Proceedings of ICRC 2001: 4056 © Copernicus Gesellschaft 2001

ICRC 2001

Geomagnetic cutoff Penumbra structure: Approach by transmissivity function

P. Bobik[1], **K. Kudela**[1], **and I. Usoskin**[2]

[1]Institute of Experimental Physics, SAS, Watsonova 47, 04353 Košice, Slovakia
[2]Sodankylä Geophysical Observatory, PO-3000, FIN-90014 Univesrity of Oulu, Finland

Abstract. Numerical tracing of cosmic ray trajectories in the model magnetospheric field is widely used to understand the "magnetospheric optics" of the Earth's magnetosphere for primary cosmic rays and their access to ground based observation sites. Recent review on the subject can be found, e.g. in (Smart et al., 2000). Penumbra structure is usually described as a system of allowed and forbidden trajectories (A,F) between low, R_L , and upper, R_U , cutoff rigidities. The probability of a particle in a given rigidity interval within (R_L,R_U) to access the position of a cosmic ray station, the transmissivity function TF, is deduced from the (A,F) structure which is dependent on the elementary step in rigidity for computations, on local time (if the external field is included) and on the geomagnetic activity level. We study TF using Tsyganenko'89 field model with rigidity steps $\Delta R=10^{-5}$ GV – 10^{-1} GV, for the high latitude Oulu site (65.05^o N 25.47^o E). We illustrate the penumbra structure in terms of the divergence of asymptotic direction of neighbouring allowed trajectories. The TF function weighted statistically by the Kp distribution over long time may serve as a tool for CR transparency characteristic at a particular station.

1 Introduction

The transparency of magnetosphere for cosmic rays is a subject of studies for long time. It is common to study transport of primary particles and consecutive production of secondaries above the site of a particular cosmic ray station by means of numerical back-tracing of the primary particle's trajectories in the model geomagnetic field starting from the site and inverting the sign of charge and velocity vector of particle. Progress in magnetospheric models and trajectory computations has been summarised recently by Smart, Shea and Flückiger (2000).

Correspondence to: K. Kudela (kkudela@kosice.upjs.sk)

In this paper we study in details the structure of penumbra which is described as a system of allowed (A) and forbidden trajectories (F) of particles whose rigidity is between low, R_L , and upper, R_U , cutoff rigidities. In addition to DGRF internal field models, external current systems are assuming an asymmetry of the magnetosphere (e.g. Danilova et al., 1991), changing the structure of allowed and forbidden trajectories within penumbra and shifting its range as well as the cutoff rigidities (R_L, R_C and R_U as defined by Cooke et al, 1991) to lower values with increasing the level of magnetospheric disturbance. Thus, at any particular station the transmissivity function, *TF(R,ΔR, t, Kp)*, defined as the probability of a primary particle with rigidity within the range (*R-d/2,R+d/2*) to access the site, depends on elementary step of computations ΔR, local time *t*, and geomagnetic activity level *Kp*. *d* is the width of the rigidity interval where the probability is calculated as the ratio of the number of allowed to all trajectories. Based on the TS89 model (Tsyganenko, 1989) we present here the average transmissivity function for a particular neutron monitor by averaging these functions over local times and over the *Kp* indices with their appropriate statistical weights corresponding to their distribution over 10 years.

2 Penumbra structure at different ΔR.

Figure 1 shows the transmissivity function for vertically incident particles for the high latitude neutron monitor station Oulu (65.05^o N 25.47^o E) for different values of computation steps ΔR. Figure 2 shows the corresponding structure of asymptotic directions in the penumbra for the best ΔR resolution.

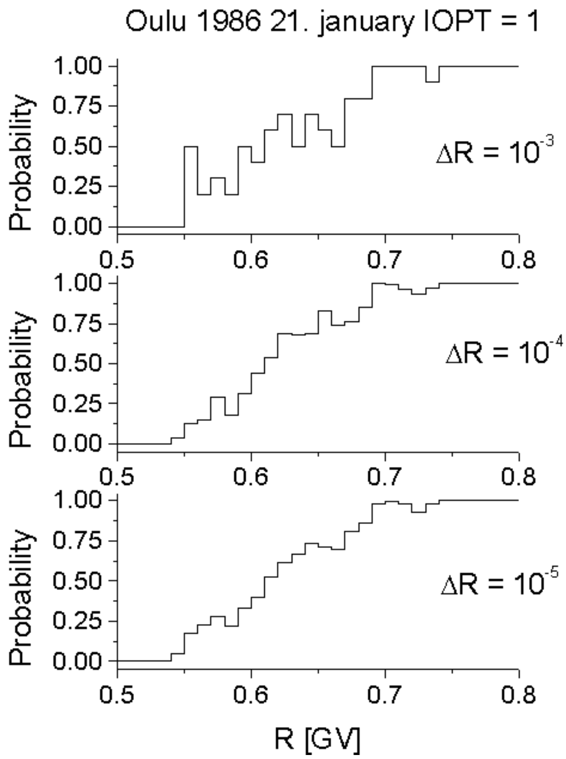

Fig 1. Results of computations of the transmissivity function for Oulu NM, as for 10 UT on January 21, 1986 using TS89 external field model, (low geomagnetic activity, IOPT=1). The elementary step for computations is (from top to bottom) $\Delta R = 10^{-3}$, 10^{-4} and 10^{-5} GV respectively. d=0.01 GV.

