhanced proton flux with maximum intensity at the L range between 1.9 and 2.7 arrive only after strong magnetic storms accompanied by solar cosmic ray events. During extreme magnetic storms in October 2003 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. October 2003 measurements were described in details by [Lazutin et al., 2006]. Our study presents description and temporal and energy features of the double penetration boundary effect, and explanation of the process of trapping of the solar proton, based on the solar proton measurements during magnetic storms in November 2001 and October 2003.

Coronas-F detectors will be used in this study, which measure proton in four differential channels (1-5, 14-26, 26-50 and 50-90 MeV). At the 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

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.

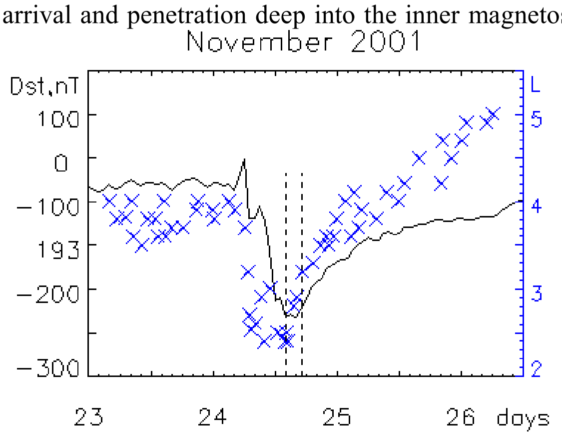

Fig. 1 Penetration boundary dynamics and Dst-index during November 24 event. Vertical broken lines show the moments of the measurements of the proton radial profiles shown by fig.2.

Dst variation and temporal variations of the solar proton penetration boundary (PB) are shown by Fig 1. PB position was taken at the background level (approximately 1/100 from the intensity maximum). Two vertical broken lines show the time when latitudinal PB presented by fig.2 were taken.

The first profile of the MeV proton shown by the solid line belong to the time of Dst minimum. It have a double boundary structure. Outer boundary reproduce 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). The inner profile was recorded by MeV proton channel alone. We suppose, that PB was there some moments before and MeV protons became trapped during PB retreat and associated depolarization of the Earth's magnetosphere. For the protons with higher energy reconfiguration process was too small as compared with magnetic drift and

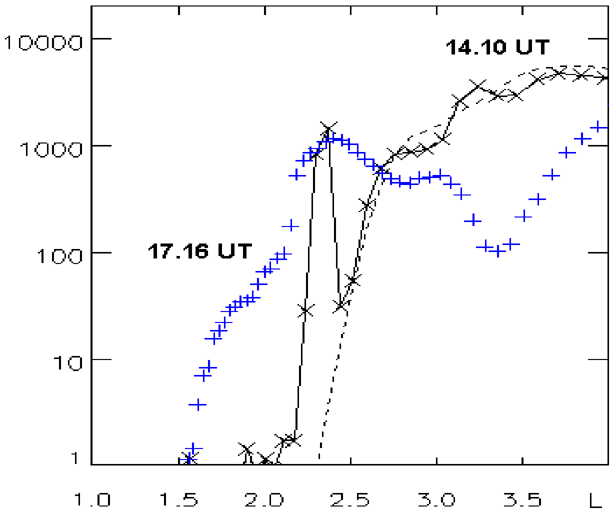

Fig. 2 November 24 1-4 MeV proton latitudinal profiles

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 revealed MeV protons trapped in the additional inner belt with maximum at L=2.3. 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 {Vakulov et al, 1976). Precipitation from the proton belt due to the pith-angle diffusion might cause increase of the proton flux near the loss cone. From 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. 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 on fig 2 might be as well of solar proton origin.

October 30-31, 2003. During the chain of the October 2003 extreme superstorms PB approached the Earth even closer, than in November 2001. The closest to the Earth position of the of the PB was registered at the evening of the October 30, 2003. The PB intensity profiles of four proton energy channels usually coincide without notable differences, but several exceptions from this rule were registered during this retreat.

Current PB position was easy to follow by the measurementsof three high energy channels (14-90 MeV). At the same time low energy protons have double-boundary structure.

