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Cusp confinement zones on quiet and disturbed dayside magnetosphere

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Abstract

The possibility of the charged particle confinement in the dayside regions of magnetosphere cusps is investigated. The analysis, on the basis of Tsyganenko geomagnetic field model, consisted of a numerical simulation of the single charged particle trajectories passing through the regions of the high latitude magnetic field minima. It is shown that the magnetic field topology with off-equatorial field minima itself does not guarantee a particle trap in cusps. In determined conditions relatively stable particle traps exist at different levels of magnetic disturbance, and the topology strongly depends on the seasonal influence. The particles captured in the zones form a kind of cusp radiation belt where particles drift with periods of several minutes conserving the 1st and 2nd adiabatic invariants. This capture and other features of the cusp trapped radiation are discussed.

Keywords: Geomagnetic field model; Polar cusp; Particle orbits; Magnetic traps

1. Introduction

The latest extraordinary discovery in the physics of magnetosphere is the trapping temporarily of the energetic heavy ions in the cusp polar region observed by the CAMMICE detector on board the POLAR satellite (Chen et al., 1997). The discovery was not unexpected. This was earlier considered in theoretical analysis by Antonova and Shabansky (1968), Shabansky and Antonova (1968), Shabansky (1971). Due to the solar wind pressure the remote magnetic field lines on the front side magnetosphere exhibit two minima in the geomagnetic field strength along the field line at high latitudes on either sides of the equator, opposite to the classical minimum in the geomagnetic equatorial region at lower magnetospheric L-shells. Now the existence of a two-minimum magnetic field line structure at the distance of ~7–10 R_E (marked with red in Fig. 1) is a well-known feature of the dayside magnetosphere, experimentally confirmed by Zhou et al. (1997) also with POLAR observational data. Between the magnetic field lines that closed on the dayside of the Earth and the tail field lines bent to the nightside an axially symmetric funnel-shaped structure, named a cusp, is located. These minima belong to the cusp regions. This structure with the geomagnetic field minimum could serve as a confinement zone for energetic particles. However, it was difficult to comprehend to idea that local minimum in

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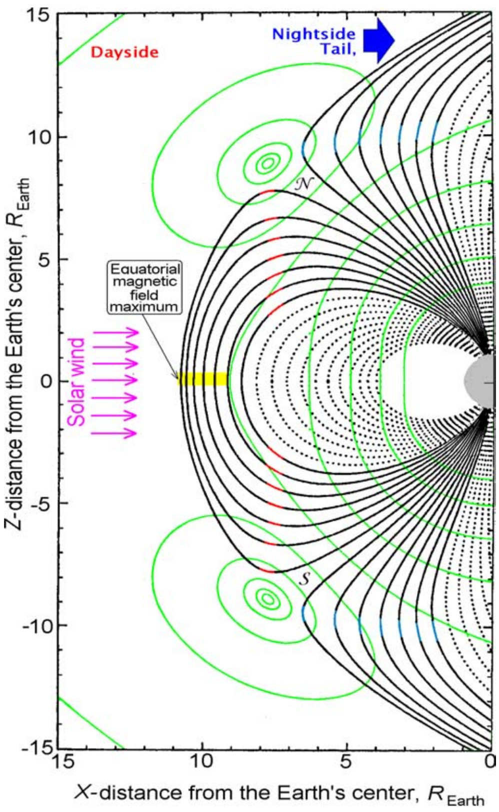

Fig. 1. Magnetic field lines in the noon meridian plane according to Tsyganenko-89 geomagnetic field model with 90° tilt and $K_p = 2$. N and S mark the northern and southern cusps, respectively. Black solid lines depict magnetic field lines with equatorial field maximum (marked with yellow) separating two local minimums (marked with red) at the closed lines. Field minimums at the unclosed lines are marked with blue. Black dotted lines depict field lines without the equatorial maximum. Green lines show contours of the constant magnetic field magnitudes separated by a factor 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the magnetic field strength exists on the field lines bent from the sunward side to night side (marked with blue in Fig. 1). Antonova and Shabansky (1968) using a simple two-dipole approximation, noted that a magnetic field strength maximum between the two off-equatorial minima serves as a bifurcation point ("branching point") for trajectories of some trapped particles in their drift around the Earth. As a result a corresponding drift shell ought to be represented with a double-connected surface, i.e., possessing a "hole" on its dayside, facilitating a mixture the tail and high latitude particle sources.

