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Cusp region radiation belts in the dayside magnetosphere

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Abstract

The possibility of quasi-stable trapping of charged particles of hundreds keV–MeV energy on the front side Earth magnetosphere is explored in this article by numerical modeling of the single particle orbits in the geomagnetic field utilizing empirical Tsyganenko model. On the front side magnetosphere the remote equatorial magnetic field lines are compressed to balance the solar wind pressure and exhibit two minima in the geomagnetic field strength magnitude along the field line in high latitudes on both sides of the equator which results in stable confinement structures in the north or/and the south hemispheres, providing energetic particle trapping for times from several minutes to durations of seasonal scale. Simulation of the energetic proton orbits in magnetosphere passing through the regions of magnetic field minima with different disturbance level and the Earth's tilt shows when and where these trapped radiation zones could exist. It is noted that the existence of this adiabatic confinement zone depends on the tilt of the geomagnetic dipole axis to the Sun–Earth direction. As a result the northern polar cap (cusp) confinement zone appears only during a summer solstice and similarly the southern hemisphere capture zone appears during a winter solstice. During equinox the confinement zones exist in both hemispheres in the disturbed magnetospheric conditions, however, they are less pronounced. The zones are essentially restricted to the sunlit magnetosphere. They form a kind of cusp radiation belt, where a proton drifts with a period of several minutes, conserving its 1st and the 2nd adiabatic invariants. The latitudinal width of the belt is very thin, about 2–5 latitudinal degrees. The particle orbits passing through opposite off-equatorial field minimum reveal another effect: a bound of the geomagnetic equatorial plane on the day sector. These and other features of the confinement zones in the two minima off-equatorial magnetic field regions are discussed.

Keywords: Magnetosphere; Cusp region; Trapped particles; Radiation belts

1. Introduction

The recent in situ measurements of energetic protons, ions and relativistic electrons with Polar (Chen et al., 1997; Sheldon et al., 1998) and Interball (Pissarenko et al., 2001) satellites showed that in the dayside magnetosphere in the high latitudes there exist zones

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with trapped radiation. Although the existence of trapped radiation zones in polar latitudes looked farfetched, the mechanism of formation of confinement zones in high latitudes was considered about 30 years ago by Antonova and Shabansky (1968) and Shabansky (1971), and is theoretically developed recently by Antonova et al., (2001, 2003). Distant dayside magnetic field lines under compression by solar wind modify their almost dipolar form and become more intense at the geomagnetic equator than in higher latitudes. Due to this dayside compression two off-equatorial minima appear in the magnetic field strength on either side of the equator, in the northern and southern hemispheres.

The behavior of the charged particles in the dayside magnetosphere was analyzed with numerical methods by Delcourt and Sauvaud (1998, 1999) in exploring the single charged particle trajectories utilizing the Tsyganenko geomagnetic field model with account of magnetospheric electric field effects. They demonstrated that in the presence of two minima a charged particle initially mirroring within the geomagnetic equator plane can deviate abruptly under the cuspward mirror force to one of the minima when enters the dayside sector during longitudinal drift. In further travel it descends again into the magnetic equatorial plane continuing its regular equatorial drift into the nightside magnetosphere. This motion may give rise to the presence of hundreds of keV–MeV particle population in higher latitudes observed experimentally.

Tracing of single charged particle orbits in the geomagnetic field was also used as an instrument of analysis of energetic particle origin in high latitude magnetosphere by Öztürk et al. (2001). They used a more simple dipolar geomagnetic field model with an additional shifted dipole providing magnetic field compression in the dayside magnetosphere. It was confirmed that particles drifting in the geomagnetic equatorial regions can be transported in dayside sector to high latitude field minimum regions and then return to geomagnetic equatorial plane and continue their magnetic equatorial drift motion providing mixture of the tail and the cusp particle populations.

In our study, we consider the energetic proton orbits in the magnetospheric magnetic and electric fields that pass through the region of the dayside northern hemisphere magnetic field minimum, and separately through the southern minimum, in quiet and disturbed magnetosphere. For the orbit computations we employ the empirical Tsyganenko (1989, 1995) magnetospheric field models (further referred to as T-89 and T-96), IGRF1995 internal magnetic field, and transformed Volland–Stern electric field model (Volland, 1978). The study shows that in high latitudes there exist closed particle confinement zones around the cusp regions resulting from the compression of frontside magnetosphere where charged particles could be stably trapped and reveals some characteristic seasonal effects in the topology of the zones due to the geomagnetic dipole tilt to the Sun–Earth direction.

