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COMPARATIVE ANALYSIS OF THE ENERGETIC ELECTRON AND SOLAR PROTON DYNAMICS DURING STRONG MAGNETIC STORMS

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Abstract. Transformation of the radial profiles of 0.3-3.0 MeV electrons and 1-15 MeV protons during the main and recovery phases of magnetic storms was investigated by measurements on board of the low-altitude satellites CORONAS-F and SERVIS-1. As an indicator of the transformation of the magnetosphere configuration dynamics of solar proton penetration boundary was used. It is shown that during the main storm phase electron dynamics was governed by the concurrency of the radial shift of the drift orbits and losses at the flanks of the magnetosphere and into the loss cone caused by the divergence from the adiabacity. At the recovery phase of magnetic storms similarity of radial profile dynamics of electrons and freshly trapped protons was observed indicating on the relation of the nature of acceleration of both particle species.

1. Introduction

Dynamics of trapped electrons and protons of MeV range during magnetic storms is influenced by a complex of processes, such as fast changes of the magnetospheric configuration, violation of adiabatic invariants, enhancements of electrostatic and induction electric field in the magnetosphere, and generation of electromagnetic waves.

Collective influence of these processes creates a complicated picture of spatial and temporal particle distribution and intensity variations, and its understanding is still far from perfection.

Accepted scheme of relativistic electron (RE) variation include the following two stages: during the main phase of a storm - disappearance or strong intensity decrease of the electrons outer radiation belt, during the recovery phase - appearance of the RE in the slot between the inner and outer radiation belts, intensity increase in several hours or in several days. Interaction with VLF and radial diffusion with conservation of the first adiabatic invariant are more often referred as the mechanisms of RE acceleration (Friedel et al., 2002, O'Brien et al. 2003).

To understand variations of the proton radiation belt during strong magnetic storms one should distinguish two situations - magnetic storms in absence of significant solar cosmic rays (SCR), and the storms accompanied by the arrival of SCR near the Earths orbit. In the first case decay of > 5 MeV protons flux was registered caused by the adiabatic cooling due to the magnetic field depression at the main phase of a magnetic storm (Soraas et al., 1970). Additional source of the outer proton belt intensity dropout may be created by deep distortion of the magnetosphere configuration when previously trapped protons found themselves in a quasitrapping region. In the situation with magnetic storms accompanied by considerable SCR fluxes, the effect of solar proton capture into the closed drift orbits is frequently observed and the population of the proton belt is essentially enhanced (Mineev et al., 1983, Blake et al., 1992, Lazutin et. al., 2006).

There are significant difference in explanations of protons trapping mechanism - on the one most widespread concept, the trapping is produced by radial injection of particles during the storm sudden commencement (Pavlov et al., 1993, Hudson et al., 1995, Kress et al., 2005, Lorentzen et al. 2002, Blake et al. 1997).

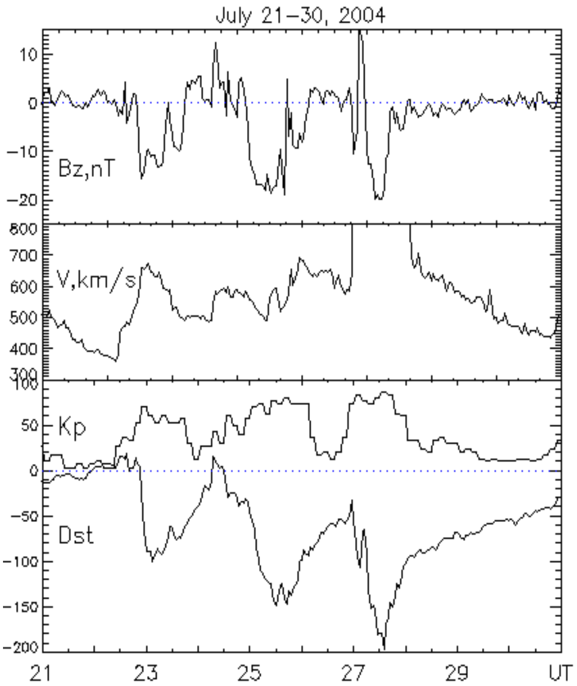

Fig. 1. Parameters of solar wind and magnetic indices during three magnetic storms on July, 22-30, 2004.