The cusp region possesses a weak magnetic field that represents an easy access the hot solar plasma and low energy particles to the Earth's magnetosphere and even upper residual atmosphere. The local minimum in the cusp region is a direct product of interaction of the solar wind with the magnetosphere and as such its existence and the parameters are controlled by the solar activity. Besides, the position and the parameters of the cusp depend on the tilt, the angle between Sun–Earth direction and the Earth's magnetic dipole axis. If the local field minimum exists around the cusp axis, it may form a confinement zone of trapped particles different from the classical radiation belt. Antonova et al. (2001)) studied analytically some properties of such a trap using a simple axially symmetric magnetic field model for the cusp vicinity. This dependence on the tilt was not examined in detail except for Shabansky (1971) who based on a two-dipole model found that the minimum becomes less pronounced with the increasing angle of tilt practically disappearing at the tilt of 90 ± 11°.

Here, the possibility of the formation of autonomous confinement zones in the cusp region is examined with the Tsyganenko models (T-89 and T-96) for the steady stable geomagnetic field (Tsyganenko, 1989, 1995). The models do not describe the large magnetic field turbulence in the cusp regions discovered by the POLAR team, (Chen et al., 1997; Chen et al., 1998; Chen and Fritz, 1998). The magnetospheric electric field influence is considered in our modeling, although we did not take into account the newly discovered variable electric fields observed by POLAR instruments (Chen et al., 2004) that can influence particle acceleration in the formation of the energetic trapped heavy ion population in the cusp region. The focus in our modeling is not to investigate the source of the cusp trapped radiation but the conditions for the existence of the cusp confinement zones through the tilt magnitude which produces noticeable seasonal variation of the zone parameters.

2. Formation of confinement zones in the cusp region

Fig. 2 shows two images of the same cusp funnel structure in the geomagnetic field lines at the summer solstice time at UT = 17:30, when the geographical north pole has a minimum inclination to the Sun and a tilt angle T between the Earth–Sun direction and the geomagnetic dipole axis which has the minimal magnitude of $T = 55.5°$. The lines are built utilizing the test code provided in the T-89 model package. In a winter solstice, at UT = 03:30, when geographic northern pole is far away from the Sun, the angle $T = 124.5°$. The intermediate position of $T = 90°$ corresponds to spring equinox at UT = 11:30, when the dipole axis is perpendicular to Sun–Earth direction.

Figs. 3(a) and (b), show the magnetic field strength along the magnetic field lines against the geodetic latitudes for spring equinox time and summer solstice time correspondingly. The lines are built for minimal (K_p = 0–1) and maximal ($K_p \geqslant 5$) levels of geomagnetic activity, which in the Tsyganenko model correspond, respectively, to values of 1 and 8 for the IOPT parameter. The lines are traced for various latitudes from the Earth's surface: the greatest latitude corresponds to the last closed dayside line; lines anchored at higher lati-