2. Particle motion in geomagnetic and geoelectric fields

2.1. The Three-Dimensional Case

Traditionally, a single charged particle transport in magnetosphere is simulated by the guiding center motion of equatorially mirroring particles with the second adiabatic invariant vanishing (i.e. $J = 0$). Instead of this approximation, the alternative, the particle orbit simulations based on the numerical solution of the full Lorentz force equation for a particle motion in geomagnetic and geoelectric fields (Gusev and Pugacheva, 1982) is used here. The equation for a charged particle trajectory in the magnetic field of strength $\boldsymbol{B}$ and in an electric field of strength $\boldsymbol{E}$ is described as

$$\frac{\mathrm{d}(m\boldsymbol{V})}{\mathrm{d}t} = q(\boldsymbol{E} + \frac{1}{c}\boldsymbol{V} \times \boldsymbol{B}), \qquad (1)$$

where q, m and $\boldsymbol{V}$ are particle charge, relativistic mass and velocity and c is the light velocity. In a simple dipolar geomagnetic field, in the absence of any electric fields, particles drift around the Earth due to the geomagnetic field gradient with the trajectories forming concentric circles around the dipole center. But in the presence of even small electric field in the morning–evening direction, charged particles drift in $\boldsymbol{E} \times \boldsymbol{B}$ direction from the nightside towards noon independent of the sign of their electric charge.

Eq. (1) is solved numerically applying the Runge–Kutta–Gill method. A corresponding Fortran code uses double and where necessary quadruple precision. The solution of the equation for the geomagnetic field has a form of auto control whereby charged particles drift around the Earth conserving the L-shell parameter, and after one drift period approximately return to the initial starting point, i.e. perform a finite motion. In this case it is not necessary to check the solution by computing the reversed trajectory, utilizing methods employed in the calculation of arrival directions of particles from infinity such as cosmic rays reaching neutron monitors, etc.

We adopted the procedure earlier used for the modeling of keV–MeV proton orbits in a dipolar geomagnetic field with superposed dawn–dusk directed electric field (Pugacheva et al., 2004). The electric fields considered both the corotation and the convection fields in the equatorial plane with the corotation field potential $U_{\mathrm{cor}} = -CR_{\mathrm{e}}/R$, where $C = 91.5\,\mathrm{kV}$ (Roederer, 1970), and the convection field potential $\mathrm{U}_{\mathrm{V-S}} = -AR^2 \sin\phi$, of Volland–Stern model with coefficient A dependent on geomagnetic activity $A = 0.0449/$

$(1-0.159K_P+0.009K_P^2)^3$, in units of kV/R_e^2; R_e is the Earth's radius and ϕ is the azimuthal angle between the directions of the field vector and the sunward axis, R is the radial distance from magnetic dipole center.

The electric field structure away from the Earth's equatorial plane is much less well known. In the 3D modeling, we assume the geomagnetic field lines are equipotential with the potential equal to that at the point of field line crossing geomagnetic equatorial plane. Tracing the potential along the neighboring lines, one can compute the electric field vector as $\boldsymbol{E} = -\mathrm{grad}\,\boldsymbol{U}$. We do not detail these calculations because further we analyze the orbits of protons with energies great enough (0.1–several MeV) such that they drift primarily because of gradient-B rather than $\boldsymbol{E}\times\boldsymbol{B}$ effects. For the geomagnetic field we use T-89 and T-96 field models.

2.2. *The dayside magnetic field line topology*

We analyzed the dayside geomagnetic field line topology at three special time periods characterized by inclination of the Earth's rotation axis to the Sun direction: summer and winter solstices (traditionally, for northern hemisphere) and the spring equinox. The tilt is in the range of 55–77° in the summer solstice; of 79–101° in the equinox, and of 102–124° in the winter solstice. The building of the lines is done utilizing the test code provided in T-89 model package. Figs. 1a and b depict the magnetic field strength versus the geodetic latitudes for a set of field lines anchored in the Earth's surface at different northern latitudes in the Greenwich meridian for 12:00 LT, for summer solstice for quiet and active times characterized in the model by index IOPT. The index represents the geomagnetic activity with the extreme activity IOPT = 8 when $K_p > 5$ and in quiet time IOPT = 1 represents $K_p = 0$–1.

Figures show an existence of two off-equatorial minima in the field strength magnitude, both at quiet and active times during the solstice. The similar topology of magnetic field line with two off-equatorial minima exists during the winter solstice (Figs. 2a and b) and the equinox (Figs. 3a and b). Even in quiet time the solar wind compresses the distant magnetosphere, but both northern and southern minima are nearly flat, although they are more remarkable during active magnetosphere (Fig. 1b). The deeper magnetic field lines ($L\sim 6$) show only one traditional field minimum at the regular equatorial plane even at active times (see Fig. 2b, Lat = 65°).

