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Influence of the Solar Wind and Geomagnetic Activity Parameters on Variations in the Cosmic Ray Cutoff Rigidity during Strong Magnetic Storms

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Abstract—The correlation between the variations of geomagnetic cutoff rigidity ΔR and interplanetary parameters and the *Dst* index of geomagnetic activity during one moderate and six strong storms of solar cycles 23 and 24 has been calculated. The ΔR values have been obtained with two methods: (1) the spectrographic global survey method (SGS), in which the determination of the cutoff rigidity R_{SGS} is based on observational data from the neutron monitor network, and (2) a method in which the particle trajectories are calculated numerically in a model magnetic field of the magnetosphere to determine the cutoff rigidity R_{eff}. In general, the results obtained by the two methods are in close agreement. The *Dst* index of geomagnetic activity has the greatest effect on ΔR, and the correlation increases with storm intensity. The sensitivity of ΔR to interplanetary parameters vary greatly for different storms. The most geoeffective interplanetary parameter is the solar-wind speed V. A significant anticorrelation of ΔR and V can be traced for almost all storms. The correlation of ΔR_{SGS} with the Bz component of the interplanetary magnetic field is observed only for two storms, on November 7–14, 2003, and November 7–8, 2004, for which the absolute Bz value was very high (≈−50 nT). At the same time, there is a rather high correlation of ΔR_{eff} with Bz for most storms. The azimuthal component of the interplanetary field By and the solar-wind dynamic pressure P show almost no connection with ΔR.

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1. INTRODUCTION

The arrival of cosmic rays at a certain point on the Earth's surface is governed by the configuration and intensity of the Earth's magnetic field, which acts as a screen for charged particles. The geomagnetic field allows or prohibits the arrival of CR particles at a given point in the magnetosphere and atmosphere, depending on their energy. The lowest latitude that energetic particles can reach is known as the cutoff latitude. This latitude is a function of the cutoff rigidity (momentum per unit charge). The geomagnetic cutoff rigidity, by definition, is the threshold rigidity below which the particle flux becomes zero due to geomagnetic shielding. The properties of the magnetic screen vary greatly over time, depending on the dynamic interaction of the magnetic and electric fields of the solar wind with the intramagnetospheric fields and currents.

Especially significant changes in the currents, plasma, and magnetic field of the magnetosphere occur during a geomagnetic storm (Leske et al., 2001). The solar wind (SW) energy is transmitted to the Earth's magnetosphere by coronal solar mass ejections or high-speed corotating regions of perturbations from coronal holes. The strongest geomagnetic storms are caused mainly by transient events: coronal mass ejections and the magnetic clouds associated with them.

The determination of variations in cosmic ray cutoff rigidity and their dependence on parameters of the SW and interplanetary magnetic field (IMF), as well as on geomagnetic activity, was considered in a number of papers based on various experimental and theoretical approaches using direct spacecraft observations of charged particles or numerical simulation.

Based on the measurement data from the SAMPEX spacecraft, it was found (Kanekal et al., 1998) that cutoff rigidity of high-latitude energetic particles are associated with the IMF Bz component and the SW speed. Shimazu (2009) used the magnetohydrodynamic (MHD) approach to consider the trajectory of solar-proton movement and concluded that the particle penetration at a distance of four Earth radii *Re* (where the particles did not penetrate during quiet time) is due to an increase in the solar-wind pressure during storms. Most of these protons penetrated the magnetosphere when the absolute value of the IMF southern Bz component was small or even positive. Magnetodynamic examination of the proton motion (Shimazu et al., 2006) showed that cutoff rigidity of particles with a 1 MeV energy decrease when the *Bz* component becomes negative, whereas cutoffs of protons with a 10 MeV energy are almost independent of *Bz*. Tyssøy and Stadsnes (2014) found a close connection between the cutoff latitude and the SW pressure. At the same time, the correlation with pressure was negative.