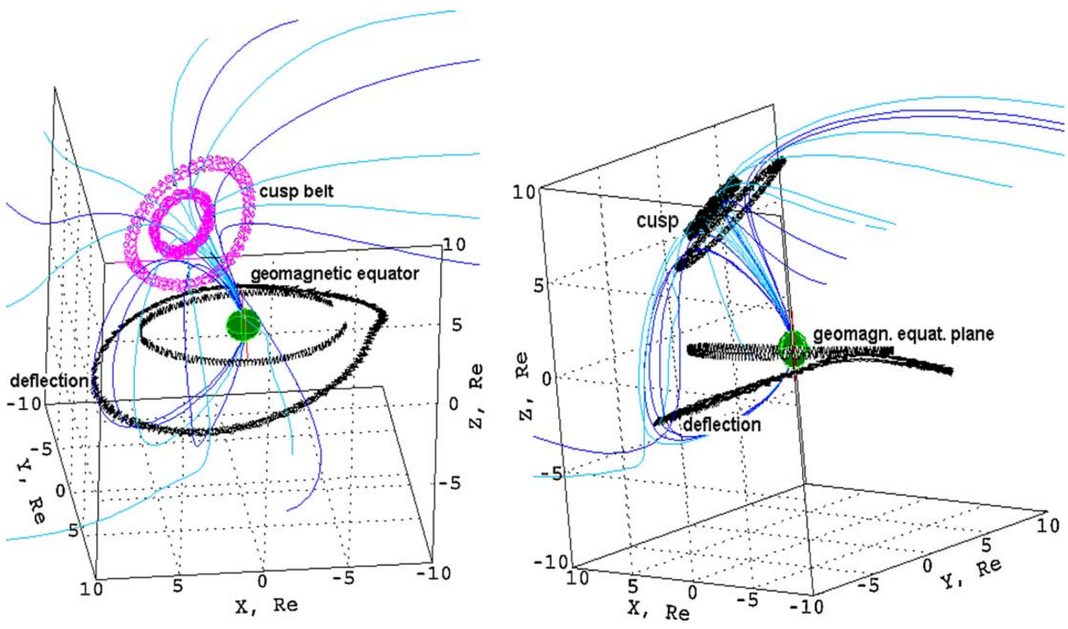

Fig. 2. The cusp funnel structure formed with the geomagnetic field lines in the summer solstice time and three-dimensional image of the 0.3 MeV proton orbit passing along the northern field line minimum in summer solstice in the disturbed magnetosphere. The lower orbit (deflection) belongs to proton passing through the southern field minimum.

tudes go to the tail, and the line anchored at the lowest latitude (Fig. 3(a)) exhibits only one field strength minimum. The field minima settle almost symmetrically relatively the equator. The local maximum and adjacent minima are located on the lines anchored between 73° and 80° of geodetic latitudes during quiet time (Fig. 3(a)). The minimum magnetic field strength reaches $\approx 5 \times 10^{-4}$ G for latitude of 80°. When the solar wind pressure increases the two minima structure shifts inwards the magnetosphere to latitudes between 71° and 75°. Two distinct field minima point to a possibility of existence of local magnetic traps, at high latitudes in the both hemispheres. The picture for an autumn equinox differs insignificantly from that for the spring one.

In summer solstice the picture becomes even more symmetric with increased solar wind pressure (Fig. 3(b)) exhibiting again two distinct minima in the both hemispheres, however in quiet magnetosphere the southern minima broaden significantly becoming less pronounced. The structures with minimum local magnetic field strength at high latitudes exist for any tilt both in quiet and disturbed conditions. This result differs from that for the two-dipole model, where it exists only for a tilt range reduced to 90° ± 11° (Shabansky, 1971).

It is important to underline that the presence of a local minimum on the closed lines (as in Fig. 3(a)) is only a necessary but not a sufficient condition for formation of the local confinement zone. Their existence in the cusp regions is checked by numerical simulation of orbits of protons within the energy range of 0.1–2 MeV starting from the point of local field minimum with the velocity vector condition $(\boldsymbol{V} \cdot \boldsymbol{B}) = 0$, i.e., with the pitch angle 90°. The simulation is based on the numerical solution of the full Lorentz force equation for a particle motion in geomagnetic and geoelectric fields. 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