The topology with two distinguished minima in the field strength is also found at all meridians from 0° to 360° when they are exposed to the dayside, i.e. in the whole range of the tilt values. The existence of the two dayside minima does not depend on UT, but their quantitative characteristics depend on it: the depth of minima, their geographic position, the McIlwain parameter L of the drift shell (L, B) where the minima occur, etc.

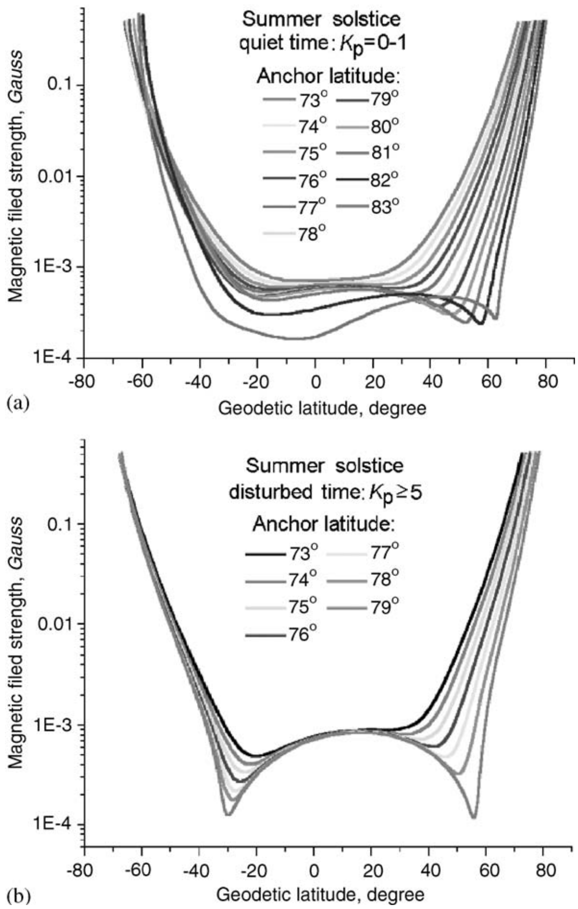

Fig. 1. The geomagnetic field strength along dayside field lines versus latitudes for the lines anchored at different latitudes for a summer solstice period: (a) in the quiet magnetosphere; (b) in the disturbed magnetosphere.

3. Confinement zones of trapped radiation in the cusp region

Finding the field minima, we intended to search if these minima indeed correspond to some closed confinement zones. Our task was to study the characteristic features of these zones, utilizing the reliable empirical geomagnetic tilted field models (Tsyganenko, 1989, 1996). Differently from the modeling of the single charged particle orbits performed by Öztürk et al. (2001) and by Delcourt and Sauvaud (1999) we do not seek the sources of the particles that populate these minima, for from the history of magnetosphere science one knows that if a confinement region exists, the trapped particles

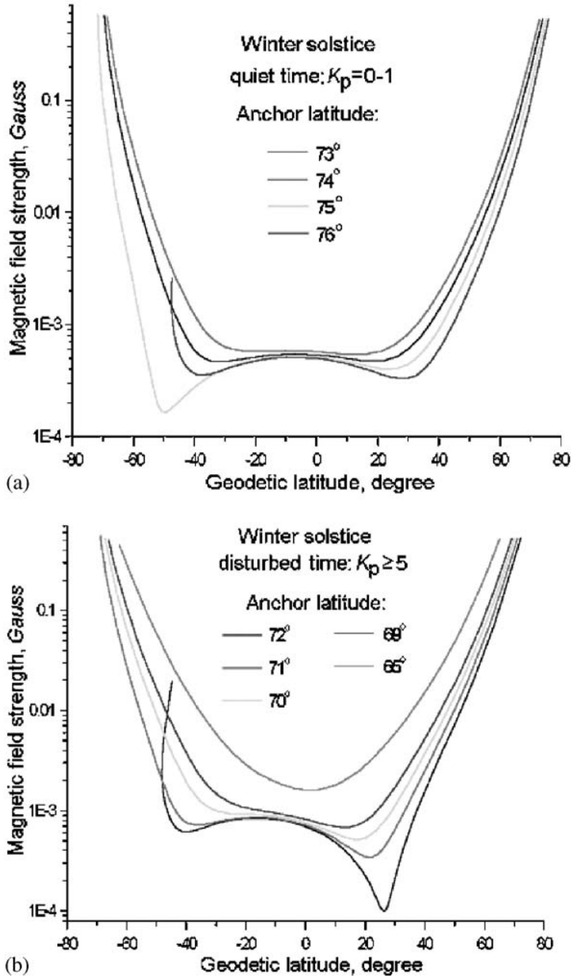

Fig. 2. The geomagnetic field strength along dayside field lines versus latitudes for the lines anchored at different latitudes for a winter solstice: (a) in the quiet magnetosphere; (b) in the disturbed magnetosphere.