Figure 3 shows PB crossings in the south-evening sector at 2330UT and 0110 UT, October 31. Intensity profiles along PB of the 50-90 MeV are shown by dotted lines and PB of 1-5 MeV channel by solid lines. Counting rates of both energy channels are normalized to coincide in the polar cap. One can see that 1-5 MeV channel has double

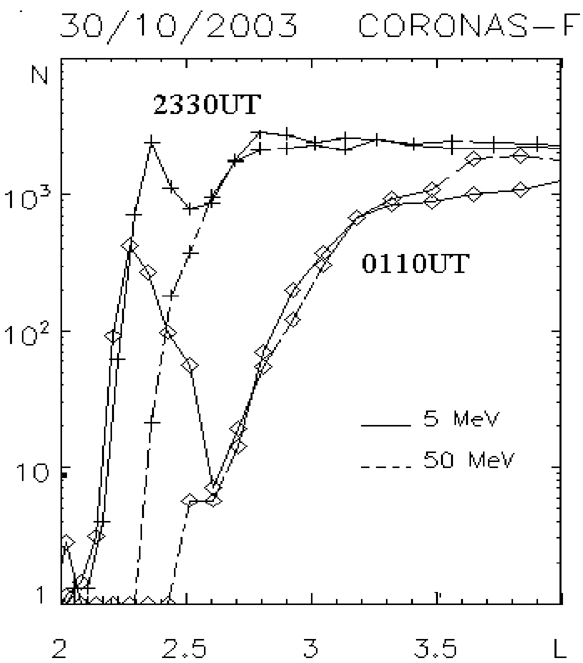

Fig.3. Double boundary effect of 1-5 MeV protons

boundary structure: during the first part of the satellite flight toward high latitudes intensity increase follows the old, closer to the Earth boundary, then after interval of the decrease, counting rate again begin to grow along the new boundary, which coincides with the boundary of energetic protons.

Similar double boundary was observed in other sectors, both during the flight toward the lower latitudes and back, therefore it was not a 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 during fast retreat of the penetration boundary. Their drift trajectories which were open in a quasitrapping region became closed, thus creating new solar proton belt.

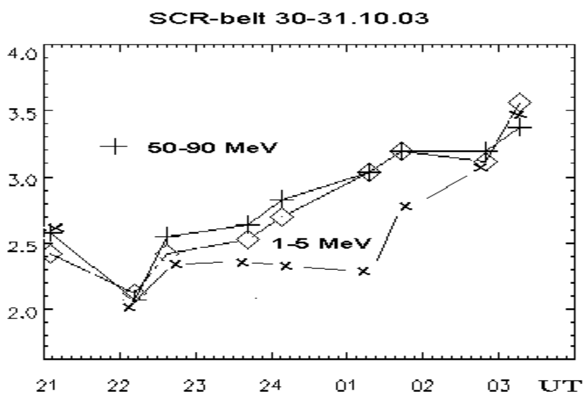

Fig.4. Dynamics of the outer and the inner PB position during double boundary event

Figure 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 MэB 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 31.10.03.

The intensity of the protons at the inner boundary decreased rapidly approximately ten times during an hour. Fast decrease of the registered proton flux does not mean the decay of the solar proton belt. It only means the disappearance of the proton flux in the loss cone, while magnetic field lines recover dipolar shape, 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 BMA

November 6, 2001. During the November 6 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 at the 500 km altitude most of the flight time went below the radiation belts with the exception of the Brazilian and South Atlantic anomaly. Here we can register the radial profile of the inner radiation belts and study their transformation.

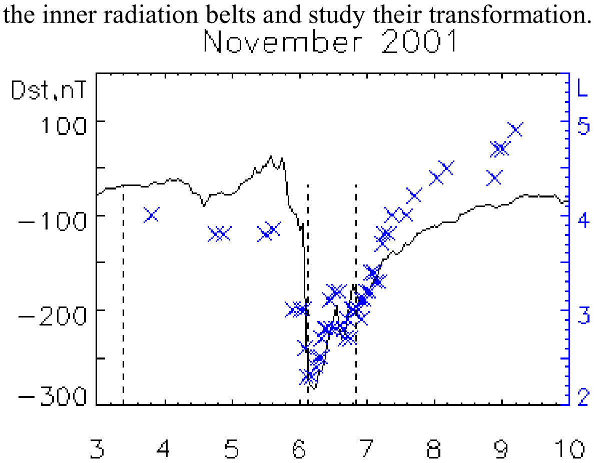

Fig.5 The same as fig.1 for November 6 event.