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

where q, m, and $\boldsymbol{V}$ are particle charge, relativistic mass, and velocity and c is the speed of light. Eq. (1) is solved numerically applying the Runge-Kutta–Gill method with the Fortran code (Gusev and Pugacheva, 1982) having double and where necessary quadruple precision. For the geomagnetic field we use T-89 and T-96 field models. The electric fields consider both the corotation and the convection fields in the equatorial plane with the respective field potentials represented by $U_{\mathrm{cor}} = -CRe/R$ and $U_{\mathrm{V-S}} = -AR^2 \sin\phi$, of Volland–Stern model (Volland, 1978). The coefficient $C = 91.5$ kV and $A = 0.0449/(1 - 0.159K_{\mathrm{p}} + 0.009K_{\mathrm{p}}^2)^3$, in units of kV/Re^2; with Re representing the Earth's radius, R the radial distance from magnetic dipole center, and ϕ the azimuthal angle between the directions of the field vector and the sunward axis.

The electric field away from the Earth's equatorial plane is computed tracing the field potential from the equatorial plane to given space point along the neighboring magnetic field lines (Pugacheva et al., 2004).

A 3-D example of a confined trajectory in the cusp is shown in Fig. 2 for summer solstice time. The trajectories are frozen at the local field minima of the magnetic

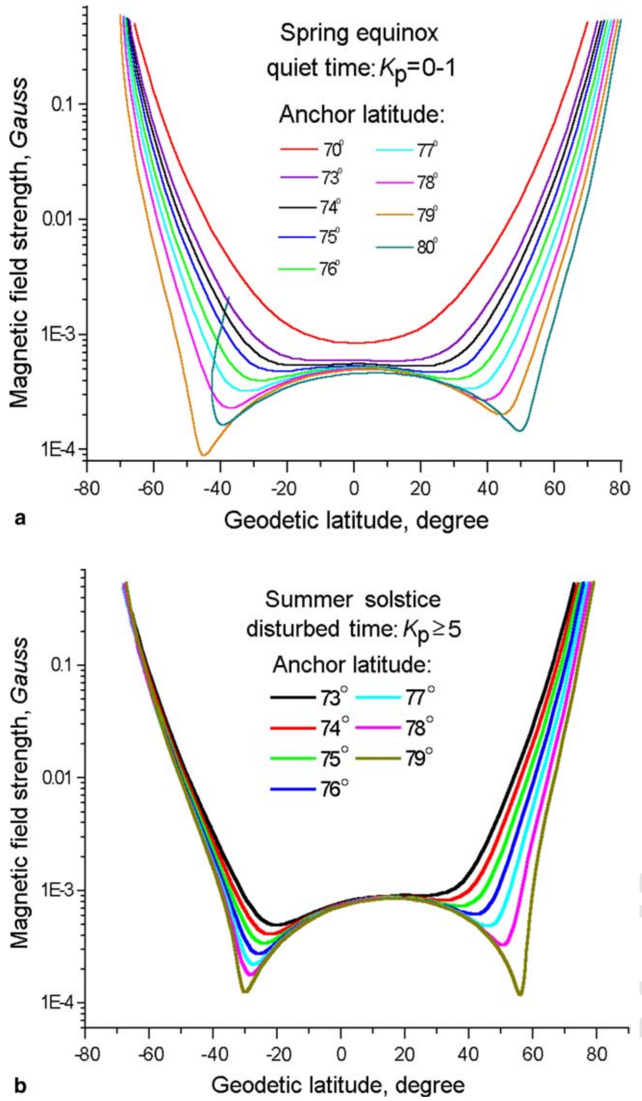

Fig. 3. The geomagnetic field strength along dayside field lines versus Cartesian latitudes for the lines anchored at different latitudes: (a) for equinox time in the quiet magnetosphere and (b) for summer solstice in the disturbed magnetosphere.