Figure 1 shows the effect of the rigidity resolution ΔR on TF when d is fixed (0.01 GV). Improvement of the rigidity resolution below 10^{-4} does not significantly change the shape of TF. Wide and random scatter of dα vs. R points in Figure 2 (upper panel) at R < 0.675 GV indicates an unstable structure of asymptotic trajectories, at least in this rigidity range. Above this rigidity, the complicated structure of asymptotics is interlaced with relatively narrow regions of R with regularly changing both longitudes and latitudes (e.g., 0.676-0.677 or 0.692-0.694 GV with a fine structure inbetween). Such a structure is not discernible in rougher computations (larger ΔR). A similar fine structure is observed at higher rigidities for the middle latitude station Lomnický Štít. We note that these "islands" of regularity correspond to the asymptotic directions in the day-side magnetopause for a particular day and local time. On the other hand, the penumbra does not display any regular structure if the asymptotic directions correspond to the night side. This is probably related to a more complicated trajectory of low rigidity particles in the geomagnetic tail and to the complicated geometry of the night-side magnetosphere (Pulkkinen and Tsyganenko, 1996). (In our calculations, we limited the size of the night-side magnetopause by 25 Earth radii. Varying the size between 24 and 26 Earth radii we found no significant change for the asymptotics structure.)

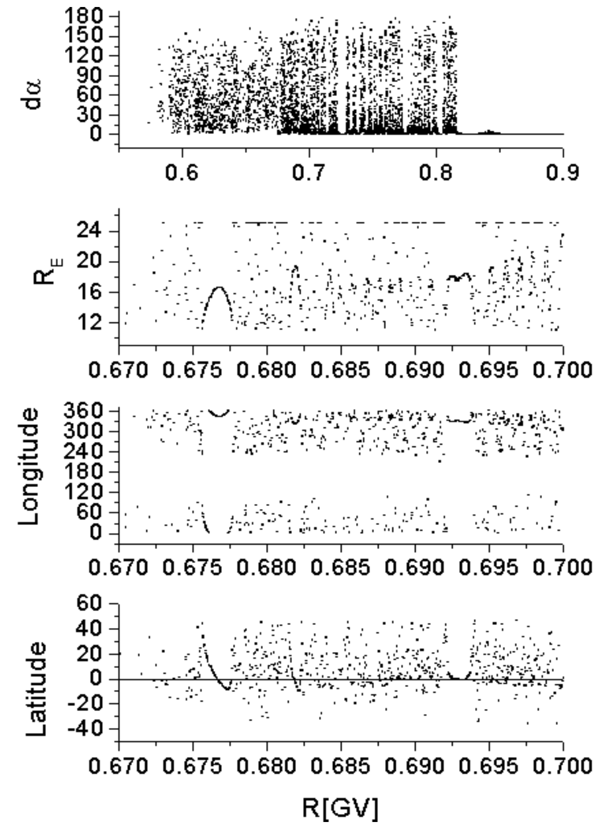

Fig. 2. Characteristics of the computed asymptotic directions for Oulu NM for $\Delta R = 10^{-5}$ GV. From top to bottom: the angle dα (in degrees) between the neighbouring allowed trajectories asymptotic directions; the geocentric distance (in R_E), longitude and latitude of the point of intersection of the allowed trajectory with the model magnetopause (using the model by Sibeck et al, 1987), respectively.

An important factor restricting the accuracy of low energy particle trajectory calculations is related to uncertainties of the magnetic field description (Smart et al., 2000). We made a set of computations for the Oulu position fixing the same date and time as well as the level of geomagnetic disturbance as described above and changing slightly the magnetic field vector **B** in Tsyganenko'89 model. Two simple variations of the model magnetic field **B** were adjusted: (1) at each step of the trajectory computation, a "new" value of **B** was obtained from the model value by scaling it with the factor f, and (2) at each step, a constant value of 10nT (-10 nT) was added to the model value of **B**. The calculated results of the corresponding changes of vertical cutoff rigidities R_c and R_u are listed in Table 1 for the Oulu NM. One can see that changes of the effective (R_C) and the upper (R_U) cutoff rigidities are roughly proportional to the variations of **B** (i.e., 5% increase of the magnetic field results in an ~5% increase of the rigidity cutoff). Note that the model magnetic field uncertainties can be large, parcticularly in the midnight sector (Pulkkinen and Tsyganenko, 1996), which accordingly results in large uncertainties of the computed fine structure of the penumbra.

