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ESTIMATION OF NONADIABATIC MOTION REGIONS IN THE MAGNETOSPHERE DURING SUBSTORM

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Abstract. The dynamics of regions of nonadiabatic motion of the particle in the midnight sector of the near-Earth (5-15 Re) magnetosphere are estimated by CRRES spacecraft data. We used the time-dependent magnetic field model which is composed from the Tsyganenko-89 static model and the additional magnetic field produced by variable current system. The observed magnetic field perturbations by CRRES have been used to identify the additional current loop with field-aligned currents at the edges. We assume that the parameters of the loop and the position of the loop may be arbitrary. We present examples of modelling of the configuration of magnetic field lines, which penetrated across the CRRES and geosynchronous satellite 1990 095 (eastward and tailward of the CRRES) during the substorm on February 9,1991. We are using the 'delta' parameter for the estimation of the type of particle motion in the model magnetic field.

Introduction

The motion of charged particles in a magnetic field can happen in different modes. In adiabatic motion the particle «is bound» to a certain magnetic field line and (in a dipole field) produces oscillations between mirror points. In non-adiabatic motion the dynamics of a particle can be essentially more complex and even chaotic. In a number of papers /Delcourt et al., 1994, 1996/ it was noted, that the violation of an adiabaticity of the ion motion can result in the appearance of an effective current promoting the development of instability, causing the beginning of the explosive phase of substorm.

In paper /Buchner and Zelenyi, 1989/ it was shown, that the character of particle motion at the given point of magnetosphere is controlled by the curvature parameter:

$$\kappa^2 = (R_{curv}/\rho_{max}), \qquad (1)$$

where R_{curv} - the minimum radius of the curvature of the magnetic field line, ρ_{max} - Larmor radius for the particle of the given energy with pitch-angle of 90^o at the point with the minimum radius of the field line curvature. The values of $\kappa>1$ correspond to the region of adiabatic motion, and for non-adiabatic regions $\kappa<<1$. The boundaries of these regions in the magnetosphere are not fixed: they depend on the particle energy and the level of magnetospheric activity.

In some papers the position of boundaries of non-adiabatic motion regions is evaluated by the position of boundary of the measured isotropic pitch-angle distributions of protons and electrons /Imhof et al., 1979; Pytte and West, 1978; Sergeev et al., 1983; and Popielawska et al., 1985/. The region for $\kappa\sim3$ is identified in /Sergeev et al., 1983/ as equatorial boundary of intensive precipitations of energetic ions in the ionosphere. In /Lui et al., 1992/ by observations of AMPTE CCE at $\sim8R_E$ it was shown, that for low-energetic (~12 keV) ions in the region of current disruption the κ value is ~1 and consequently their orbits are in the non-adiabatic motion region.

Anderson /1997/ introduced new parameter δ_B for systematization of modes of particle motion in the magnetosphere:

$$\delta_B = \frac{2.8053}{\varepsilon^{1/8}\sin\alpha}\exp\left(-\frac{F(\sin\alpha)}{\varepsilon}\right) \qquad (2)$$

Here: α is the equatorial pitch-angle of particle, $\varepsilon = \rho_{max}/R_{curv} = 1/\kappa^2$, function F defined in /Anderson et al., 1997/. The δ_B describes the pitch angle dependence of irreversible changes of the particle magnetic moment:

$$\frac{\Delta\mu}{\mu} \cong -\delta_B \cos\psi_{eq} \qquad (3)$$

Here $\mu = mv_\perp^2/2B$ is the first adiabatic invariant, m is the particle mass, B is the magnetic field strength, $v_\perp$ is velocity perpendicular to the magnetic field; ψ_{eq} is the equatorial gyrophase angle of particle. Using the model of Tsyganenko-89, Anderson /1997/ have shown, that the transition from adiabatic (δ_B~0.001) to non-adiabatic (δ_B ~0.1) mode happens in a narrow range of radial distances: $2R_E$ at midnight meridian for protons of 30 keV at Kp = 2.