lines forming the cusp funnel, revealing a magnetic trap zone. During this solstice, the zone appears only in the northern hemisphere. For the orbits in Fig. 2, the closed trajectories occupy the dayside cusp region forming something like a shallow funnel covering ~5° latitudinal width and a large diameter of about 20 R_{Earth}. This local confinement zone is located within the latitudes of 79–83° in quiet magnetosphere shifting to the lower latitudes of 74–78° at disturbed times. However, the proton orbit test showed that in spring equinox two local confinement zones exist simultaneously but only in disturbed magnetosphere (Fig. 4, X, Z orbit projection is closed for $Z > 0$ and for $Z < 0$). In spite of during spring equinox time in quiet magnetosphere the field minima (Fig. 3(a)) are equally pronounced as in summer solstice in disturbed magnetosphere (Fig. 3(b)), they do not guarantee a particle trap zone there in the sense of closed region around a cusp. It means that a modeling of the field minima in polar cusp regions done in the past did not always signify the closed confinement zone existence. There might be done test with the real particle orbits in these zones.

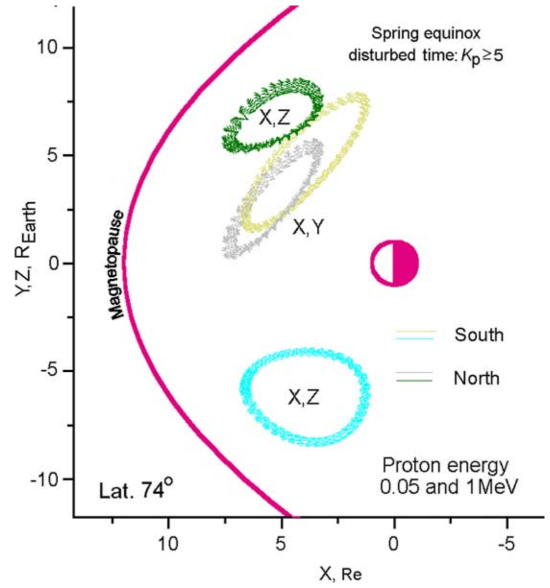

Fig. 4. The X, Y and X, Z projections in Cartesian coordinates of the 0.3 MeV proton orbits passing along the northern and southern field line minima in equinox time in disturbed magnetosphere.

In a winter solstice a rather pronounced confinement zone appears only around the southern cusp (Fig. 5; X, Z orbit projection is closed for $Z < 0$) and mostly in the disturbed magnetosphere (Pugacheva et al.,

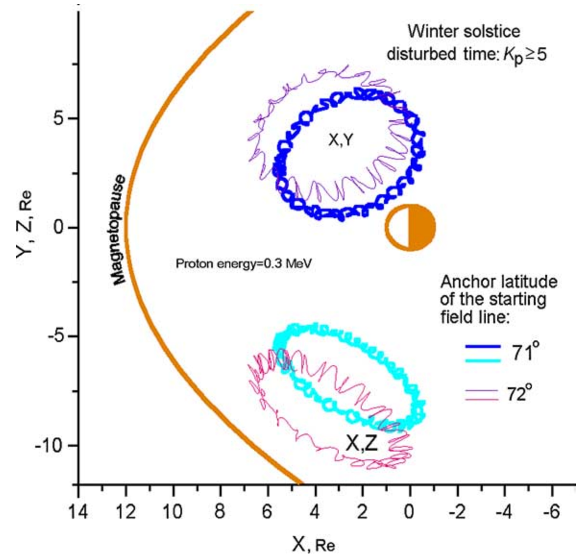

Fig. 5. The X, Y and X, Z projections in Cartesian coordinates of the 0.3 MeV proton drift orbits passing along the southern field line minimum in winter solstice in disturbed magnetosphere.

2005). During quiet time the width of the zone decreases to ≈1° in latitude.

The particle drift period around the cusp is about several minutes and the particles could drift for many periods within the zone perhaps, accumulating flux. Even protons of relatively higher energies can be held in that zone; the orbit remains closed for 2 MeV proton, while proton of 3 MeV energy escapes from the trap to infinity.