Table 1. Changes of vertical cutoff rigidities (Oulu NM) for different variations of the model magnetic field (see text).

R_c [GV]	R_u [GV]	Variation in model **B**
0.590	0.682	(2) -10 nT
0.581	0.674	(1) f=0.95
0.605	0.677	(1) f=0.99
0.613	0.725	No change
0.617	0.732	(1) f=1.01
0.638	0.761	(1) f=1.05
0.631	0.726	(2) +10 nT

3 Averaged transmissivity function.

Although the computations of TF described above show clear effects of numerical and magnetic field related uncertainties, they have little real influence in the case of high-latitude Oulu NM whose penumbra rigidity range is close to or within the atmospheric cutoff range (for protons). However, the obtained results can be quite important for low altitude nearly polar orbiting satellites. On the other hand, the penumbra structure is important for the middle latitude ground stations with rigidity cutoffs being well above the atmospheric cutoff.

A structure of TF for Lomnický Štít (LS, geographic location 49.20°N, 20.22°E) was examined in detail for the entire range of parameters. We performed calculations for all local time sectors with the step of 1 hour, and for 6 different levels of geomagnetic activity parameter of the Tsyganenko´89 model. In the upper panel of Figure 3, computed values of the effective rigidity cutoff for LS are plotted for the same epoch as for Oulu. The lower panels of Fig. 3 show the averaged over local time transmissivity functions of LS for different levels of geomagnetic disturbance. Apparently, the structure of TF strongly depends on the level of geomagnetic disturbances. For specific occasions, the time (UT) should be adjusted. In particular, a large increase of count rate at LS was observed at around 9 UT on March 31, 2001 due to a very strong geomagnetic disturbance (Kp up to 9-). Using the specific TF for that particular time we calculated the transparency of magnetosphere. The corresponding increase of count rate at Lomnický Štít was calculated (using the specific yield function of NM by Nagashima et al. (1989)) to be about 4.2 % with respect to the pre-event level which is in good agreement with the observed increase of 5.22 per cent at that NM.

