Variations in solar wind parameters and cosmic ray cutoff rigidities during strong geomagnetic disturbances

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Abstract. Relations between geomagnetic cutoff rigidities of cosmic rays (CR) and solar wind parameters during several strong geomagnetic storms and a moderate storm of solar cycle 23 are investigated. It is shown that dynamic processes in the magnetosphere affected by the solar wind plasma and interplanetary magnetic field are major reasons for the cutoff rigidity changes that lead to CR flux variations in the magnetosphere and on Earth's surface. Theoretical geomagnetic cutoff rigidities calculated by using the magnetospheric Tsyganenko TS01 model and experimental thresholds obtained by the spectrographic survey method were used for analysis.

Keywords: Cosmic rays; Cutoff rigidity; Geomagnetic storms; Magnetospheric Models

Introduction

Variations in the solar wind density and velocity and interplanetary magnetic field cause changes in the intensity and spatio-temporal structure of the magnetospheric magnetic field. These variations in the magnetospheric magnetic field lead to changes in the trajectories of charged particles, i.e., changes in the asymptotic directions of CR arrival, and the geomagnetic cutoff rigidities (geomagnetic thresholds) which control the arrival of particles at a given point of the Earth. Each direction of the particle arrival at each geographic point at the Earth's surface is characterized by its own geomagnetic cutoff rigidity (Dorman, Smirnov, and Tyasto 1973; Dorman, 2009). Therefore, during interplanetary disturbances changes in the solar wind velocity, density, and frozen-in magnetic field give rise to changes in the planetary distribution of the CR geomagnetic cutoff rigidities.

Major features of the magnetospheric dynamics associated with the solar wind pressure on the magnetopause and also growth or decay of basic magnetospheric current systems are bound to manifest themselves in the CR geomagnetic thresholds (Tsyganenko, 2002a, 2002b; Tsyganenko, Singer, and Kasper, 2003).

In this paper, the relation between variations in geomagnetic cutoff rigidities and solar wind density, velocity, and dynamic pressure during strongly disturbed periods of some magnetic storms are considered.

Data and Methods

Theoretical effective vertical geomagnetic thresholds were calculated for a number of cosmic ray stations by integrating trajectories of charged particles in the magnetic field of the empirical magnetospheric Ts01 model (Tsyganenko, 2002a, 2002b; Tsyganenko, Singer, and Kasper, 2003). Experimental geomagnetic thresholds were obtained by the spectrographic global survey (SGS) method by using the data of the world-wide network of cosmic ray stations Dvornikov and Sdobnov (2002). The magnetic field of the Tsyganenko Ts01 model is a sum of the main geomagnetic field from internal sources and the magnetic field from external sources (magnetospheric current systems) (Tsyganenko 2002a, 2002b; Tsyganenko, Singer, and Kasper. 2003). The main geomagnetic field from internal sources was represented by the International Geomagnetic Reference Field (IGRF) model for epoch 2000 and was extrapolated to the storm periods by taking into account secular variations (http//www.ngdc.noaa./gov/IAGA//vmod/igrf.html).

The investigations were carried out for strongly disturbed periods of magnetic storms of the 23rd solar cycle of 7–14 November 2003, 7–8 and 9–13 November 2004, and 15–19 May 2005 and for the moderate magnetic storm of 9–15 January 1997 (Tyasto, Danilova, and Sdobnov, 2011; Tyasto et al., 2008, 2009, 2012). The quiet-time geomagnetic thresholds at cosmic ray stations Tokyo, Alma-Ata, Rome, Irkutsk, Moscow, and Hobart cover the range from 1.75 GV (Hobart) to 11.0 GV (Tokyo), i.e., the main range in which the geomagnetic field affects cosmic rays. A quiet pre-storm period was chosen for each storm, and changes in geomagnetic thresholds relative to the quiet-time thresholds were determined. The quiet–time geomagnetic thresholds were found to differ by not more than 0.01 GV for the strong storms and by not more than 0.05 GV for the moderate storm of 1997.

It should be reminded that fundamentally different methods were used to calculate the geomagnetic thresholds, i.e., the method of trajectory tracing in the magnetic field of the magnetospheric model based on satellite magnetic field measurements and the spectrographic global survey (SGS method) of the data of the world-wide network of cosmic ray stations.

Results and Discussion

Table 1 lists extremum magnitudes of interplanetary parameters and Dst-variations during the magnetic storms of interest.

As one can see from Table 1, the storms considerably differ in the solar wind density Nsw (from 17.6 to 74.8 1/cm^3) and velocity Vsw (from 468 to 959 km/s) and also Bz (from 14.9 to –50.9 nT) and By (positive magnitudes range from 13.9 to 39.6 nT, negative magnitudes range from –13.7 to –39.6 nT) components of the interplanetary magnetic field IMF. The differences in the Kp level for strong storms of 2005, 2004, and 2003 are small.