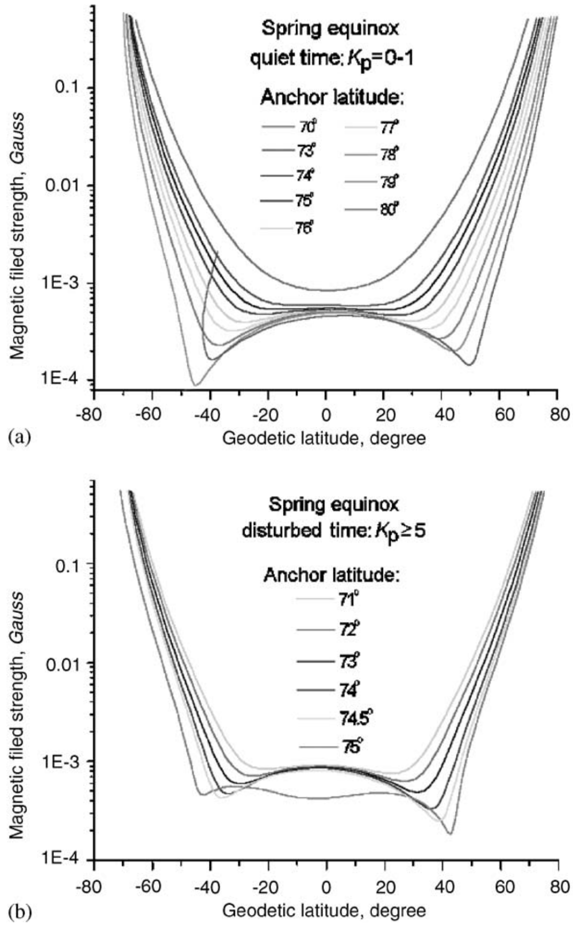

Fig. 3. The geomagnetic field strength along dayside field lines versus latitudes for the lines anchored at different latitudes for equinox time: (a) in the quiet magnetosphere; (b) in the disturbed magnetosphere.

will be there. The interest is to know the morphological and confinement details of the population in these regions at quiet and disturbed conditions.

We examined these by simulating the orbits of protons within energies of 0.1–2 MeV starting from the point corresponding to the northern minimum of each field line of Figs. 1a and b for summer solstice, of Figs. 2a and b for winter solstice, and of Figs. 3a and b for spring equinox, with condition $(\boldsymbol{V} \cdot \boldsymbol{B}) = 0$ when the proton velocity vector is perpendicular to the magnetic field vector and proton does not almost oscillate between mirror points.

Fig. 4 shows the drift trajectories of protons trapped during summer solstice in the northern minimum for quiet and disturbed times. They are finite, circular concentric trajectories along the minima associated with the field lines connected to 74° and 78° latitudes of the Greenwich meridian in disturbed magnetosphere and to 79–83° latitudes in quiet one. They keep pitch-angle essentially near 90° with $J = 0$ conserved. They occupy the sub polar, cusp region in a form of a plain belt, or a ring. Their one drift period around cusp region is about several minutes and the particles could drift for many orbits within the belt accumulating flux until some dynamical process (there are many in the polar region) precipitate them from these stable orbits. It is a confinement zone of energetic charged particle radiation in the cusp region, which could be named a cusp radiation belt of the Earth, or a cusp ring. Fig. 5 demonstrates 3D image of proton orbits belonging to the cusp radiation belt. The existence of the cusp trapped radiation zones does not depend on UT.

During quiet time the belt belongs to more distant field lines. As in disturbed conditions, its width spreads