In this report, using δ_B parameter, we estimated the dynamics of non-adiabatical regions in the near-Earth magnetosphere during a substorm by the data of the CRRES satellite. We used the dynamic model of the magnetosphere composed from the static statistical model of Tsyganenko-89 and an additional magnetic field of a time-varying current system. Disturbances of the magnetic field observed by the CRRES were used for calculation of parameters of this additional current system.

Dynamical model of the magnetic feld

The magnetospheric substorm is very dynamical phenomenon. Therefore, when studying it, it is desirable to use dynamic model of the magnetic field. The existing statistical models (for example, Tsyganenko models) do not allow one to use them directly in one's studies of a particular situation and require additional adapting.

Here, for studies of the dynamics of non-adiabatical regions we use the dynamical model of magnetosphere composed from static statistical model /Tsyganenko, 1989/ and the magnetic field of an additional current system. It is supposed, that the current system consists of: 1) the linear current flowing in an equatorial plane (Z_{GSM} = 0), and 2) field-aligned currents to both hemispheres, at the ends of the equatorial current. The configuration of field-aligned currents was calculated in the assumption , that the currents flow along magnetic field lines of Tsyganenko-1989 model. Concerning the direction (orientation) of the current in an equatorial plane, its intensity and distance from the Earth no additional assumptions were made, they were selected for each moment so that the model magnetic field was equal to the one observed by the CRRES. Initial length of the current in an equatorial plane was equal to $2R_E$ and it was magnified with the step of $0.4R_E$, if by the changing of other parameters it was not possible to achieve the sufficient consent of the model field with the one observed. The position of the middle of the current loop at MLT for the considered case (484 orbit of CRRES) was fixed at 23:00, so the intensity of necessary additional currents had a minimum value.

Fig.1 shows z-component of the magnetic field, measured by the CRRES satellite at the 484-th orbit during the substorm of February 9, 1991. The explosive phase of the substorm began at T_0 = 16:58 UT. The B_z-component calculated along the CRRES trajectory by Tsyganenko-1989 is also shown in Fig.1. One can see, that the statistical model differs essentially from the observed one and does not describe the dynamics of transition from growth to explosive phase of the substorm.

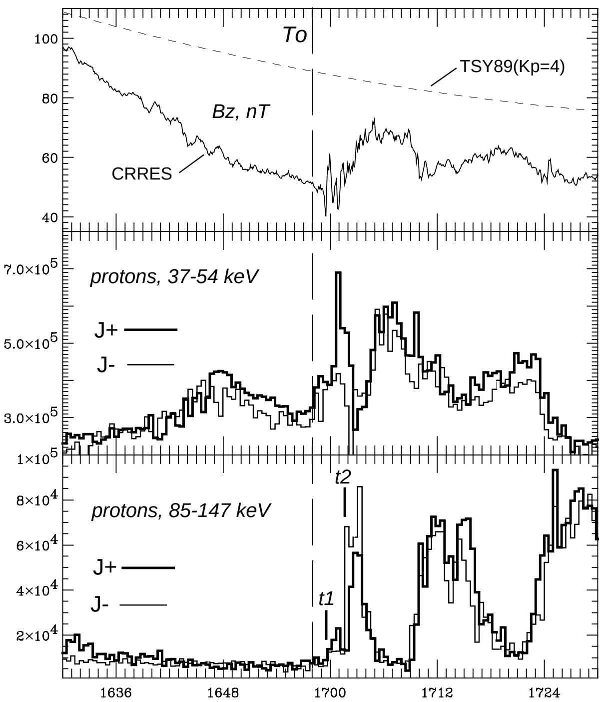

Fig.1. Substorm observation at 484 orbit of CRRES.