Relation between variations in the solar wind density Nsw and ΔRef and ΔRsgs

Table 2 lists correlation coefficients between variations in the solar wind density Nsw and variations in the theoretical ΔR_{ef} (numerators) and experimental ΔR_{sgs} (denominators) geomagnetic thresholds. It is evident from Table 2 that the level of correlation of Nsw with ΔR_{ef} and ΔR_{sgs} considerably varies (from K_{sgs}~0.1 and less to K_{ef}~0.7). This relation is most pronounced for the storm of 7–8 November 2004, for which the correlation coefficients between Nsw and ΔR_{ef} and ΔR_{sgs} are related as ~0.5–0.6/0.6–0.7 and also for the storm of 7–14 November 2003 (~0.7/0.4–0.6). The correlation coefficients between ΔR_{ef} and ΔR_{sgs} and Nsw for one and the same storm do not exhibit a large difference and are nearly independent of the station latitude. However, the correlation coefficients K_{sgs} between Nsw and ΔR_{sgs} for 15–19 May 2005 and 7–8 November 2004 are somewhat higher than K_{ef} between Nsw and ΔR_{ef}. On the contrary, for the storm of 18–24 November 2003 the correlation between Nsw and ΔR_{ef} is higher than that between Nsw and ΔR_{sgs}. The correlation between Nsw and ΔR_{ef} and ΔR_{sgs} for the storm of 9–13 November 2004 is very poor (K_{sgs}<0.2) and the correlation between Nsw and ΔR_{ef} and ΔR_{sgs} for the storm of 9–15 January 1997 is not high but significant.

Relation between solar wind velocity Vsw and ΔRef and ΔRsgs

Table 3 summarizes correlation relations between variations in the theoretical ΔR_{ef} and experimental ΔR_{sgs} geomagnetic thresholds and solar wind velocity Vsw. As one can see from Table 3, the character of correlation of ΔR_{ef} and ΔR_{sgs} with Vsw somewhat differs. The correlation between Vsw and ΔR_{ef} and ΔR_{sgs} for the storms of 15–19 May 2005, 7–8 November and 9–13 November 2004 (K>0.5) is rather good and the correlation for the storm of 7–14 November 2003 and the moderate storm of 9–15 January 1997 (K<0.2) is low for all stations except Tokyo. The correlation coefficients between ΔR_{sgs} and Vsw at the low-latitude station Tokyo for all the storms except that of 7–8 November 2004 are low (K_{sgs}<0.22).

Relation between solar wind dynamic pressure P_{dyn} and ΔRef and ΔRsgs

Table 4 lists correlation coefficients between ΔR_{ef} and ΔR_{sgs} and solar wind dynamic pressure P_{dyn}.

It is evident from Table 4 that ΔR_{ef} and ΔR_{sgs} correlate very poorly with the variations in the dynamic pressure for the storms of 15–19 May 2005 and 9–13 November 2004 (K<0.25). The highest correlation coefficient is observed between P_{dyn} and ΔR_{ef} for the storm of 7–14 November 2003 (K_{ef}~0.6), for other storms it does not exceed ~0.4. The correlation between the dynamic pressure and ΔR_{sgs} for station Tokyo is K_{sgs} ~ 0.2–0.3 for all the storms. Note that in some cases, e.g., for the storm of 7–8 November 2004, the correlation coefficients between P_{dyn} and ΔR_{sgs} are higher than those between P_{dyn} and ΔR_{ef}.

The correlation relations we obtained (see Tables 2–4) lead to the conclusion that the correlation between the geomagnetic thresholds and dynamic pressure is, on the whole, lower than the correlation between the geomagnetic thresholds and the solar wind density or velocity. During some storms the geomagnetic thresholds have high correlation coefficients with solar wind density or velocity. Thus, the contributions of the dynamic pressure and also of solar wind density or velocity into the geomagnetic thresholds can be traced not for all the storms of interest. Probably, this can be explained by specific features of the model.

The Ts01 model does not take into account the dependence of dynamic pressure variations on the IMF orientation: the magnetospheric boundary is compressed or extended without changing its shape in response to variations in pressure P_{dyn} with the linear coefficient χ=(Pd/$\langle Pd \rangle$)^k, where $\langle Pd \rangle$ is the average pressure and k is the free parameter estimated by the least squares method (k~0.158) (Tsyganenko 2002a, 2002b; Tsyganenko and Sitnov, 2003). Negative Bz leads to a more appreciable broadening of the nightside magnetopause tail. However, in order to take into account the tail broadening, recalculation of screening fields is needed. Therefore, the variations in the dynamic pressure manifest themselves mainly in the magnetosphere sizes, and the IMF effect on the magnetopause shape is neglected in the Ts01 model.