Adriani et al. (2016) measured variations in the cutoff rigidities of high-energy protons during a storm in December 2006 as part of an experiment on the PAMELA spacecraft. The variations in the measured cutoff rigidity correlated with the SW and IMF parameters. The strongest correlation (negative) of the cutoff latitudes was obtained with the general magnetic field *B* and *Bz* component, as well as with the speed *V* (also negative). Neither the dynamic pressure *P* nor the density *N* of the SW showed a significant correlation with the time scale of the entire storm. A high positive correlation of the cutoff latitudes with pressure was obtained only for the main storm phase.

A number of studies investigated the correlation of cutoff variation with geomagnetic activity. The most common characteristic of geomagnetic activity is the *Dst* index, which is an indicator of a storm disturbance and the development of a ring current. Tyssøy and Stadsnes (2014) found that the cutoff variations for the 2006 storm correlate with *Dst* rather closely. In this case, the correlation coefficients decrease when *Dst* is small in absolute value or becomes positive. Adriani et al. (2016) obtained a high correlation with the geomagnetic *Kp* index and a smaller correlation with *Dst*. The strongest correlation with *Dst* is observed during the recovery phase of the storm (Adriani et al., 2016). Tyasto et al. (2013) found that the greatest correlation of the cutoff variations with *Dst* for the storm in November 2004 is observed during the main phase, at the storm's maximum (minimum *Dst*). Conversely, it was found (Kress et al., 2010; Belov et al., 2005) that the greatest correlation of cutoff variations with *Dst* for the 2003 storm was observed not in the main phase, but 10 h prior to it.

Thus, the results of studies of the dependence of geomagnetic cutoff rigidity on interplanetary parameters and geomagnetic activity are rather inconsistent. This requires further research that would clarify the dynamics of the geomagnetic screen for different conditions in the heliosphere and magnetosphere. In addition, knowledge of the rigidity variations with respect to the SW parameters is becoming increasingly important for the safety of space vehicles and their crew, as well as for air travel (e.g., Smart and Shea, 2003; Iucci et al., 2005; Kress et al., 2015, and references therein). The study of such connections is especially important for periods of strong perturbations.

The present paper is a continuation of our studies examining the sensitivity of cutoff rigidities (regardless of the correlation sign) to various IMF components and SW parameters for individual intense storms (Tyasto et al., 2008, 2011, 2013, 2015). In this paper, we carried out a joint analysis of the correlations of cutoff rigidity variations with respect to the interplanetary parameters for the seven most significant magnetic storms of solar cycles 23 and 24. The storms observed in 1997, 2012, and 2015 have been added to those that we had already considered earlier. The correlations in this work are studied in more detail, in particular, with consideration of their sign. The focus of the study has shifted from the distribution of cutoff variations across individual stations to consideration of the averaged global picture.

2. DATA AND METHODS

2.1. Data on Interplanetary and Geomagnetic Parameters

In the present study, we estimated the relationship of cutoff variations with variations in the density *N*, velocity *V*, and dynamic pressure *P* of the SW; the *Bz* and *By* components of the interplanetary magnetic field; and the *Dst* index of geomagnetic activity. The studies were carried out for the following periods of disturbances, i.e., magnetic storms of the 23rd and 24th solar activity cycles: January 9–15, 1997; November 7–14, 2003; November 7–8, 2004 (2004 I); November 9–13, 2004 (2004 II); May 15–19, 2005; March 7–11, 2012; and June 21–25, 2015. The data on the SW and IMF parameters are taken from the website https://omniweb.gsfc.nasa.gov/form/dx1.html, and the data from the global network of cosmic ray stations are taken from http://www.nmdb.eu/.

Table 1 shows the maximum values of the parameters observed during the studied storms. All of the storms were caused by the arrival of coronal mass ejections to the Earth. From Table 1 it can be seen that the storm of January 9–15, 1997, is moderate, while the other six storms are very strong.

2.2. Methods of Research

The geomagnetic cutoff rigidity was calculated with two different methods: spectrographic global survey (SGS) and the tracing of the trajectories of cosmic ray particles in a model magnetic field.