. Fig 5 shows Dst variation and the penetration boundary motion during this event. Dotted lines indicate the time of three profiles measurements presented by the fig. 6.

The first profile was measured three days before the magnetic storm and before the arrival of the solar protons from associated solar flare. Only the stable inner radiation belt with maximum at L=1.6 was registered there. The next latitudinal profile was taken right at the maximum of the Dst and closest PB approach to the Earth measured during this event. Background level boundary position was at L=2.2 as shown by the arrow on fig.6, while if define PB position as 0.5 of the polar cap value, then it will be at L=2.7.

The third profile was the nearest after the previous one measured over the BMA, One can see, that PB shifted to L= 3.2-3.7, leaving behind enhanced flux of 1-4 MeV protons with maximum at L=2.4, which was there all the BMA crossings untill the next magnetic storm which take place at November 24, 2001.

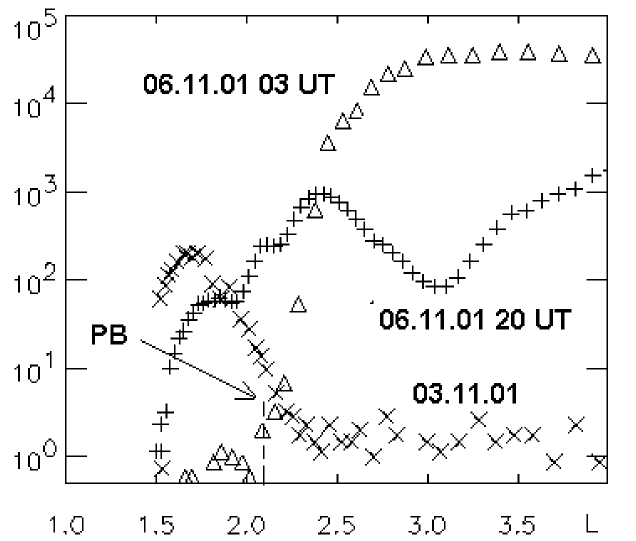

Fig.6. Three MeV proton profiles: over BMA before the event, during the innermost PB position and during following fight over BMA during magnetic storm recovery.

November 24, 2001. After the first arrival of the enhanced 1- 4 MeV protons at 24.11.01 shown on fig.2, similar profiles were registered during all flight over BMA with decreasing intensity. Figure 7 shows three radial profiles illustrating the intensity decrease for one order in 15 days. Also one can observe gradual shift of the intensity maximum from L= 2.5 to 3.0. It is possible also to suppose, that of two intensity maxima, recorded on November 24, the closest the Earth (L=2.5) disappeared more rapidly while at L=3.0 intensity decrease went on more slowly. Temporal and spatial resolution of our observation does not allow to decide, whether shift of the maximum or differential decay are correct.

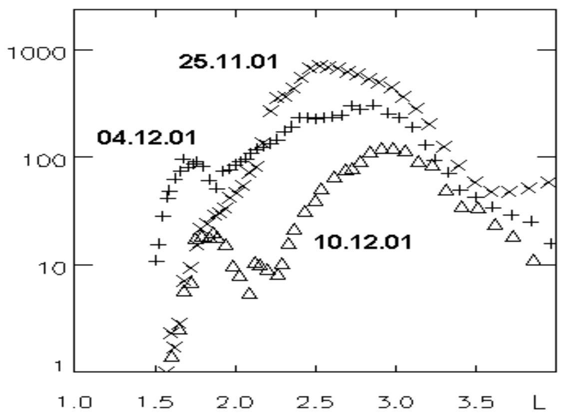

Fig.7. Trapped solar protons as seen during Coronas-F flights over Brazilian Magnetic Anomaly

Fig 8 shows 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.