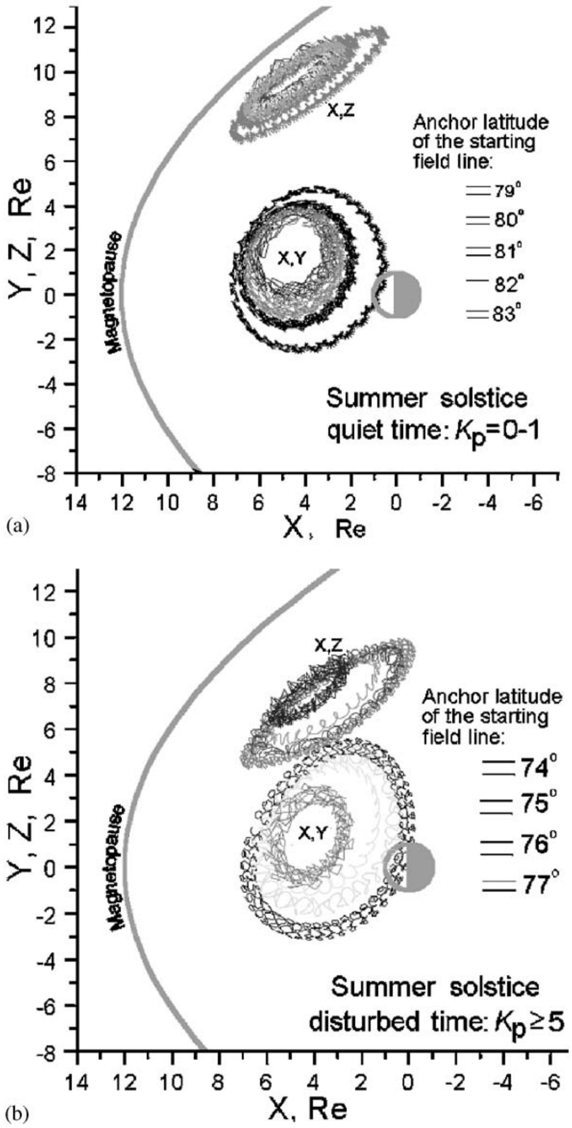

Fig. 4. The X,Y and X,Z projections in Cartesian GSM coordinates of the 0.3 MeV proton drift orbits passing along the northern field line minimum of Fig. 1 with zero 2nd adiabatic invariant during summer solstice: (a) in quiet magnetosphere; (b) in disturbed magnetosphere.

to about 5 latitudinal degrees. When another meridian, another magnetic field line exposes to the Sun direction (i.e. the whole range of the tilt values was checked), the cusp ring/belt still exists with the similar topology only changing its position in geodetic coordinates. In summer solstice this polar belt appears only in the northern hemisphere (Fig. 5). The protons having their orbits in the southern hemisphere minimum established on the basis of the same condition of $(\boldsymbol{V}\cdot\boldsymbol{B})=0$ do not create confinement zone around the southern cusp, as it will be shown in the next chapter.

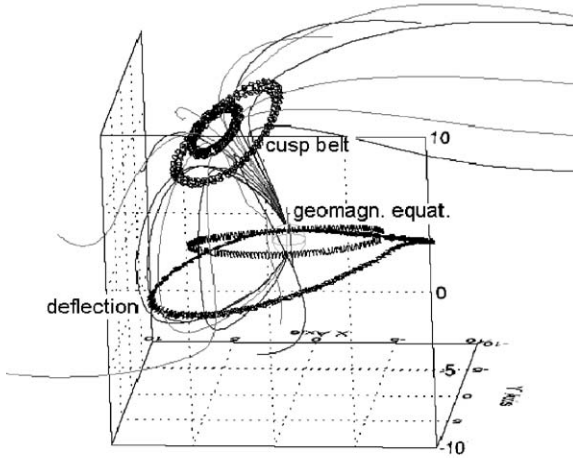

Fig. 5. Three-dimensional image of the 0.3 MeV proton drift orbit passing along the northern field line minimum in summer solstice in the disturbed magnetosphere (Fig. 1b, anchor latitude 75°). The lower orbit (deflection) belongs to proton passing through the southern field minimum.

Fig. 6 demonstrates the similar structure of confinement zone with the radiation belt around the southern cusp in winter solstice during active magnetosphere, obtained with the method of single particle orbit building. The northern cusp belt at the same time is absent. During spring equinox in disturbed magnetosphere there appear two cusp confinement zones (Fig. 7) where the energetic protons orbiting in both northern and southern off-equatorial field minima are captured.

The protons with the energy up to 2 MeV could be trapped in such kind of cusp belts: the 2 MeV proton orbits remain closed (Fig. 8), while the proton, for example, of 3 MeV energy escapes out of the trap to infinity.

Recognizing that even greatest electric field values provided with Volland–Stern model with $K_p=8$ do not affect significantly on the orbits of the energetic 0.1–2 MeV protons ($L=3$–10) in the geomagnetic equatorial plane, we, at the same time, tested the influence, modeling the proton orbits in these polar rings utilizing simultaneously the T-89 model with IOPT $=8$ and Volland–Stern model with $K_p=5$–8. We still found a stable confinement. At least for summer solstice orbits we still observed finite, closed characteristic trapped particle trajectories. Nevertheless, the electric field influence still needs to be searched more accurately, especially on the orbits of less energetic particles.