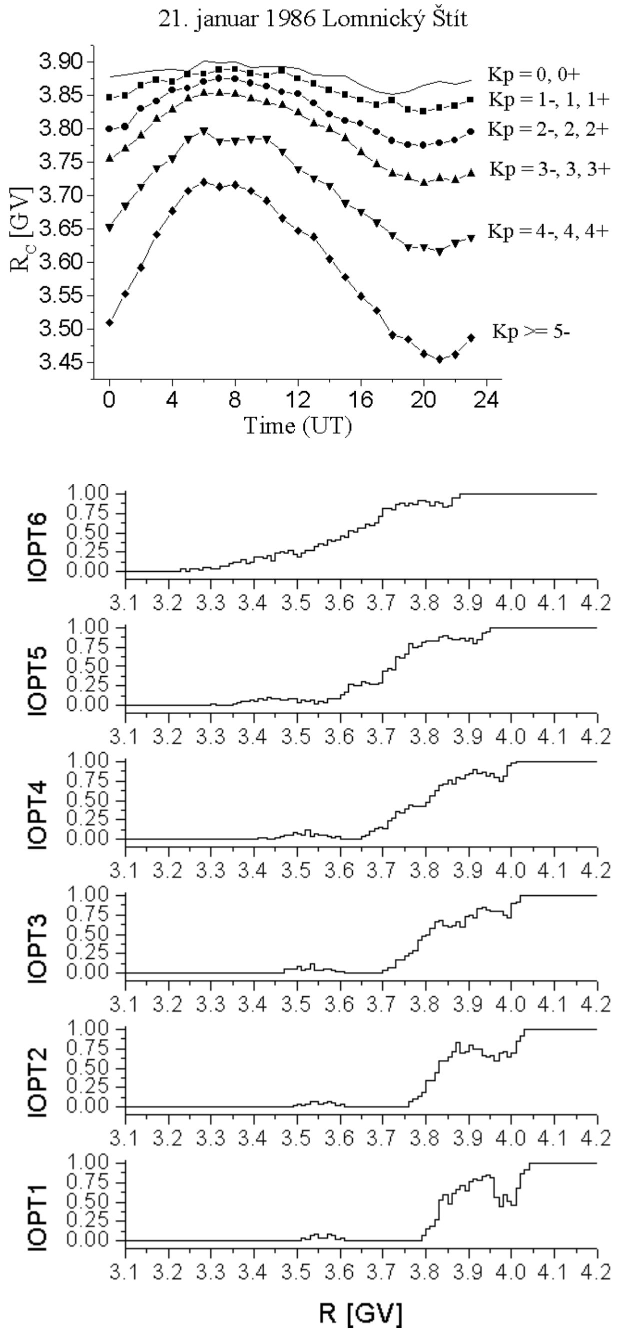

Fig. 3. Uppert panel: The effective cutoff rigidity, R_C, as a function of UT and of the geomagnetic activity index, Kp for vertical directions. Lower panels: the transmissivity functions at Lomnický štítt averaged over all UT, using Tsyganenko´89 model for different levels of geomagnetic activity.

In order to study long term variations of cosmic rays, one needs to know TF averaged over times longer than one day. Such a long-term averaged transmittivity function is shown in Fig. 4 (lower panel) for Lomnický Štít. The long-term averaged TF was obtained by weighted averaging of the transmittivity functions calculated for given Kp (Fig. 3, lower panels). The statistical weight shown in Fig. 4 (upper panel) is proportional to the frequency of occurrence of time intervals with the given value of Kp-index. This histogram is a result of statistical analysis of the geomagnetic data since 1980 available at http://nssdc.gsfc.nasa.gov/omniweb. The corresponding long-term averaged values of the vertical rigidity cutoff for Lomnický Štítt are R_L=3.46635 GV, R_U=3.92591 GV and R_C=3.80186 GV, for the low, upper and effective cutoffs, respectively. Note that the cutoffs did not change significantly during the last 20 years on that station (Kudela and Storini, 2001).

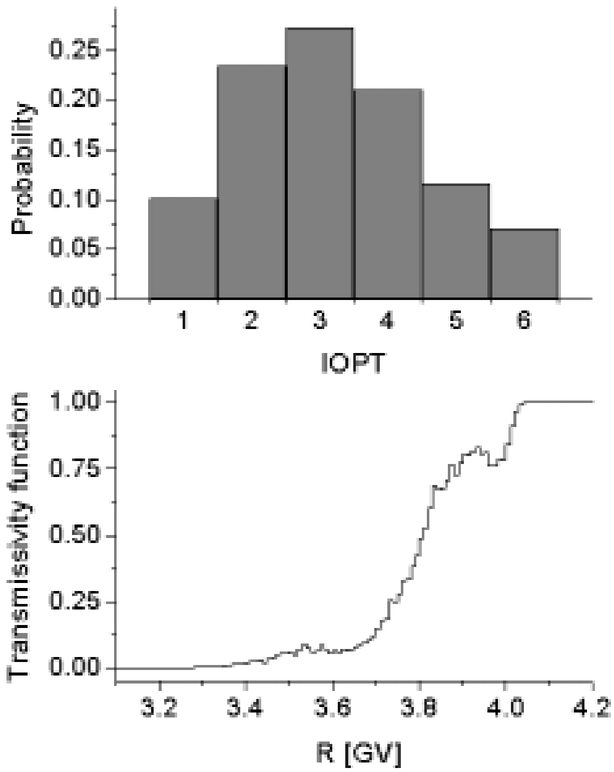

Fig. 4. Upper panel: histogram of relative frequencies of occurrence of time intervals with a given value of the parameters IOPT in Tsyganenko'89 model during the period 1980-1990. Lower panel: the long-term averaged transmisivity function for Lomnický Štít.

4 Concluding remarks

We have studied the stability of the fine structure of geomagnetic rigidity cutoff penumbra for high latitude (Oulu) and middle-latitude (Lomnický Štít) cosmic ray stations using the Tsyganenko'89 model geomagnetic field. The stability of computed particle's trajectories was tested against both small variations of the model magnetic field and against the rigidity resolution. We found that the elementary computation step over rigidity of $\Delta R=10^{-3}$ GV is sufficient to estimate the flux of primary cosmic rays entering the atmosphere above the station and to reproduce adequately its variation depending on the time of day and the level of geomagnetic activity. Results obtained with high rigidity resolution ($\Delta R=10^{-5}$ GV) show that the computed trajectories ending in the day-side magnetopause are quite stable and reliable. However, those trajectories which are connected to the night magnetopause are very unstable and, therefore, the corresponding fine structure of the penumbra is unreliable.

For the purpose of the study of long-term variations of cosmic rays at middle latitude station, we used a concept of the long-term averaged transmissivity function.

Acknowledgement. The work has been supported by Slovak garnt agency VEGA, project 1147 and by the cooperation between University of Oulu, Finland and IEP SAS Košice, Slovakia.

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