Alternative model introduced by Lazutin et al., (2006, 2007) suggests that capture of solar protons into the closed drift orbits occurs without injection during magnetosphere reconfiguration at the magnetic storm recovery phase. This approach will be supported and extended in present work, based on particle observation on board of two polar orbiters during strong magnetic storm 0f July 2004.

We will compare transformation of the radial profiles of energetic electrons and protons and discus possible joint mechanisms of trapped particle auxiliary acceleration during the storm recovery phase.

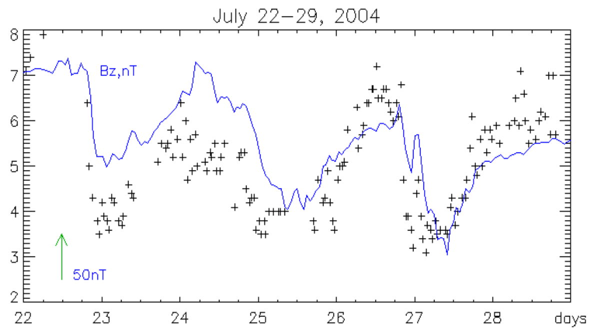

Fig. 2. Dynamics of penetration boundary of SCR protons into the magnetosphere and Dst an index of a ring current.

2. Observations

Fig. 1 presents the basic solar wind characteristics and indexes of magnetic activity from July, 21 till July, 30, 2004. Not going into the details of the solar wind influence on the Earth's magnetosphere, we should note, that this influence has led to consecutive development of three magnetic storms with increasing power of the ring current (Dst -100, -150 and -200 nT). The main phases and some part of the recovery phases of all storms were accompanied by auroral activity and significant southern component of IMF. Since 21.07 SCR fluxes were measured near the Earth and have penetrated deeply into internal magnetosphere.

Measurements of energetic particles were made onboard two low-altitude satellites, CORONAS-F and SERVIS-1, both with a polar orbit at 500 and 1000 km altitudes accordingly. Channels with electrons energy of 0.3-6 MeV and 1-15 MeV protons will be used for the analysis.

During strong storms solar protons penetrate into the inner magnetosphere down to L~3 and even deeper and as was already mentioned above, can be trapped on the closed drift shells. The process of SCR capture has been found out on measurements onboard the CORONAS-F during magnetic storms 7.11 and 24.11, 2001 and 29-31.10.2003 (Lazutin et al., 2007). Initially the purpose of present research was to obtain the new data on development of trapping using measurements onboard two satellites during a magnetic storm with complicated temporal structure, but some new founding became achievable.

Trapping effect became possible if solar protons penetration boundary (PB) approach L=3, or nearer to the Earth.

Indeed, during each of three storms main phase PB moved Earthward and back during recovery phases, approximately tracing ring current index Dst development (Fig. 2). PB position was determined in this case by the beginning of protons flux decrease from a level of the polar cap in the nighttime radial profiles measured onboard CORONAS-F. The SERVIS-1 satellite because of its higher orbit was not so good for the PB determination, since at the certain distance SCR fluxes can merge with a flux of trapped particles of the proton belt. CORONAS-F at the most of longitudes registered only precipitating SCR protons, which pitch-angular distribution is always isotropic in a polar cap and in the quasitrapping region during strong magnetic storms. Therefore determination of PB by CORONAS-F data was reliable except the third storm interval when SCR flux was mixed with precipitation of trapped protons, which flux was already great enough for development of the ion-cyclotron instability.

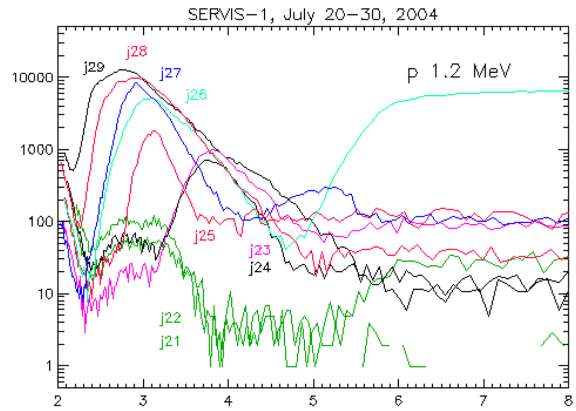

Fig. 3. Radial structures of 1.2 MeV protons measured above the Brazilian magnetic anomaly onboard the SERVIS-1 satellite during evening flights.

