Geomagnetic Effects on Cosmic Ray Antiprotons

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Abstract
Experiments on the International Space Station (ISS) are soon expected to play a key role in cosmic ray research, in particular in the search for antimatter of cosmological origin. Using the trajectory-tracing technique with an advanced model of the quiescent and perturbed magnetospheric magnetic field we have studied the transport of cosmic ray antiprotons in near-Earth space. Results for a typical ISS position and specific viewing directions are compared with corresponding proton transport.

1 Introduction:

Experiments on the International Space Station (ISS) are soon expected to play a key role in cosmic ray research, in particular in the search for antimatter of cosmological origin. Using the trajectory-tracing method with an advanced model of the quiescent and perturbed magnetospheric magnetic field we investigate the access of charged particles to a spacecraft orbiting at 450 km altitude. Cutoff rigidities as a basic reference for charged particle access to the ISS during magnetically quiet and active times have been calculated by Smart, Shea, & Flückiger (1999a, b). In this paper we present results of trajectory calculations made for antiprotons. Cutoff rigidities for a typical ISS position, selected viewing directions, and two levels of geomagnetic activity are discussed and compared with the corresponding proton results.

2 Method:

The trajectory-tracing method employed was developed by Kobel (1990) and utilizes the Bulirsch-Stoer numerical integration technique (Stoer & Bulirsch 1980; Press et al. 1989) to minimize the number of steps required in a charged particle trajectory computation. The magnetic fields in the magnetosphere were a combination of the IGRF 1995 internal magnetic field (Sabaka, Langel, & Conrad 1997) and the Tsyganenko (1989) magnetospheric model combined by the method described by Flückiger and Kobel (1990). Cosmic ray trajectory calculations were initiated in a specified direction from a distance of 6821.2 km from the geocenter (450 km altitude above the average Earth with a radius of 6371.2 km). In this work "vertical" is the direction radial from the Earth center.

Cutoff rigidities were determined by calculating charged particle trajectories at discrete rigidity intervals starting with a rigidity value high above the highest possible cutoff and decreasing the rigidity to a value that assures that the lowest allowed trajectory had been calculated. As these calculations progress down through the rigidity spectrum, the results change from the easily allowed orbits to a complex structure of allowed, forbidden, and quasi-trapped orbits (loosely called penumbra) and finally to a set of rigidities where all trajectories intersect the solid Earth. As a result of the trajectory calculations we determined the calculated upper cutoff rigidity (R_U) which is the rigidity value of the highest allowed/forbidden pair of adjacent cosmic ray trajectories, the calculated lowest cutoff rigidity (R_L) which is the rigidity value of the lowest allowed/forbidden pair of adjacent cosmic ray trajectories, and an "effective cutoff rigidity" (R_C) that allows for the transparency of the penumbra (see Cooke et al. 1991, for definitions of cosmic ray cutoffs). Rigidity intervals of 0.01 GV were used for trajectories below R_U to provide a reasonable sample of the penumbra. The effective cutoff rigidity R_C was found by summing the allowed orbits through the penumbra as described by Shea, Smart, & McCracken (1965).

3 Results and Discussion:

The results presented in this paper were calculated for a magnetospheric configuration that has a high degree of symmetry in the geocentric solar magnetospheric (SM) coordinate system (21 March 1998, 23:59 UT, dipole tilt angle -2.5º). The location of the ISS was set arbitrarily to 45ºN, 180ºE.

Figure 1 illustrates the principal differences between the access of positively charged particles (left panel) and negatively charged particles (right panel) to the point of observation. In this figure the trajectories of cosmic ray particles with rigidity R = 5.11, 5.2, and 5.6 GV arriving from the vertical direction at the ISS are shown in a projection to the xy-plane of the SM coordinate system. The difference in the direction of the bending of the trajectories in the geomagnetic field according to the charge of the particles is of course obvious. It can also be seen that the trajectories of particles with the same rigidity but with different charge sign are not symmetric. Flückiger, Smart, & Shea (1983) have shown that the cutoff rigidities of mid-latitude neutron monitor stations are most sensitive to variations in the geomagnetic field at longitudes within ~90º to the east of these stations. For negatively charged particles the corresponding longitude region is west of the point of observation. Differences in the cutoff rigidities and in the penumbral structures for positively and negatively charged particles must therefore be expected due to the existing latitudinal and longitudinal inhomogeneities in the magnetospheric magnetic field. Also, the effect of local changes in the geomagnetic field during geomagnetic storms on the cutoff rigidities will depend on the charge sign of the particles.