4. Deflection of geomagnetic equatorial plane

The behavior of the protons during summer solstice showed the possibility of confinement around the off

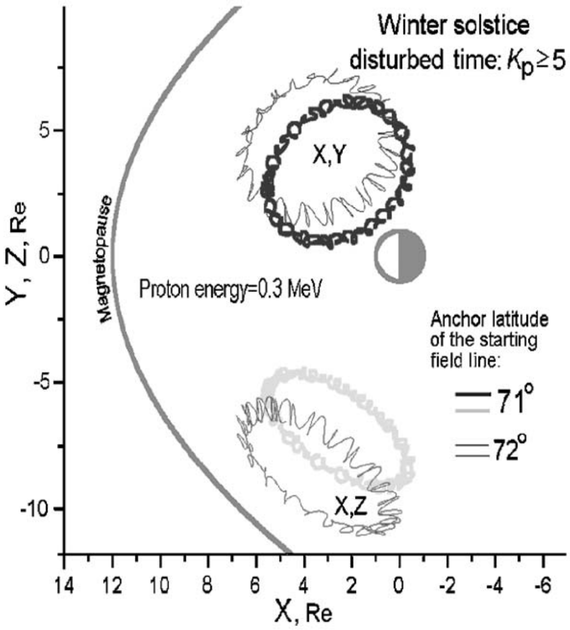

Fig. 6. The X,Y and X,Z projections in Cartesian coordinates of the 0.3 MeV proton drift orbits passing along the southern field line minimum of Fig. 2 during winter solstice in disturbed magnetosphere.

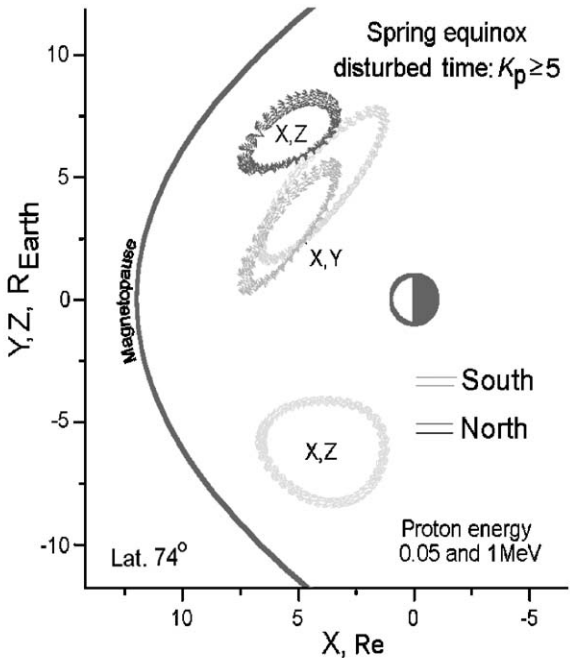

Fig. 7. The X,Y and X,Z projections in Cartesian coordinates of the 0.3 MeV proton drift orbits passing along the northern and southern field line minima of Fig. 3 in equinox time in disturbed magnetosphere.

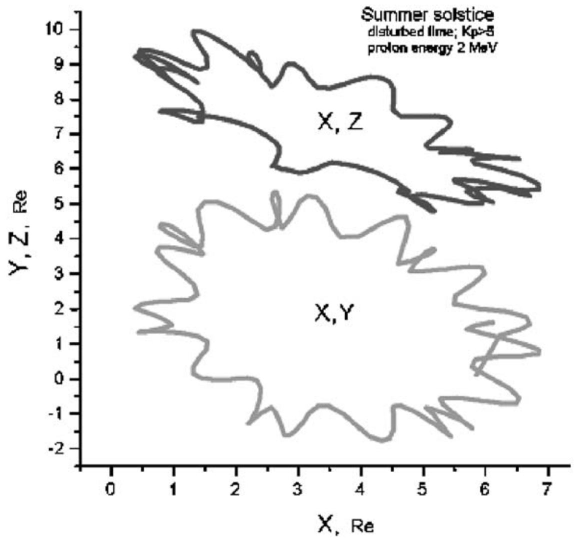

Fig. 8. The X,Y and X,Z projections in Cartesian coordinates of the 2 MeV proton drift orbit started in the northern field line minimum of Fig. 1.

equatorial field minimum. Further we studied what happens with the hundreds keV protons starting their orbits from another off-equatorial field minima in the southern hemisphere, with the same condition $(\boldsymbol{V} \cdot \boldsymbol{B}) = 0$. They are shown in Figs. 9–11. They do not create confinement zone around southern cusp, they drift around the whole Earth.