Measurements of particles dynamics on two satellites with different altitude have allowed to reveal several new features, from which we shall consider here proton trapping and electrons and protons acceleration process.

Radial profiles of 1.2 MeV protons, measured every day from July, 21 till July, 30 are presented by the Fig. 3. All measurements were carried out above the South-Atlantic anomaly at the same time (20-22UT) in a Southern hemisphere. Let us consider radial structure features and changes step by step.

21.07 - before the beginning of the storm, a typical structure with position of a maximum at L=3 was registered.

22.07 - after SC, before the beginning of the main phase of the first storm: the same radial structure, without visible effects of particle injection during SC.

23.07 – at the recovery phase of the first storm, closerto the end. The structure with maximum at L=3 is still seen, but the new maximum at L=3.8 has appeared, in our opinion it was created by SCR protons which PB at the end of the main phase reached L=3.2 (fig. 2).

24.07 - before the beginning of the main phase of the second storm - the structure is similar to previous one.

25.07 - at the beginning of the recovery phase of the second magnetic storm. The maximum of a trapped protons is shifted closer to the Earth, intensity in a maximum grows approximately twice. The place of the old maximum occurs behind PB, when SCR plateau with the polar cap intensity is observed. Movement of penetration boundary toward the Earth also moves area with isotropic pitch-angular distribution. To precipitate into the loss cone protons, which was trapped earlier even by moderate pitch-angular diffusion at this L-shell takes first tens minutes, it can explain disappearance of a maximum at L=3.8.

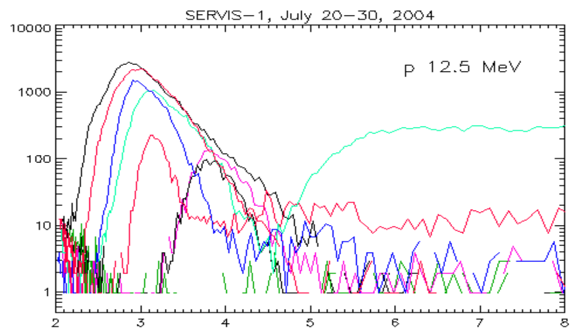

Fig. 4. The same as Fig 3. for 1.7 MeV of electrons

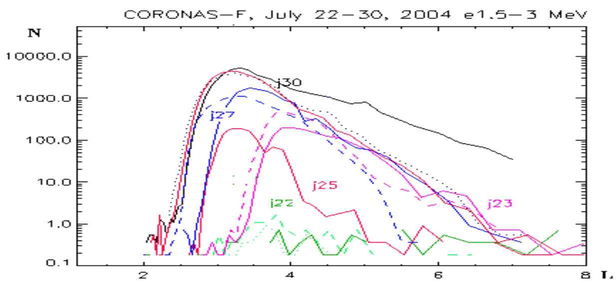

Fig. 5. The same as Fig 3. for 1.5-3.0 MeV electrons, CORONAS-F

26.07 - the end of the recovery phase of the second magnetic storm. Some agent during magnetic storm recovery increases intensity and shifts a maximum of already trapped protons closer to the Earth whereas the border of penetration is rolled away to L ~ 6, as one can see at this structure.

27.07-30.07 - a recovery phase of the third, final magnetic storm. Sudden commencement of this storm also has not brought any noticeable effect which can be regarded as an indication on SC-injection. By the end of the main phase the SCR penetration boundary has not reached recently trapped protons location and during these four days we see only intensity increase and shift of the intensity maximum toward the Earth.

Let's address now to a similar picture of 1.7 MeV electron radial profile dynamics (fig. 4). Surprising similarity of protons and electrons transformation is evident. Certainly, the initial profiles are different, for electrons maximum is located at L=4, at the standard position the maximum of the outer electron radiation belt. Also electron belt can not be refreshed or replaced by external source, as an electron fluxes in SCR usually are too small as compared with radiation belt population, but consecutive radial movements of both profiles to the Earth are very similar.

On the CORONAS-F satellite at lower altitude proton profile picture is not so picturesque apparently because of smaller intensity, but electron ones shows, that belts' dynamics on both satellites is similar. As an example, CORONAS-F 1.5-3 MeV electron profiles are shown on Figure 5.