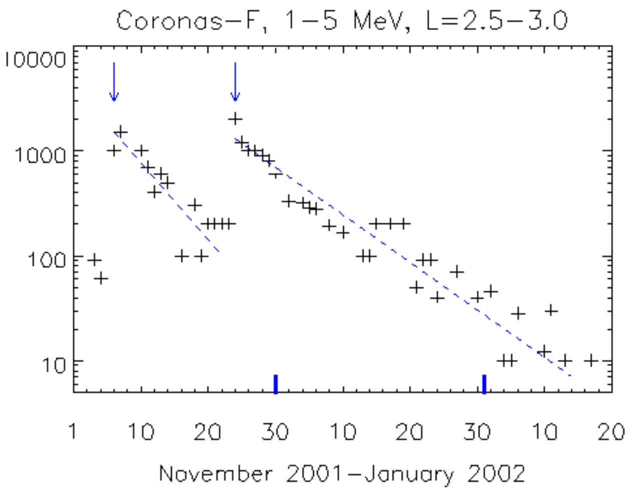

Fig.8. Decay of the solar proton belts intensity, measured by Coronas-F over BNA during November 2001-January 2002 flights

Decrease of the 1-4 MeV proton intensity at the 500 km altitude does not mean total disappearance of the additional proton population. Quite possible that pitch angle diffusion or other type of particle losses went more effectively in a small pitch-angle range leaving trapped particle at the enhanced level for more long interval.

October-November 2003. Enhanced proton fluxes were recorded over BMA all the time from October 20 to November 25, 2003 but with different intensity and position. The number of additional peaks at intensity profiles varied from one before the October 29 to three after November 4.

Peak intensity versus position (L) are presented by Fig. 9.

Although the position and intensity of the belts maximum are recorded with obvious uncertainity, it is clearly seen that points are combined into four groups with similar intensity and position.

Before the extreme storms, single proton flux was seen at L=3.4 (stars on fig. 7). This flux disappeared at the morning October 29 when the proton penetration boundary approached the Earth and previously trapped protons found itself free to escape from the trapping region.

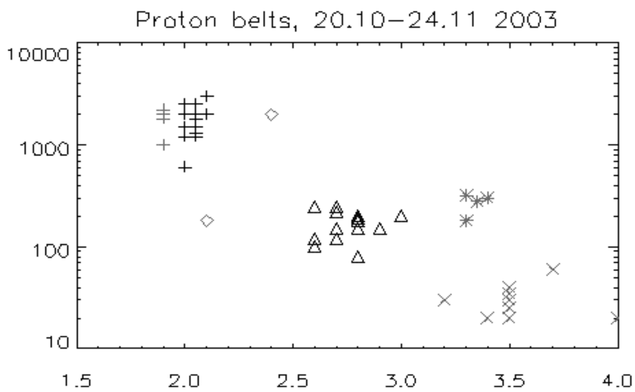

Fig.9. Solar cosmic ray belts, amplitude versus position

During the disturbed interval from October 29 to 31 when one storm came after another and penetration boundary move several times toward the Earth and back, several temporal solar proton belts were created and destroyed (diamonds).

Two solar proton belts seen for the first time in the morning of October 31, were created at the end of the last main storm phase with maximum L=2.1 и L=2.6-2.8 (crosses and triangles on Fig 7), their formation was recorded as double-boundary effect described above. There were no magnetospheric disturbances strong enough to destroy these two belts until November 20 magnetic storm. One can see that those two maxima exist without significant change of the amplitude and position.

The third additional maximum joins previous two after the moderate magnetic storm, which occurs on November 4.

It was found by Vakulov et al, 1067, that enhanced 1-4 MeV proton flux at L=3 and higher may be found during intervals when there were no magnetic storms or SCR events.

Inspection of the BMA profiles for extended interval from September 2001 to May 2005 supports that conclusion, indeed there were intervals without magnetic storms with the enhanced proton fluxes at L=3-4. Study of the dynamics of this events will be reported elsewhere From the other hand, the enhanced proton flux with maximum intensity at the L range between 1.9 and 2.7 arrive only after strong magnetic storms and only accompanied by solar cosmic ray events.