Due to the Earth's rotation, the confinement zone shifts to the other geodetic meridians subjecting the respective magnetic lines with frontal exposure to solar wind. This process of reconnection of the geomagnetic field lines possibly results to the appearance of intensive variable electric fields observed in POLAR satellite experiment. For fields of strength of about 100 mV/m (Chen et al., 2004), the trapped particles going through the long circular orbits as 20 R_{Earth} can be accelerated up to several MeV energy for during a drift period of several minutes.

The influence of the convection electric field on the process of capture in the cusp region was tested by tracing selected proton trajectories in the simultaneous presence of geomagnetic field (T-89 model for IOPT = 8) and electric field (Volland–Stern model with K_p = 5–8). At least for summer solstice we still observed the usual closed trapped particle trajectories.

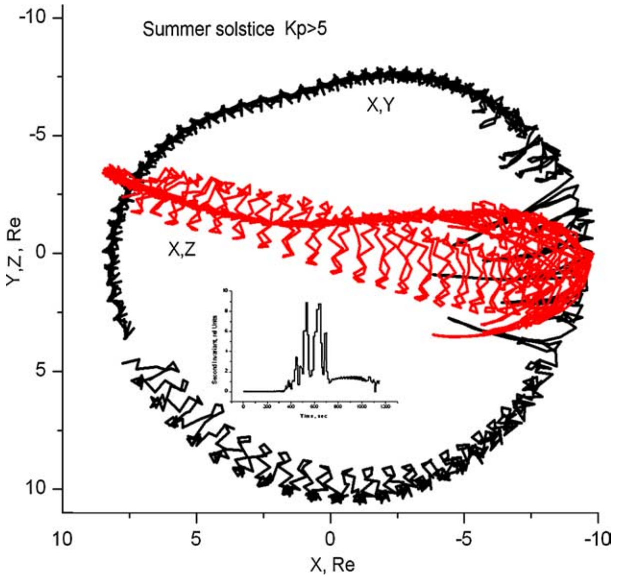

Fig. 6. The *X*, *Y* and *X*, *Z* projections in Cartesian coordinates of the proton drift orbits starting from the southern off-equatorial field minimum in summer solstice at *L* cong 10–12 showing a violation of 2nd adiabatic invariant.

3. Deflection of geomagnetic equatorial plane under the solar wind pressure

As we noted above an existence of a local minimum not always result in the formation of a local confinement zone. Nevertheless, the minimum significantly changes the behavior of the common radiation belt trapped particles passing through these local minima. For example, the behavior of the protons during summer solstice showed the possibility of confinement around the northern off equatorial field minimum. Further, we studied what happens with protons of hundreds of keV starting their orbits from the other off-equatorial field minimum in the southern hemisphere for $(\boldsymbol{V} \cdot \boldsymbol{B}) = 0$, i.e., with pitch angle equal to 90°. The orbit as shown in Fig. 2 (curve noted as deflection) do not create confinement zone around the southern cusp but trace the drift of the particles around the whole Earth. Here, on the night side the orbit resides in the common geomagnetic equatorial plane and when they approach the evening side, the particles begin to climb to higher latitudes reaching the culmination point on the noon side. In the dawn lobe they descend to lower latitudes returning to the geomagnetic equatorial plane. The trajectory plane (on the day side) describes a deflection from the geomagnetic equator plane at the angle determined by solar activity. The protons conserve their second invariant with pitch-angle near 90° when the orbit belongs to *L*-shells of values 8–9. For the particles drifting at higher *L*-shells 10–12, the second invariant is violated, as shown in Fig. 6. This effect was earlier considered by Shabansky (1971), and then by Antonova et al. (2001). The invariant suffers strong variations on the night side and it implies that particles could not be trapped in such orbits for more than 2–3 drift rotations and should be considered as quasi-trapped.