As a maximum on the radial profile counting rate is wide, and therefore maximum position is rather uncertain, we will follow an earthward motion of a point on the inner slope with tenfold intensity decrease. The resulting plots for different energies and species are shown on fig. 6. The main result of comparison is that speed of displacement is identical and does not depend on energy, particle species, and the satellite onboard which measurements were carried out.

If one assumes, that the displacement is result of the uninterrupted radial ExB drift, it is easy to estimate the magnitude of the electric field. Taking average velocity 0.9 Re per 7 days we will have 0.02 mV/m. It is relatively small value, but possibly more realistic to suppose, that radial shift or diffusion is not continuous, but impulsive, for example driven by substorm associated induced electric fields. Such fields may be of the order of several mV/m (Hori et al., 2005) but in action during several minutes of the 100 min. substorm duration time.

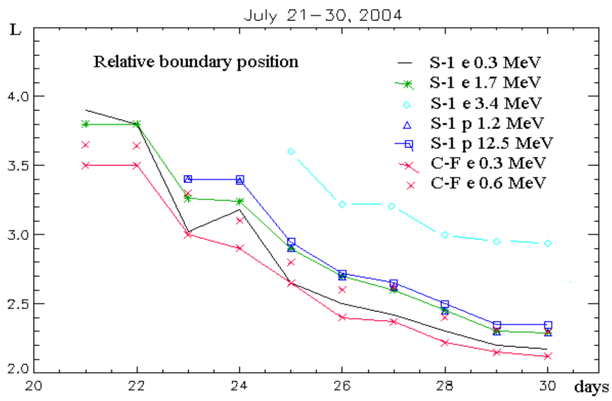

Fig. 6. Shift of radial structures of energetic particles

3. Discussion and conclusions

Basic physics of the capture and dynamics of 1-15 MeV SCR protons during magnetic storms are the same, but specific features of the magnetic storms, especially of a multiple storms, result in various scenarios of capture, acceleration and destruction of SCR belts. Thus, in the series of extreme storms of 29-31.10.2003 trapping of SCR protons and alpha particles occurred both during the recovery phase of the first, and the second storms, but the main phase of the next storm shifted PB to the Earth and wiped the

belt that just materialized. And only at the recovery phase of the third, strongest storm the final formation of the solar proton belt occurs (Lazutin et al., 2006).
In a case under discussion, the second magnetic storm was stronger that the first one and the proton belt with maximum at L= 3.8 was destroyed. But the second new belt with maximum at L=3 survived because the PB at the main phase of the third storm has not moved close, moreover, the proton belt itself has moved toward the Earth and its intensity has increased. Therefore in July 2004 chain of magnetic storms solar proton belt was created by the second storm while the last one participates in particle acceleration.
It was known that magnetic field reduction by the ring current during magnetic storm main phase and following magnetic field recovery may decelerate and adiabatically accelerate energetic protons in the inner radiation belt with the zero effect at the end . In our case acceleration was dominant, therefore we shall look for some special driver for radial drift or diffusion, possibly related to substorm activity. It is well known, that epicenter of auroral and substorm activity shifts during storms earthward similarly to the shift of the solar proton PB.
As for the acceleration of the relativistic electrons, it was well known from the earlier works, that magnetic storm acceleration take place during recovery phase. What may regarded as new and unexpected result of present study, it is simultaneous acceleration of protons evidently by the same mechanism.
Conclusively, typical features of energetic electron and proton dynamics can be summarized as follows:
1. After the first storm 22-23.07.2004 outer electron belt does not disappear, its maximum shifted to the Earth at L=3.8 superimposing with the new solar proton belt. The flux of electrons in a maximum was higher then in prestorm outer belt, it's obvious that radial shift was accompanied by betatron acceleration.
2. At outer L-shells the flux of electrons sharply falls in agreement with earlier observations (Friedel et al., 2002).
3. After the second storm, 25.07.2004, the maximum was sharply displaced toward the Earth, but is not farther, than PB of SCR, intensity dropout at L=3.5-4.5 is observed. As for the measurements of SCR protons, the PB reaches L=3.5.
4. On the recovery phase of the second and third storms the flux of electrons and protons continues to grow, and the maximum is displaced closer to the Earth.
5. Similarity of radial structures of SCR protons and relativistic electrons demonstrate a common of mechanisms of transfer and acceleration of particles.
6. The flux of electrons at height 1000 km is much higher, than on 500 km, that speaks about the normal (trapped) pitch-angular distribution.

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