Comparison of cosmic ray cutoff rigidities as calculated with two empirical magnetospheric models for the extreme event of November 2003

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Abstract. Cosmic ray cutoff rigidities control the access of CR particles to any location in the magnetosphere, and, hence, they are an important factor of space weather. The accuracy of determining geomagnetic cutoff rigidities is closely connected with the magnetospheric model used for the calculations. Using the trajectory tracing method and the Tsyganenko magnetospheric Ts01 and Ts04 models, we estimated changes in the effective vertical cutoff rigidities for a highly stormy period of November, 2003. The Ts01 and Ts04 models were developed on the basis of the same experimental data. The results of our calculations are compared with the geomagnetic cutoff rigidities obtained by the spectrographic global survey method using the neutron monitor world-wide network data. Our calculations were performed for several stations with quiet cutoff rigidities covering the major part of the cutoffs influenced by the geomagnetic field. Comparison shows that the cutoff rigidities calculated by using the Ts01 and Ts04 models differ by 0.8–0.9 GV during the main phase of the storm.

1. Introduction

Cosmic rays (CR) passing through the magnetosphere are affected by its magnetic field, and the CR geomagnetic cutoff rigidities (geomagnetic thresholds) and asymptotic directions change during disturbances in the solar wind and the magnetosphere. This leads to a redistribution of charged particle fluxes in the magnetosphere. When geomagnetic cutoff rigidities become lower, an access of additional particle fluxes to the Earth’s surface is allowed. Geomagnetic cutoff rigidities are typically estimated theoretically by the method of trajectory tracing of charged particles in the magnetic field of the magnetosphere described by any selected model [McCracken, 1962; Shea et al., 1965; Dorman et al., 1972]. The theoretical accuracy of the cutoff rigidity calculation is determined by the accuracy of the magnetospheric field model [Smart et al., 2000]. Thus, investigations of variations in cosmic rays give valuable information on the magnetospheric magnetic field that can be used as an independent information source for testing of magnetospheric models [Tyasto et al., 2004; Tyasto et al., 2008].

In the last decade, a number of empirical models using magnetic field measurements by spacecrafts [Tsyganenko, 2002a; 2002b, Tsyganenko et al., 2003; Tsyganenko and Sitnov, 2005] have appeared in addition to purely theoretical models of the magnetospheric magnetic field. These models are attractive because they are based on direct magnetic field satellite measurements, on the one hand, and use the modern ideas on the major external sources of the magnetospheric magnetic field, on the other hand.
In the study reported here, two empirical models, i.e., TS01 (also known as T03) and TS04, were used to calculate the geomagnetic cutoff rigidities and compare them with the cutoffs obtained by the spectrographic global survey method based on the CR neutron monitor data of the world-wide network during the stormy period of 18-21 November, 2003 [Dvornikov et al., 1986; Dvornikov and Sdobnov, 1991; Dvornikov and Sdobnov, 2002]. Both models are based on the data sets of satellite magnetic field measurements, the same for both models [Tsyganenko et al., 2003; Tsyganenko and Sitnov, 2005].

2. The TS01 and Ts04 magnetospheric models and methods

The magnetospheric Ts01 and Ts04 models were developed on the database of satellite magnetic field measurements during 37 geomagnetic storms with Dst < −65 nT. The models use different approximations of the same experimental data sets [Tsyganenko, 2002a, 2002b, Tsyganenko Tsyganenko et al., 2003; Tsyganenko and Sitnov, 2005]. The Ts01 model focuses on describing the middle magnetosphere under specified conditions in the solar wind (SW) and the interplanetary magnetic field (IMF).

Both models have the following principal magnetic field sources: symmetrical and partial circular currents, tail currents of the magnetosphere, longitudinal Region 1,2 Birkeland currents, and magnetopause currents. To limit the field within the magnetosphere, a block that describes the field of interaction that represents the effect of the interplanetary magnetic field penetration inside the magnetosphere is included. The interaction field is presented in the form of a homogeneous magnetic field proportional to the cross-sectional component and directed along it.

The input parameters determining the impact of interplanetary conditions on the magnetosphere in both models are the Dst variation, the solar wind density Nsw and velocity Vsw, and the interplanetary magnetic field (IMF) components.

The total magnetic field from the external sources is approximated by a linear combination of vectors from these basic sources, and the state of the magnetosphere is assumed to be a predictable function of conditions in the solar wind, i.e., the same magnetosphere configuration and the same response of the magnetospheric currents are expected under the same conditions and their identical changes.

Magnetospheric disturbances are treated as dynamic phenomena the nature of which is determined by not only current conditions in the SW and IMF, but also the inertia of the magnetosphere, the "memory" effects, i.e., the finite response time of the magnetosphere associated with the processes of accumulation and dissipation of energetic trapped particles in the magnetosphere [Tsyganenko et al., 2003; Tsyganenko and Sitnov, 2005].