The parameters of an additional current system calculated with a 1 minute step, are shown in Fig.2. From the figure we can deduce: 1) During the growth phase the additional current moves nearer to the Earth by ~ $1R_E$, its direction is changed from an almost transversal one (West-East) up to radial (from the Earth). 2) At the beginning of the growth phase there is a fast increase of current intensity (5 times higher during 12 minutes), but its length does not vary. However, during the last 12 minutes before the beginning of the explosive phase the current intensity practically does not vary, but the current length in an equatorial plane gradually grows (3 times). 3) After the onset of the explosive phase the direction of the change of all parameters of additional current varies.

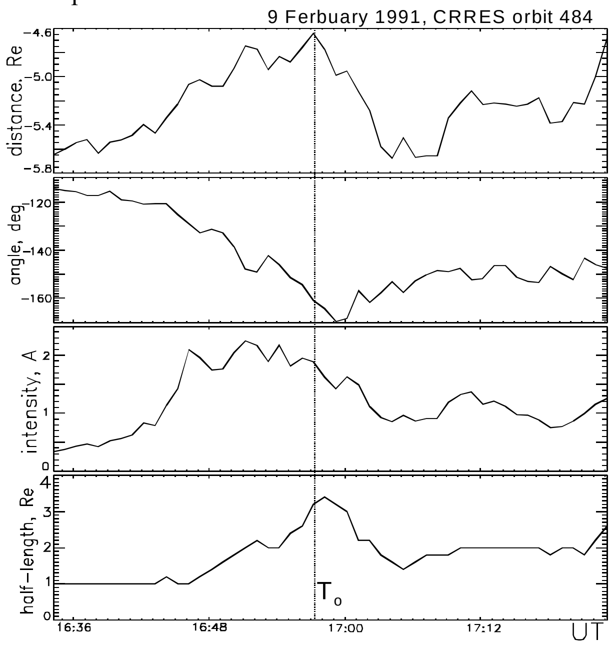

Fig.2. Parameters of the additional current system (from top): distance from the Earth; angle with X_{GSM} axis; intensity; half-length in the equatorial plane.

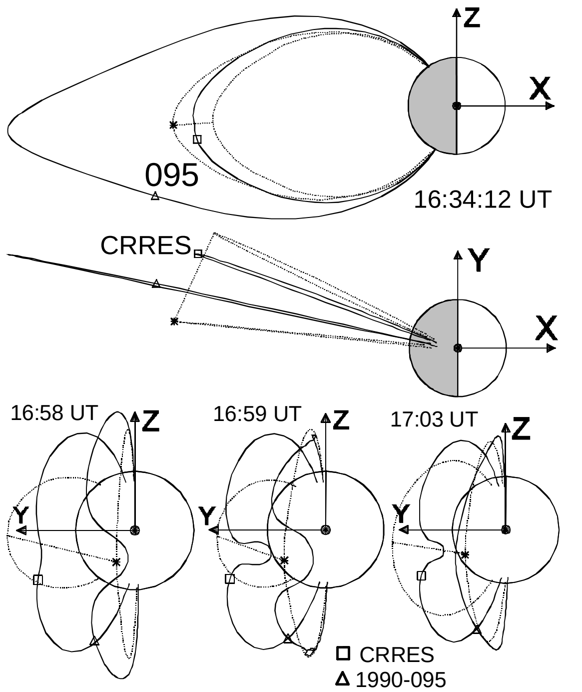

Fig.3. Examples of configuration of the current system and magnetic field lines passing through CRRES and 095.

The behaviour of additional current agrees with the existing performances concerning the distribution of currents near the inner edge of the plasma sheet. The appearance of a radial current (radial loop) can be associated with spatial distribution of gradients of the plasma density and the magnetic field during the substorm.