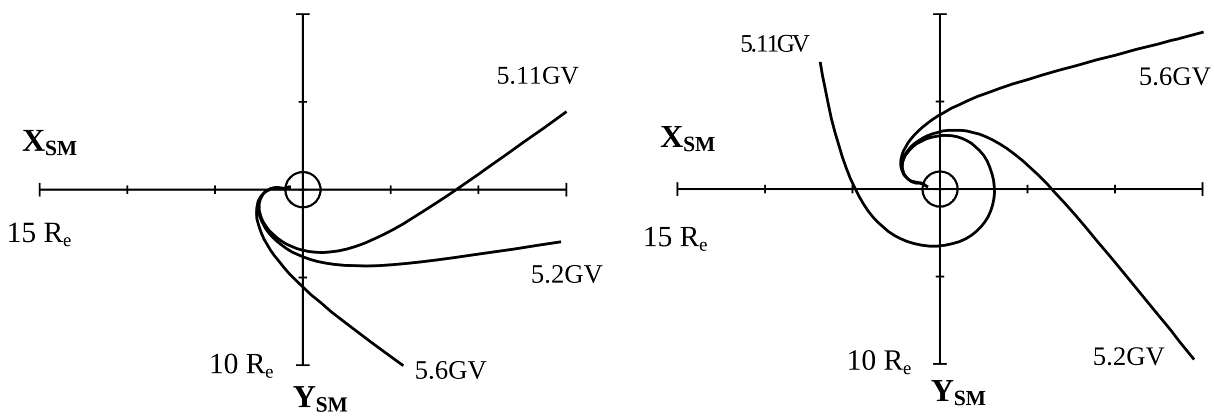

Figure 1: Comparison of trajectories of positive (left) and negative (right) particles with the same rigidity. The panels show a projection to the xy-plane of the solar magnetospheric (SM) coordinate system. The open circle in the center of the coordinate systems marks the Earth. For details see the text.

In figure 2 we show the penumbral structures at the specified ISS location for positive (left panels) and negative (right panels) particles of vertical incidence. Black areas and vertical lines represent forbidden trajectories while white areas and vertical lines represent allowed trajectories. Two levels of geomagnetic activity are considered: quiet (Kp=0, top panels) and disturbed (Kp=5, bottom panels). The results demonstrate that even if the main structure of allowed and forbidden bands looks similar for positive and negative particles, significant differences exist if the details are considered. It is also important to note that "forbidden trajectory" strictly means no direct access from space. Theoretically it is not impossible for an antiproton to arrive at the ISS from the vertical direction with a rigidity well below R_L. However this particle then cannot come from distant space but must originate e.g. from an interaction in the high atmosphere.

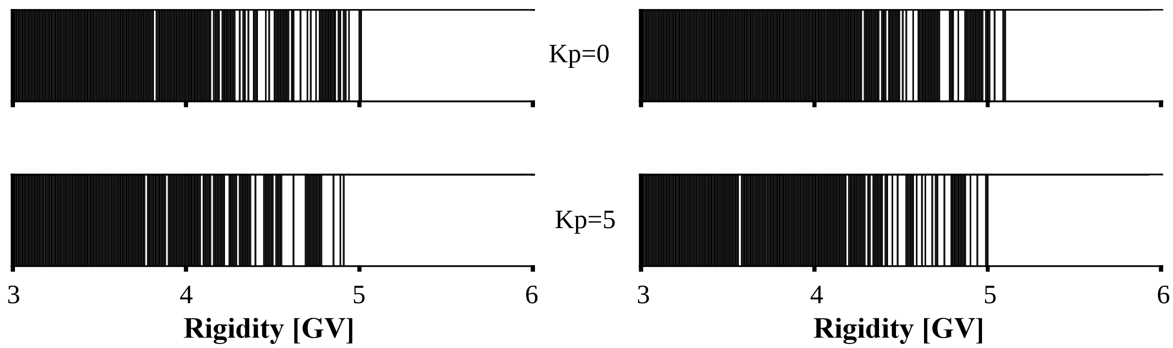

Figure 2: Penumbral structure for positive (left) and negative (right) particles arriving from the vertical direction at the specified ISS location. Black areas and vertical lines represent forbidden cosmic ray trajectories while white areas and vertical lines represent allowed trajectories. Top panels: quiet magnetosphere (Kp = 0); bottom panels: perturbed magnetosphere (Kp = 5). For details see the text.

Finally, an illustration of the dependence of the cutoff rigidities on the viewing direction is given in figure 3. The results for positive particles are again plotted on the left side, those for negative particles on the right side. The two panels show the cutoff rigidity values R_U (top curve), R_C (middle curve), and R_L (bottom curve) as a function of the zenith angle of the particle arrival direction in the east-west vertical plane. The results refer to quiet magnetospheric conditions (Kp = 0). The shaded area in the left panel for zenith angles >80ºE represents the shadow effect for the access of positive cosmic ray particles due to the solid Earth (see e.g. Humble, Smart, & Shea 1985). It is not impossible for positive cosmic ray particles to access the specified location from a 90ºE direction; however in order to get around the Earth shadow effect the rigidity required is more than 25 GV. For negatively charged particles (right panel) the Earth shadow effect is not visible in the range of zenith angles considered.