The Ts01 model simulates delays in the magnetosphere response to changes in the SW and IMF empirically [Tsyganenko, 2002a, Tsyganenko 2002b, Tsyganenko et al., 2003], i.e., the fields from separate external field sources (except the magnetopause currents) are parametrized by sliding time averages of the geoeffective SW which are calculated for preceding one-hour intervals instead of current values.

Averaging smooth out fast and sudden variations in external parameters and result in more gradual variations in the model field with a characteristic timescale of growth (or decline) on the order of 1 hour comparable with the observed response times of the magnetosphere. As parameters that determine the intensity of the SW effects in the TS01 model, special indexes G2 and G3 calculated as hourly averages $\langle VB_s \rangle$ and $\langle NVB_s \rangle$, respectively, are used. Here $N$ and $V$ are the solar wind density and velocity, respectively, and $B_s$ is the south IMF component. The model also takes into account the effects of nonlinear saturation of the currents.

The Ts04 model focuses on a large-scale description of temporal changes in the magnetospheric currents. Each source is described by his own response to the SW and IMF effects and by its own relaxation time and saturation threshold because simple averaging fails to take into account the fact that different magnetic field sources have different response and decay times. The symmetric ring
current requires at least a few hours to build up and 1-2 days to decay, while the tail currents change much more quickly.

A typical response time of the tail lobe field to SW pressure impulses is only a few minutes [Tsyganenko et al., 2003], though the response times to the southward change in the IMF $B_z$ can be as long as 2–3 hours. So every source of external fields of the Ts04 model is defined by a separate variable calculated as a time mean from the geoeffective parameter combination $N\nabla V B$ [Tsyganenko and Sitnov, 2005]. The dynamics of each source is the result of a competition between the solar wind influence and internal dissipation in the magnetosphere. Like in the Ts01 model, all quantitative characteristics of the model current systems, including their quiet magnitudes, geometries, variations in input functions, time decays and saturation thresholds, are obtained in the TS04 model by minimizing deviations of the model fields from the fields observed during 37 geomagnetic storms.

In the study, theoretical geomagnetic cutoff rigidities were calculated by integrating charged particle trajectories in magnetic fields of the TS01 and Ts04 models [Dorman et al., 1972] for the disturbed period of 18–21 November, 2003 [Ermolaev et al., 2005]. Experimental geomagnetic cutoff rigidities were calculated by the spectrographic global survey method using the data of the world-wide network of cosmic ray stations [Dvornikov and Sdobnov, 2002].

3. Results and discussion

3.1. Time variations in geomagnetic cutoff rigidities

Time variations in theoretical geomagnetic cutoff rigidities $\Delta R_{\text{eff,TS01}}$ (circles) and $\Delta R_{\text{eff,TS04}}$ (triangles) calculated by using the TS01 and TS04 models and also experimental $\Delta R_{\text{sgs}}$ (crosses) are shown in figure 1 for stations Tokyo (a), Almaty (b), Rome (c), Irkutsk (d), Moscow (e), and Hobart (f). Cutoff rigidity changes relative to the quiet level of 12 October, 2003, were obtained for each hour of the storm as in [Tyasto et al., 2008] (quiet-time geomagnetic cutoff rigidities were 11.02 GV for Tokyo, 6.19 GV for Almaty, 6.08 GV for Rome, 3.25 GV for Irkutsk, 2.10 GV for Moscow, and 1.75 GV for Hobart). The quiet cutoff rigidities of these stations occupy the major part of the cutoff interval influenced by the geomagnetic field. Figure 1 (lower part) shows geomagnetic $Kp$ and $Dst$ indexes and solar wind velocity $V_{sw}$ and density $N_{sw}$.

It is evident from figure 1 that, as expected, a maximal decrease in the cutoff rigidities coincides in time with the main phase of the magnetic storm [Tyasto et al., 2008]. Figure 1 also demonstrates that there is a difference between $\Delta R_{\text{eff,TS01}}$ and $\Delta R_{\text{eff,TS04}}$, which is especially pronounced during the main phase of the storm. The difference between the $\Delta R_{\text{eff,TS04}}$ and $\Delta R_{\text{eff,TS01}}$ curves does not exceed $-0.3$ GV till ~16 UT at Tokyo and till ~17-19 UT on 20 November, 2003 at other stations when the storm is already in its most active phase and the $Dst$-index is below ~368 nT. The most significant differences between the $\Delta R_{\text{eff,TS04}}$ and $\Delta R_{\text{eff,TS01}}$ curves are observed for the period from 15 UT on 20 November to 03 UT on 21 November, 2003, when $Dst = -200$ nT (the differences were ~0.6–0.7 GV for Tokyo, Alma-Ata and Rome, and ~0.7–0.9 GV for Irkutsk, Moscow and Hobart). The differences between the $\Delta R_{\text{eff,TS04}}$ and experimental $\Delta R_{\text{sgs}}$ curves also reach ~0.9 GV, as seen in figure 1 (~18 UT at Tokyo, ~21 UT at Irkutsk, ~22 UT at Hobart).