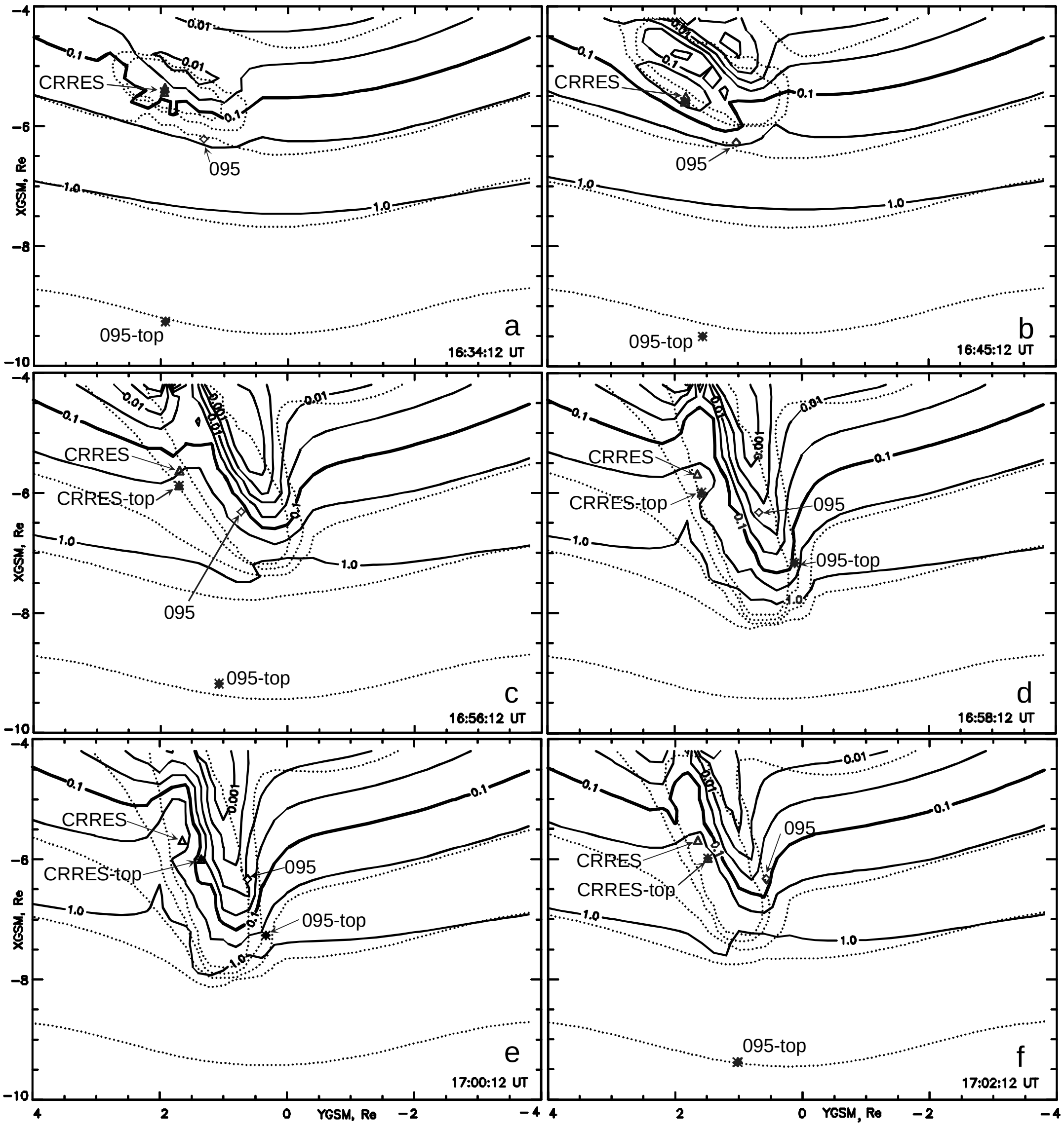

Fig.4. Solid lines - isocontours of δ_B in the midnight sector of equatorial plane for 150 keV protons with α_{eq}=45°; dotted lines - isocontours of B=const. Projections of the CRRES and 095 are shown. Projections along the magnetic field lines passing through the satellites are marked as CRRES-top and 095-top.