By this reason we cannot attribute for sure enhanced flux at L>3 to the solar protons.

After the magnetic storm of 20.11.03 the radial profile of the trapping region was changed again: two outer solar proton belts disappeared, the inner belt survived but was noticeably shifted earthward from L=2.05 to L=1.9 approaching closer to the main inner radiation belt. There were no solar cosmic rays registered during this storm and therefore additional SCR belts has not been created.

Fig. 10 shows how proton flux at the maximum of the inner and the strongest additional belt was seen over BMA

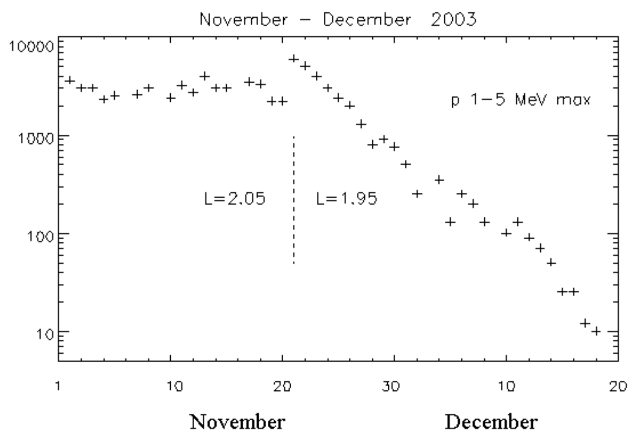

Fig. 10 Temporal development of the solar cosmic ray belts created during October 30-31 magnetic storm recovery phase.

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 steady decrease of the intensity maximum took place.
It does not necessary mean that solar protons leave the trapping region. More reasonably to support, that only part of the particle flux with pitch angles close to the loss cone precipitated into the atmosphere or increased their pitch angle. The belt transformation toward stable condition with more normal PAD can be expected.

4. Energy spectrum of the trapped solar protons

The probability for the protons to be trapped decreased as the drift velocity exceeds the rate of the magnetosphere reconstruction. Therefore we did not found double boundary effect in the high energy proton channels as well as an absence of the enhance flux in BMA after the morning of October 31. But there was one orbit over BMA on October 29, at 1640 UT, after the first PB fast retreat, which gave the possibility to measure trapping effect in high energy channels. Intensity of the solar cosmic rays was extremely high at this time and the effect was present in all four energy channels as shown by fig. 11. The counting rates in the temporary proton belt registered by 50 -90 MeV channel was only 0.1% of the polar cup intensity, but still well above the background. In this case low-energy alpha particles were trapped as well. The energy dependence of the relative trapped proton intensity can be approximated by the power low $\mathbf{N = No\ E^{-k}}$ when $\mathbf{k} = 2$.

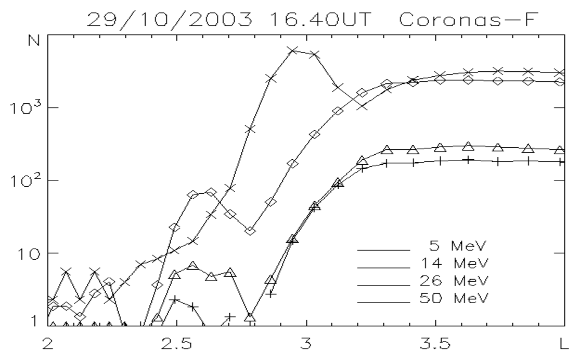

Fig.11. Soar cosmic rays belt on October 29, 2003.