Conclusions

It has been shown that the geomagnetic thresholds of cosmic rays during some storms have high correlation coefficients with solar wind density or velocity. The correlation between the geomagnetic thresholds and dynamic pressure is, on the whole, lower than the correlation with the solar wind density or velocity. The main factor in the Ts01 model responsible for the magnetopause size (and, hence, contribution of magnetopause currents) is the average solar wind dynamic pressure P_{dyn}. Therefore, in the case of strong and fast variations in the solar wind pressure, density, and velocity, the difference from the average pressure and, hence, the average position of the magnetospheric boundary will be considerable. This can explain a low correlation between P_{dyn} and the theoretical geomagnetic thresholds ΔR_{ef}, but it hardly explains a low correlation between P_{dyn} and the variations in experimental thresholds ΔR_{sgs}. Probably, the contributions of solar wind density, velocity and dynamic pressure to cosmic ray geomagnetic thresholds depend on the type of the solar wind responsible for a magnetic storm Yermolaev et al. (2010).

Table 1. Extremum magnitudes of interplanetary parameters and Dst-variations during the magnetic storms of interest

	Parameter	15–19 May 2005	7–8 November 2004	9–13 November 2004	18–24 November 2003	9–15 January 1997
1.	Dst_{min}, nT	–263	–373	–289	–472	–64
2.	$B_{z\,min}$, nT	–24.7	–44.9	–24.7	–50.9	–14.9
3	B_y, nT	34.1/–17.7	38/–19.8	13.9/–30.7	39.6/–19.8	13.9/–13.7
4.	V_{max}, km/s	959	719	810	704	468
5.	N_{max}, cm^{-3}	17.6	64.5	19.7	20.5	74.8
6.	Kp	8.3	8.7	8.7	8.7	6.0

Table 2. Correlation coefficients K_{ef} between theoretical ΔR_{ef} and experimental ΔR_{sgs} and Nsw

	Station	15–19 May 2005 Kef/Ksgs	7–8 November 2004 Kef/Ksgs	9–13 November 2004 Kef/Ksgs	18–24 November 2003 Kef/Ksgs	9–15 January 1997 Kef/Ksgs
1.	Tokyo	0.15/0.27	0.54/0.59	0.17/0.10	0.68/0.37	0.41/0.26
2.	Alma-Ata	0.22/0.28	0.56/0.68	0.13/0.004	0.68/0.46	0.41/0.37
3.	Rome	0.24/0.28	0.60/0.68	0.07/0.005	0.67/0.47	0.30/0.38
4.	Irkutsk	0.25/0.24	0.55/0.66	0.15/0.06	0.69/0.56	0.36/0.35
5.	Moscow	0.23/0.27	0.59/0.66	0.05/0.06	0.69/0.56	0.35/0.22
6.	Hobart	0.17/0.36	0.58/0.69	0.14/0.03	0.68/0.55	0.12/0.20 *

The sign (*) means that the data are given for the Newark station the geomagnetic threshold of which for the storm of interest is very close to the threshold for Hobart (see also Tables 3 and 4)

Table 3. Correlation coefficients K_{ef} between theoretical ΔR_{ef} and experimental ΔR_{sgs} and Vsw

	Station	15–19 May 2005 Kef/Ksgs	7–8 November 2004 Kef/Ksgs	9–13 November 2004 Kef/Ksgs	7–14 November 2003 Kef/Ksgs	9–15 January 1997 Kef/Ksgs
1.	Tokyo	0.69/0.22	0.77/0.74	0.60/0.08	0.06/0.08	0.19/0.01
2.	Alma-Ata	0.63/0.53	0.80/0.84	0.59/0.60	0.05/0.15	0.11/0.03
3.	Rome	0.63/0.55	0.83/0.85	0.64/0.62	0.05/0.16	0.15/0.04
4.	Irkutsk	0.61/0.63	0.81/0.83	0.57/0.63	0.04/0.14	0.20/0.05
5.	Moscow	0.65/0.58	0.85/0.83	0.68/0.62	0.04/0.12	0.18/0.05
6.	Hobart	0.67/0.44	0.80/0.84	0.59/0.62	0.05/0.17	0.12/0.06 *

Table 4. Correlation coefficients K_{ef} between theoretical ΔR_{ef} and experimental ΔR_{sgs} and $\mathbf{P_{dyn}}$

	Station	15–19 May 2005 Kef/Ksgs	7–8 November 2004 Kef/Ksgs	9–13 November 2004 Kef/Ksgs	7–14 November 2003 Kef/Ksgs	9–15 January 1997 Kef/Ksgs
1.	Tokyo	0.14/0.21	0.36/0.33	0.07/0.20	0.59/0.28	0.36/0.30
2.	Alma-Ata	0.05/0.13	0.38/0.46	0.11/0.25	0.60/0.35	0.40/0.39
3.	Rome	0.02/0.02	0.38/0.46	0.19/0.24	0.58/0.36	0.28/039
4.	Irkutsk	0.03/0.05	0.37/0.49	0.08/0.16	0.61/0.45	0.32/0.28
5.	Moscow	0.04/0.09	0.38/0.50	0.22/0.15	0.61/0.47	0.31/0.19
6.	Hobart	0.14/0.20	0.40/0.51	0.09/0.18	0.61/0.46	0.08/0.16 *

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