On the night side these particles in their orbits reside in the common geomagnetic equatorial plane. When during the drift around the Earth they get into evening side, they begin to climb to higher latitudes reaching a peak on the noon side. Further on the dawn side they again descend to low latitudes such that its orbit remains in the same plane, inclined to geomagnetic equatorial plane (Fig. 9). This inclination has some significant angle dependent on magnetospheric activity index K_p. It looks as if the geomagnetic equatorial plane is broken and bent for particles drifting around the Earth along the southern field minimum. This occurs only on the distant peripheral regions of the magnetosphere at drift shells with $L = 8$–12. The protons orbiting in this deflected geomagnetic equator plane at lower L-shells of about 8–9 conserve their second invariant and pitch-angle near 90° (Fig. 9). Three-dimensional image of this orbit is also shown in Fig. 5 (curve "deflection"). However, for particles drifting at greater L-shells ($L \sim 10$–12), the second invariant is violated, as shown in Figs. 10 and 11. Strong variations in the invariant occur on the nightside and after one drift period the particle "forgets" its initial 2nd invariant returning to the start point with the invariant significantly changed. It implies that the particles could not be trapped on such orbits for more than 2–3 drift rotations and can be

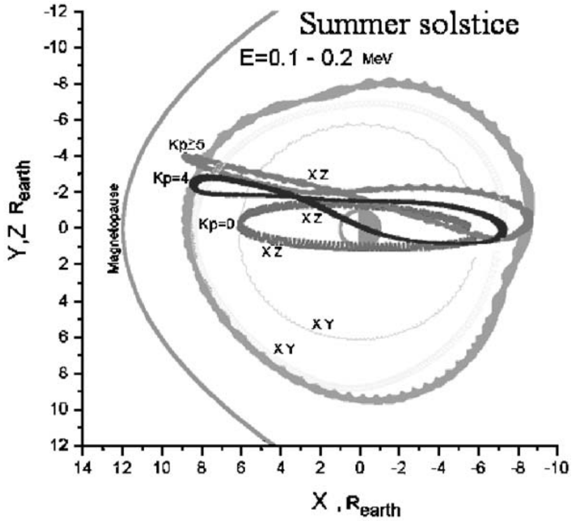

Fig. 9. The X, Y and X,Z projections in Cartesian coordinates of the proton drift orbits starting from the southern off-equatorial field minimum of Fig. 1 at $L\sim 8$–9, conserving zero 2nd adiabatic invariant in quiet and disturbed magnetosphere and showing a deflection of geomagnetic equatorial drift plane.

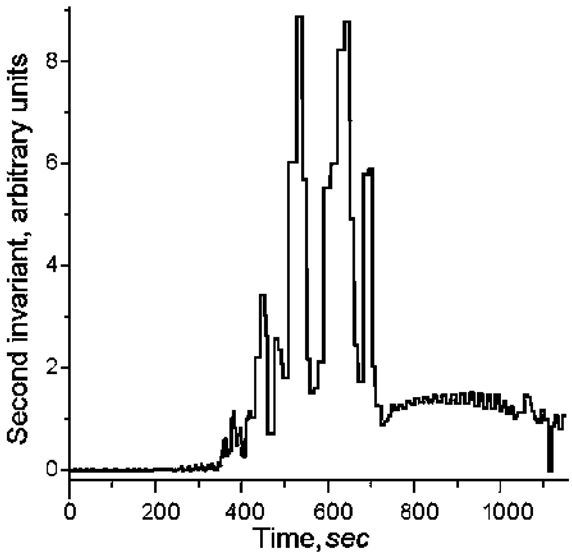

Fig. 11. The variations of the proton 2nd adiabatic invariant along the orbit shown in Fig. 10.

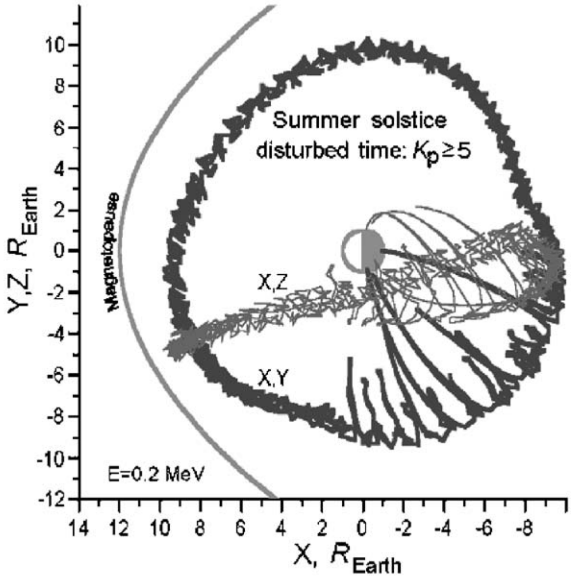

Fig. 10. The X, Y and X,Z projections in Cartesian coordinates of the proton drift orbits starting from the southern off-equatorial field minimum of Fig. 1 at $L\sim 10$–12 showing a violation of 2nd adiabatic invariant.

considered as quasi-trapped. Antonova et al. (2003) pointed out the possible violation of the second invariant for particle motion through dayside off-equatorial magnetic field minima.