Some examples of the obtained additional current systems are shown in Fig.3. Magnetic field lines passing through the CRRES and 1990-095 satellites, and calculated with the inclusion of these additional currents, are also shown.

From these figures one can see, that despite the proximity of these satellites in space, magnetic field lines differ much and are bent just near the substorm onset.

Thus, the results of magnetic field simulation show, that near the substorm onset the magnetic field lines passing through the CRRES and 1990-095satellites, are projected in different regions of magnetosphere. Such distortion of the magnetic field lines explains different behaviour of particle fluxes at these two satellites near the substorm onset /Lazutin et al., 1998/.

Characterictics of the nonadiabatic motion

Fig.4. shows the isocontours of constant δ_B for the 150 keV protons with the pitch angle in the equatorial plane α=45°. The isocontours were calculated for several time moments in the vicinity of the CRRES during the substorm of Feb 9, 1991. The contours reflect the transition region between adiabatic and nonadiabatic motion of particles. Looking over the contours in Fig.4, one can see that the isocontour δ_B=0.1 bends significantly at the end of the substorm growth phase, approaching the Earth at the CRRES meridian and coming farther toward the tail at the 1990-095 satellite meridian. This change in location of isocontours is the effect of changes of B field geometry during the substorm growth phase. The calculated isocontours for 150-keV protons with α=80° and for 45 keV protons retain the same dynamics during the substorm (not shown).

Before 1645 UT(Fig. 4 a,b) the CRRES-top was located in a more adiabatic region. At this time the PAD (pitch angle distribution) has a maximum in 90° for the more adiabatic protons (P1) and away from 90^o for the more energetic (more nonadiabatic) protons (P4-P5), see Fig.5. Then, during the substorm growth phase the more nonadiabatic region approachs the Earth (and the CRRES). The PAD of the protons in the P1 channel changes and the maximum of proton intensity moves (is displaced) away form the 90^o (Fig.5).

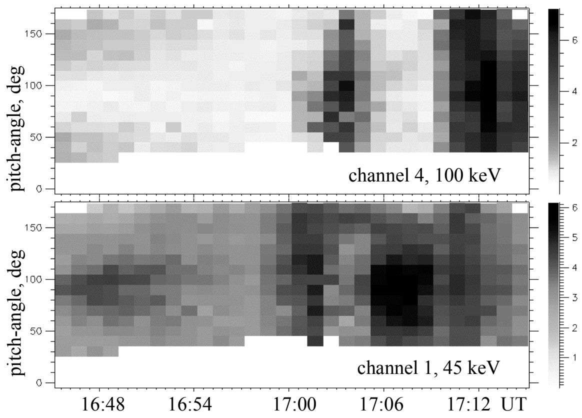

Fig.5. Pitch angle distributions of the protons in P1 and P4 channels of the CRRES.

In the interval 1658-1701 UT the magnetic field lines bend eastward and the top displaces in the more adiabatic region again. Just during this time (moment t1 in Fig.1) a small increase is observed in the fluxes (J+) of protons with the gyrocenters Earthward the CRRES. At the moment t2=1702 UT (Fig.1) the injection of the more energetic protons with the gyrocenters tailward the CRRES (J-) is observed simultaneously with the magnetic field dipolarization. During this time the CRRES-top displaces backward and is located in the more nonadiabatic region.

Similar dynamics of the magnetic field lines and proton fluxes is also observed by the 095 satellite in the interval t1-t2 (not shown). However, after t2, when 095 satellite top displaces backward at r~ 9.5 R_E, the 095 observes a particle injection 1.5 min later than the CREES. Taking into account the position of tops of the field lines passing through the CRRES and 1990-095 and the time delays it is possible to say, that the initial position of particle acceleration region was at ~ 6.3 R_E (near the CRRES), and then this region was extended to the magnetospheric tail at the speed of ~230 km/s.