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 = 2.2-2.5. As a result, previously trapped particles from higher L may escape from the radiation belt, which explain particle flux dropouts observed after magnetic storms.
2. As a result of the fast penetration boundary retreat during magnetic storm recovery phase, solar protons with energy 1-4 MeV might be trapped, creating temporary solar cosmic ray belts on L=2 - 3 or providing additional flux to the previously existed population.
Trapping action was registered as a double boundary effect in real time Coronas-F measurements and further solar proton belt transformation was observed during satellite flight over the Brazilian Magnetic Anomaly.
3. During double boundary development earthward shift of the inner boundary was registered presumably due to the ExB drift due to the induce electric field.
4. Energy spectrum of the protons in SCB decreases steeply from 4-10 MeV. Protons and alpha particles with E > 4 MэВ were recorded only occasionally and with 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 to several minutes. Magnetic drift period for 1 MeV and 50 MeV protons at L= 3 is abut 15 minutes and 20 s accordingly. For the fast drifting energetic protons will trace current position of the penetration boundary while low energy protons will be transferred to the closed drift orbits.
5. After the trapping flux of precipitation protons inside the loss cone decrease exponentially as N=No exp(-kt) , where t= 1.15 hours. 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. As the closest recorded position of the PB was at L=2.2, the inner belt part at L< 2 will be conserved during extreme magnetic storms.

Proposed mechanism of the direct trapping of the solar protons during magnetic storms does not contradicts to SC induced injection model, is is totally different processes. They differs by the energy range of the involved particle: while direct trapping affects 1-5 MeV particles, SC injection is effective for the particles with energy above 15 MeV [Pavlov et al., 1993].
Described creation of SCR belts and erosion of previously existed trapped particles might be important for the space weather radiation models.

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References

Blake, J.B., W.A.Kolasinski, R.W.Fillius, and E.G.Mullen, Injection of electrons and protons with energies of tens of MeV into L > 4 on 24 March 1991, *Geophys. Res. Lett.*, 19, 821, 1992.
Bostrem et al., Time history of the inner radiation zone, October 1965 - December 1968, *J. Geophys. Res.*, 75, 1246-1256, 1970.
Hudson, M.K. , S.R.Elkington, J.G.Lyon, V.A.Marchenko, I.Roth, M.Temerin, J.B.Blake, M.S.Gussenhoven, and

J.R.Wygant, Simulations of proton radiation belt formation during storm sudden commencements, *J. Geophys. Res.*, 102, 14087-14102, 1997.
Lazutin L. L., Kuznetsov S. N., and Podorolsky A.N., Creation and distruction of the solar proton belts during magnetic storms, Accepted by Geomag. and Aeronomy, 2006 (Both Russian and English preprints can be found at http://www.kosmofizika.ru/open/index.htm
Li, X., Roth I., Temerin M., Wygant J.R.,.Hudson M.K, and Blake J.B., Simulations of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC, Geophys. Res. Lett., 20, 2423, 1993.
Lorentzen, K.R., Mazur J.E., Loper M.E., Fennell J.F., and Blake J.B., Multisatellite observations of MeV ion injections during storms, J. Geophys. Res., 107, 1231, 2002.
Mineev Yu.V., Spirkova E.S., Glukhov G.A., Kratenko Yu.P., Features od solar cosmic ray penetration into the high-latitude regions of the Earth's magnetosphere inferred from Intercosmos-19 data. Proc. of 18-th Intern. Cosmic Ray Conf., Bangalore, India, v.3, p. 262-265, 1983
Pavlov N.N., Tverskaya L.V., Tverskoy B.A., Chuchkov E.A., Variations of the radiation belt particles during strong magnetic storm of March 24, 1991*, Geomagnetism and aeronomie*, 33, #6, 41-45, 1993 (R)
Slocum, P.L., K.R.Lorentzen, J.B.Blake, J.F.Fennell, M.K.Hudson, M.D.Looper, G.M.Masson, and J.E.Mazur, Observations of ion injections during large solar particle events, *AGU Fall Meeting,* SH61A-0501, 2002.
Vakulov P.V., Geigorov N. L., Dobrovolska B., Dubinsky Yu.,
Zakharov A. V., Kudela K., Kuznetsov S. N., Kuznetsova V. A., Pisarenko N. F., Savbnko I. A., Flsher S.. Somogyi A. And Yuzefovich L A., Studies of corpuscular radiation in the Earth's environs based on Intercosmos 5 data, in: Space Research XVI, ed. by M.J. Rycroft, Akademie-Verlag, Berlin, p. 1976