At equinox time during disturbed conditions, both cusp belts are present. At quiet times, a proton starting its motion along the northern field minimum in the dayside sector drifts in a plane almost perpendicular to the geomagnetic equatorial plane. When it achieves the geomagnetic equatorial plane on the morning side it continues its regular drift in the geomagnetic equatorial plane to midnight, then, to the evening side and again returns to the starting point in the same perpendicular plane on the midday sector (Fig. 12). Similar orbits of protons starting in the southern minimum at midday are shown in Fig. 13 in three-dimensional format. These kind of particle trajectories were also described by Delcourt and Sauvaud (1998, 1999) and Öztürk et al. (2001).

5. Conclusion

Numerical modeling of energetic proton orbits in the empirical magnetic field model of Tsyganenko shows the existence of confinement zones in the cusp region of the Earth magnetosphere. The front side magnetic field lines far from the Earth's surface compressed by the solar wind possess two off-equatorial field minima in the northern and the southern hemispheres that can permit relatively stable confinement structures where energetic particles could be temporarily trapped for times from several minutes to hours and probably, days. The possibility of capture of energetic charged particles at these two magnetic field minima depends on the seasonal inclination of the Earth's rotation axis. The energetic protons could be relatively stably captured within the

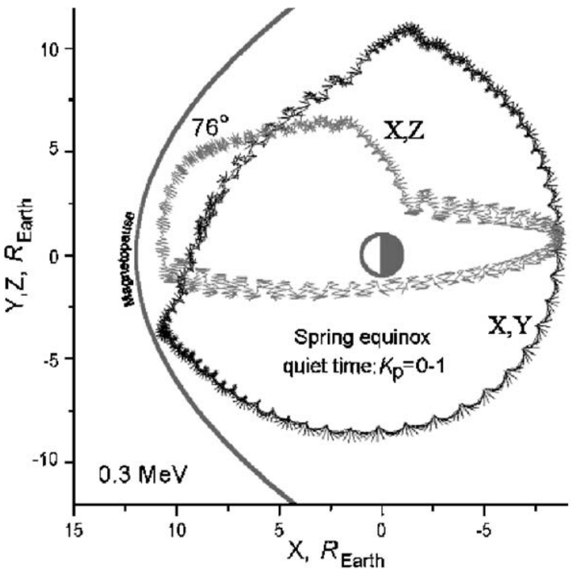

Fig. 12. The X,Y (black line) and X,Z (red line) projections of the proton drift orbit starting from the northern off-equatorial field minimum of Fig. 3 in equinox in quiet magnetosphere.

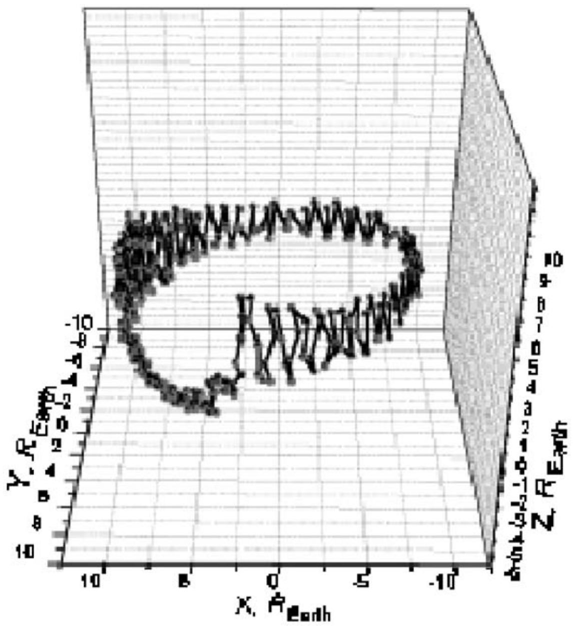

Fig. 13. 3D image of proton orbit starting from the southern off-equatorial field minimum of Fig. 3 during equinox in quiet magnetosphere.

northern cusp radiation zone during summer solstice and within the southern cusp during winter solstice. In equinox time the confinement zones exist in both hemispheres during disturbed magnetosphere, however they are weak. The zones form a kind of cusp radiation belts, they are very thin in latitude units (several latitudinal degrees). While during solstices one off-equatorial minimum region contains the trapped radiation, another off-equatorial field minimum shows the existence of another interesting feature: a deflection of geomagnetic equatorial plane on dayside distant magnetosphere.

In equinox time in quiet magnetosphere, similar deflection of the drift orbital planes is noted and the deflected plane is almost perpendicular to the geomagnetic equatorial orbital plane. The modeling results could be useful in the analysis of the observations of the trapped radiation at high latitudes. Further study of particle behavior in cusp confinement zones needs to consider in detail the magnetospheric electric fields and to define an accumulation coefficient of trapped radiation in the zones.

Acknowledgements

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