Discussion

L and energy dependence of isotropic boundary. Low-altitude satellite measuremants show that the energy dependence of the isotropic boundary may be a very steep function of L value /Popielowska et al, 1985/. It has been difficult to explain the observation theoretically using static models of the magnetic field. Our calculations show that in the more realistic B field model the transition from adiabatic to the strongly nonadiabatic motion is sufficiently rapid in the interval Δx ~ 1Re for a large proton energy range. Such a sharp transition region may produce (result in) a steep L and energy dependence of the isotropic boundary.

Injection of particles and nonadiabatic changes. During the expansion phase of substorm, the Earthward injection of energetic particles occurs under the influence of large short-lived electric fields. In the course of this injection, the particles are subjected to both impulsive parallel and perpendicular acceleration and nonadiabatic motion. The convection surge mechanism /Mauk, 1986/ for the ion acceleration is efficient in producing energetic particles, especially when nonadiabatic effects are concerned /Delcourt et al, 1994/. Our estimations show that during the substorm Feb 9, 1991, the substorm activation region was located at r ~ 6-7 Re within strongly nonadiabatic region. This implies that first adiabatic invariant suffers a large change and its value can "freeze out" when a particle crosses rapidly enough the transition region from the strong δ_B toward smaller δ_B.

Conclusions

1) Magnetic field lines can be strongly bent by local current systems.

2) Even the closely located satellites can be projected in an equatorial plane at significant distances.

3) In the considered case the regions of violation of adiabatic motion were close to CRRES satellite at the moment of the explosive phase onset.

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References

Anderson, B.J., Decker, R.B., and Paschalidis, N.P., Onset of nonadiabatic particle motion in the near-Earth magnetotail, J. Geophys. Res., 102, 17533, 1997.

Buchner, J, and Zelenyi, L.M, Regular and chaotic charged particle motion in magnetotaillike field reversals 1. Basic theory of trapped motion, J. Geophys. Res., 94, 11821, 1989.

Delcourt, D.C., R.F.Martin, Jr., and F.Alem, A simple model of magnetic moment scattering in a field reversal, Geophys.Res.Lett., 21, 1543-1546, 1994.

Delcourt, D.C., J.-A.Sauvaud, R.F.Martin, Jr., and T.E.Moore, On the nonadiabatic precipitation of ions from the near-Earth plasma sheet, J. Geophys. Res., 101, 17409-17418, 1996.

Imhof, W.L., Reagan J.B., and Gaines, E.E., Studies of sharply defined L dependent energy threshold for isotropy at the midnigth trapping boundary, J. Geophys. Res., 84, 6371, 1979.

Lazutin L.L., Rasinkangas R., Kozelova T.V. et al. Observations of substorm fine structure. Ann. Geophysicae .16. N 7. p. 775-786. 1998.

Lui, A.T.Y., Lopez, R.E. Anderson, B.J. et al., Current disruptions in the near-Earth neutral sheet region, J. Geophys. Res., 97, 1461, 1992.

Mauk B.H. Quantitative modeling of the "convection surge" mechanism of ion acceleration. J.Geophys. Res. 91. p. 13423. 1986.

Popielawska, B., Szalinska-Piechota, E., and Tsyganenko, N.A., On the non-adiabatic particle scattering in the Earth’s magnetotail current sheet, Planet. Space Sci., 33, 1433, 1985.

Pytte, T., and West, H.T., Jr., Ground-satellite correlations during presubstorm magnetic field configuration changes and plasma thinning in the near-Earth magnetotail, J. Geophys. Res., 83, 3791, 1978.

Sergeev V.A., Sazhina E.M., Tsyganenko, N.A. et al., Pitch-angle scattering of energetic protons in the magnetotail current sheet as the dominant source of their isotropic precipitation into the nightside ionosphere, Planet. Space Sci., 31, 1147, 1983.

Tsyganenko, N.A., A magnetospheric magnetic field model with a warped tail current sheet, Planet. Space Sci., 37, 5, 1989.