It should also be noted that the maximum geomagnetic cutoff rigidity decreases of the Ts04 model do not coincide with the $Dst$-index minimum; they occur at different hours of the $Dst$ decrease phase at different stations. Attention should also be paid to an extremely weak decrease in the cutoff rigidities at Tokyo, which did not exceed 0.3 GV during such a severe storm. Thus, in spite of the fact that the only distinction between the models is the use of different approximations, the experimental data being the same, significantly differing cutoff rigidities are obtained for the period of a strong $Dst$-variation.
3.2. Relation between the theoretical and experimental geomagnetic cutoff rigidities

Figure 1. Cosmic ray cutoff rigidities during the storm of November, 2003, for stations Tokyo (a), Almaty (b), Rome (c), Irkutsk (d), Moscow (e), and Hobart (f) ($\Delta R_{\text{eff}}^{\text{Ts01}}$ — circles, $\Delta R_{\text{eff}}^{\text{Ts04}}$ — triangles, $\Delta R_{\text{crc}}$ — crosses).

Table 1 presents correlation coefficients between the cutoff rigidities $\Delta R_{\text{eff}}^{\text{Ts01}}$ and $\Delta R_{\text{eff}}^{\text{Ts04}}$ (K01-04) and their correlation with the experimental thresholds $\Delta R_{\text{sgs}}$ (K01-$K_{\text{sgs}}$) and (K04-$K_{\text{sgs}}$). It is evident from table 1 that the correlation between the changes in the geomagnetic cutoff rigidities in the Ts01 and Ts04 models is quite high (0.8–0.9). The correlation between the experimental $\Delta R_{\text{sgs}}$ and theoretical (K04-$K_{\text{sgs}}$) cutoff rigidities is somewhat lower for the Ts04 model than for the TS01 one for all stations and the lowest correlation is for Tokyo (0.56). This can be explained by very low $\Delta R_{\text{eff}}^{\text{Ts04}}$ (less than 0.3 GV) and different time behaviors of $\Delta R_{\text{eff}}^{\text{Ts04}}$ and $\Delta R_{\text{sgs}}$. 
Table 1. Coefficients of correlation of $\Delta R_{\text{eff}T_01}$ with $\Delta R_{\text{eff}T_04}$ (K01-04), $\Delta R_{\text{eff}T_01}$ with $\Delta R_{\text{sgs}}$ (K01-K$_{\text{sgs}}$), and $\Delta R_{\text{eff}T_04}$ with $\Delta R_{\text{sgs}}$ (K04-K$_{\text{sgs}}$).

|        | Tokyo | Almaty | Rome | Irkutsk | Moscow | Hobart |
|--------|-------|--------|------|---------|--------|--------|
| K01-04| 0.80  | 0.88   | 0.93 | 0.91    | 0.96   |        |
| K01-K$_{\text{sgs}}$ | 0.81  | 0.92   | 0.92 | 0.95    | 0.93   | 0.88   |
| K04-K$_{\text{sgs}}$ | 0.56  | 0.73   | 0.79 | 0.84    | 0.89   | 0.87   |

Figure 2 shows correlations between theoretical $\Delta R_{\text{eff}T_01}$ (triangles, solid line) and $\Delta R_{\text{eff}T_04}$ (squares, dashed line) and experimental $\Delta R_{\text{sgs}}$ cutoff rigidities and the curves that approximate these relations for each station. As can be seen from figure 2, the correlation between the theoretical $\Delta R_{\text{eff}}$ and experimental $\Delta R_{\text{sgs}}$ for the Ts01 model differs substantially from that for the Ts04 model; the regression lines are close to each other at very low $\Delta R_{\text{sgs}}$ and diverge as $\Delta R_{\text{sgs}}$ increases. The regression lines for $\Delta R_{\text{eff}T_01}$ for all stations are markedly lower than for $\Delta R_{\text{eff}T_04}$. The divergence is the largest for Tokyo and smaller for higher latitudes.

The question arises as to what model gives a more adequate description of the magnetic field of the magnetosphere during the magnetic storm of November 2003. Higher correlation coefficients between $\Delta R_{\text{eff}T_01}$ and experimental $\Delta R_{\text{sgs}}$ during the magnetic storm of November, 2003, suggest that the Ts01 model that describes the middle magnetosphere under specified perturbed conditions in the solar wind is more correct than the Ts04 model that describes the time evolution of large-scale current systems.