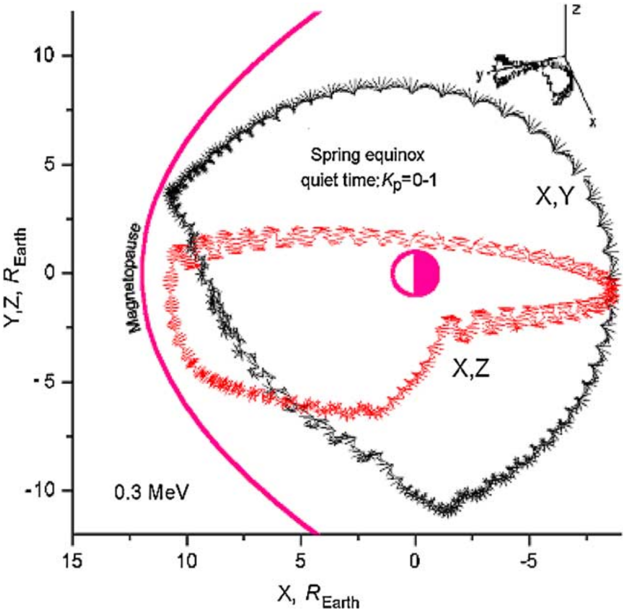

Fig. 7. The *X*, *Y* and *X*, *Z* projections of the proton drift orbit starting from the northern off-equatorial field minimum in equinox time in quiet magnetosphere; in the right top corner 3D image of proton orbit starting from the southern off-equatorial field minimum.

At equinox times, both cusp local belts exist only during disturbed magnetosphere conditions. At quiet times, a proton starting along the northern field minimum on the day side sector drifts in a plane perpendicular to the geomagnetic equatorial plane. As the proton approximates the morning side its motion gets a character of regular drift in the geomagnetic equatorial plane and continues until it approaches the day side from the evening lobe to the starting point (Fig. 7). Similar orbits are shown in the D3 image in the right corner of the same figure for particles starting in the southern minimum at midday. Similar trajectories were also predicted by Shabansky (1971) and studied by Delcourt and Sauvaud (1998, 1999).

4. Conclusion

In the frame of empirical Tsyganenko geomagnetic field model numerical simulations of energetic charged particle orbits reveals the existence of particle confinement zones in the polar cusp of the Earth's magnetosphere. The remote magnetic field lines compressed by the solar wind on the front side of the magnetosphere possess two high latitude field minima, in the northern and the southern hemispheres, which provide in determined conditions relatively stable particle magnetic traps. The existence of these field strength minima is a necessary, however, not sufficient condition for particle trapping which is not revealed with an analysis of the magnetic field topology alone. There must be done a particle orbit test.

The cusp confinement zones form a kind of funnel containing the trapped radiation. Energetic particles may be temporarily trapped there for times from several minutes to longer periods. This possibility of confinement depends on the seasonal tilt of the Earth's rotation axis. The energetic protons could be captured within the northern cusp radiation zone during summer solstice and within the southern polar cusp during winter solstice. In equinox more "shallow" confinement zones appear in both hemispheres in disturbed magnetosphere.

In addition to the trap during solstices at one hemisphere cusp, at the other corresponding off-equatorial field minimum a noticeable feature in disturbed magnetosphere is observed with a deflection of equatorial orbital motion plane on the day side. In equinox in the quiet magnetosphere, the deflected orbital plane on the dayside becomes almost perpendicular to the geomagnetic equator.

The magnetic fields in the regions of cusp minima are strongly variable according to POLAR satellite observations, which the Tsyganenko model does not predict. This and the variable electric fields which are also discovered with POLAR satellite instruments certainly could change the features of the phenomenon described here. However, we would like to establish the main characteristics of the cusp trap in the frame of the T model purposing later to analyze and to compare this model and those observed phenomena of particle trapping in cusp zones.

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