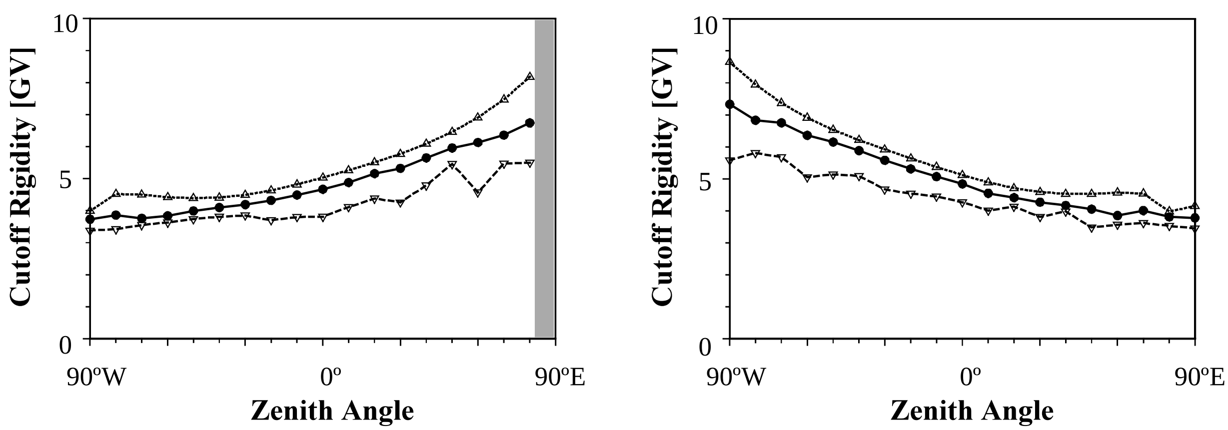

Figure 3: Cutoff rigidities R_U (top curves), R_C (middle curves), and R_L (bottom curves) as a function of the zenith angle for positive (left) and negative (right) particles arriving at the specified location from a direction in the east-west vertical plane. For details see the text.

4 Conclusions:

Positively and negatively charged particles arriving at a specific location at or near the Earth traverse considerably different regions of the magnetosphere, and therefore their transport characteristics, as e.g. the cutoff rigidities show significant differences. Størmer theory (Størmer 1955), in a coordinate system using a "proper" magnetic vertical direction (a radial direction from the dipole center), and "proper" magnetic north direction, has been shown to be extremely effective in ordering trajectory-derived cutoffs for positive particles. Smart & Shea (1967) also found that the McIlwain (1961) parameter is very useful in interpolating cutoff rigidities to other altitudes. Cutoff rigidity values calculated for antiprotons can be ordered and interpolated in the same way.

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References

Cooke, D.J., Humble, J.E., Shea, M.A., Smart, D.F., Lund, N., Rasmussen, I.L., Byrnak, B., Goret, P., & Petrou, N. 1991, Il Nuovo Cimento C, 14, 213
Flückiger, E.O., & Kobel, E. 1990, J. Geomag. Geoelect., 42, 1123
Flückiger, E.O., Smart, D.F., & Shea, M.A. 1983, J. Geophys. Res., 88, 6961
Humble, J.E., Smart, D.F., & Shea, M.A. 1985, Proc. 19th ICRC, 5, 340
Kobel, E. 1990, Lizentiatsarbeit, Physikalisches Institut, University of Bern
McIlwain, C.E. 1961, J. Geophys. Res., 66, 36814
Press, W.H., Flannery, B.P., & Vettering, W.T. 1989, Numerical Recipes (Cambridge: Cambridge Univ. Press)
Sabaka, T.J., Langel, R.L., & Conrad, J.A. 1997, J. Geomag. Geoelect., 49, 157
Shea, M.A., Smart, D.F., & McCracken, K.G. 1965, J. Geophys. Res., 70, 4117
Smart, D.F., & Shea, M.A. 1967, J. Geophys. Res., 72, 3447
Smart, D.F., Shea, M.A., & Flückiger, E.O. 1999a, paper SH3.6.28, Proc. 26th ICRC (Salt Lake City, 1999)
Smart, D.F., Shea, M.A., & Flückiger, E.O. 1999b, paper SH3.6.29, Proc. 26th ICRC (Salt Lake City, 1999)
Stoer, J., & Bulirsch, R. 1980, Introduction to Numerical Analysis, Chapt. 7 (New York: Springer-Verlag)
Størmer, C. 1955, The Polar Aurora, (Fair Lawn, N.J.: Oxford University Press)
Tsyganenko, N.A. 1989, Planet. Space Sci., 37, 5