3.3. Relation between the theoretical geomagnetic cutoff rigidities and Dst-variation and interplanetary parameters

Table 2 summarizes correlation coefficients between theoretical $\Delta R_{\text{eff}T_04}$ and $\Delta R_{\text{eff}T_01}$ and Dst-variation, solar wind velocity $V_{\text{sw}}$ and density $N_{\text{sw}}$, IMF Bz and By components, and solar wind dynamic pressure. It follows from Table 2 that the correlation coefficients between the cutoff rigidity changes derived from the Ts04 model and Dst are rather high for all stations (0.77–0.89), though they are somewhat lower than those for the Ts01 model (0.97–0.99).

The IMF components which are among input parameters for the Ts01 and Ts04 models can manifest themselves in the geomagnetic cutoff changes to a greater or lesser degree. Table 2 shows the degree of connection between the geomagnetic cutoffs $\Delta R_{\text{eff}T_04}$ and $\Delta R_{\text{eff}T_01}$ and IMF Bz and By components. $\Delta R_{\text{eff}T_04}$ is more closely related to Bz than $\Delta R_{\text{eff}T_01}$ at all stations, except Tokyo, where the situation is opposite (see table 2: the correlation coefficient between $\Delta R_{\text{eff}T_01}$ and Bz (0.64) is higher). The correlation between the theoretical cutoffs and By does not exceed 0.3 for Ts01 and 0.13 for Ts04. It is clear from table 2 that By affects only slightly the theoretical cutoffs in both models. It also follows from table 2 that the correlation between $\Delta R_{\text{eff}T_04}$ and solar wind velocity $V_{\text{sw}}$ is very weak (the correlation coefficient is as low as 0.11). The correlation coefficients $\Delta R_{\text{eff}T_01}$ and $\Delta R_{\text{eff}T_04}$ with Nsw are in the limits 0.68–0.70 and 0.49–0.66, respectively.

The connection between the solar wind dynamic pressure $P_{\text{dyn}}$ and geomagnetic cutoffs $\Delta R_{\text{eff}T_04}$ and $\Delta R_{\text{eff}T_01}$ is rather pronounced, it is 0.49–0.64 and 0.58–0.62, respectively. Comparison of the correlation coefficients between the geomagnetic cutoffs and Nsw and $V_{\text{sw}}$ leads to the conclusion that the magnetosphere size during the storm of November, 2003, was mainly determined by the solar wind pressure, the leading role in which was played by the Nsw density.
Figure 2. Relation between ΔReffTs04 (triangles, solid line) and ΔReffTs01 (squares, dashed line) and ΔRsgs for stations: Tokyo (Т), Almaty (AA), Rome (R), Irkutsk (I), Moscow (M), and Hobart (H).
Table 2. Coefficients of correlation between $\Delta R_{eff}^{}$Ts04 (numerator) and $\Delta R_{eff}^{}$Ts01 (denominator) and Dst variation and solar wind parameters

| Station | Dst  | Bz    | By   | Nsw  | Vsw  | Pdyn |
|---------|------|-------|------|------|------|------|
| Tokyo   | 0.77/0.99 | 0.43/0.64 | 0.03/0.29 | 0.49/0.69 | 0.05/0.12 | 0.49/0.60 |
| Almaty  | 0.84/0.99 | 0.80/0.67 | 0.02/0.29 | 0.63/0.69 | 0.01/0.11 | 0.59/0.60 |
| Rome    | 0.88/0.98 | 0.84/0.70 | 0.13/0.30 | 0.66/0.68 | 0.05/0.11 | 0.61/0.58 |
| Irkutsk | 0.86/0.98 | 0.80/0.71 | 0.03/0.27 | 0.62/0.70 | 0.001/0.09 | 0.61/0.62 |
| Moscow  | 0.88/0.98 | 0.84/0.71 | 0.05/0.25 | 0.66/0.70 | 0.05/0.10 | 0.61/0.61 |
| Hobart  | 0.89/0.97 | 0.73/0.70 | 0.02/0.18 | 0.66/0.69 | 0.03/0.10 | 0.64/0.62 |

4. Conclusions

1. Comparison of the geomagnetic cutoff changes during the magnetic storm of November, 2003, calculated in the magnetic fields of two magnetospheric models Ts01 and Ts04 that use different approximations of the same experimental database of satellite magnetic field measurements has shown that the Ts01 model that describes the middle disturbed magnetosphere is in better agreement with the experimental cutoff rigidities than the Ts04 model that describes the time evolution of the large-scale current systems of the magnetosphere.

2. Analysis of the correlation and regression relations between the geomagnetic cutoffs and interplanetary parameters and Dst variation leads to the conclusion that the geomagnetic cutoff rigidities $\Delta R_{eff}^{}$Ts01 better correlate with Dst, Bz, and Nsw and, in general, are more “sensitive” to changes in the interplanetary parameters than $\Delta R_{eff}^{}$Ts04.

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