The SGS method is based on consideration of the processes of change in the energy of charged particles in the regular electromagnetic fields of the heliosphere (Dvornikov et al., 2013). The SGS method makes it possible to obtain information on the energy and pitch angle distribution of primary cosmic rays in the IMF from the observations of the global network of stations. The method also makes it possible to estimate changes in the planetary system of geomagnetic cutoff rigidities for each hour of observations and to use for analysis the entire available complex of ground-based record-

Table 1. Extreme values of the interplanetary parameters and *Dst* variations in the period of magnetic storms

Parameter	1997	2003	2004 I	2004 II	2005	2012	2015
Dst_{min}, nT	–78	–472	–373	–289	–263	–143	–204
Bz_{min}, nT	–14.9	–50.9	–44.9	–24.7	–24.7	–16.4	–26.3
By_{max}, nT	13.9/–13.7	39.6/–19.8	38/–19.8	13.9/–30.7	34.1/–17.7	12.8/–18.2	25.6/–10.3
V_{max}, km/s	468	704	730	810	959	737	742
N_{max}, cm^{-3}	74.8	20.5	64.5	19.7	17.6	22.9	49.9
Kp	6.0	8.7	8.7	8.7	8.3	7.3	8.3
P_{max}	24.9	17.9	31.8	26.5	22.8	9.1	44.1

ing equipment (the world network of neutron monitors located at all levels of the Earth's atmosphere, ground-based and underground meson telescopes, etc.). The statistical error of the determination of ΔR_{SGS} with allowance for the statistical accuracy of measurements at the cosmic ray stations of the world network does not exceed 0.05 GV in absolute value. The cutoff variations obtained by this method will further be referred to as "observational."

The method of tracing of the trajectories of cosmic ray particles in the geomagnetic field to determine the cutoff rigidity was developed earlier (McCracken et al., 1962; Shea et al., 1965; Dorman et al., 1972). To calculate the geomagnetic thresholds, it is necessary to specify the magnetic field, which is usually described by a model (Shea et al., 1965). The accuracy of the determination of the geomagnetic thresholds depends on the accuracy of the magnetospheric model used in the calculations. We used the magnetospheric model Ts01, which is constructed from a database of satellite magnetic field measurements over a period of 37 geomagnetic storms with $Dst \leq -65$ nT (Tsyganenko, 2002a, 2002b; Tsyganenko et al., 2003). The model Ts04 was also developed to describe strong storms (Tsyganenko and Sitnov, 2005). However, our analysis (Tyasto et al., 2008; Tyasto et al., 2013) showed that the Ts01 model is better at describing the magnetospheric disturbances during major storms in November 2003 and 2004. In the Ts01 model, the main sources of the magnetic field of the magnetosphere are symmetrical and partial circular currents, the magnetotail current system, the Birkeland field-aligned currents of regions 1 and 2, and magnetopause currents. A block delineating the interaction field (which results from magnetospheric penetration by the interplanetary magnetic field) was included to limit the field inside the magnetosphere. The interaction field is represented as a uniform magnetic field that is proportional to the transverse component and is directed along it. The *Dst* variation, SW density and speed, and IMF components were used as the input parameters determining the effect of interplanetary conditions on the magnetosphere. The cutoff variations obtained by this method (ΔR_{eff}) will further be referred to as "model."

At the first stage of the study, we calculated the geomagnetic thresholds for cosmic rays with the two methods described above. The observational ΔR_{SGS} and model ΔR_{eff} were calculated for each hour in the storm periods listed above. The calculations for the first five storms (1997, 2003, 2004 I, 2004 II, and 2005) were carried out for the following stations: Tokyo (35.75° N, 139.72° E) Almaty (43.20° N, 76.94° E) Rome (41.90° N, 12.52° E), Irkutsk (52.47° N, 104.03° E), Moscow (55.47° N, 37.32° E), and Hobart (42.90° S, 147.33° E). In the calculations for the storms of 2012 and 2015, due to the shut-down of Tokyo and Hobart stations, stations close in latitude were used: Emilio Segrè Observatory in Israel (ESOI) (33.30° N, 35.80° E) and Kingston (42.99° S, 147.29° E). The threshold rigidities of all stations in quiet time span the range from ~10 to 2 GV. The variations in the geomagnetic cutoff rigidity ΔR_{eff} and ΔR_{SGS} were determined as the differences between the cutoff-rigidity values calculated with both methods and the rigidities in the quiet period (before the storm onset).

At the second stage, the correlation coefficients *k* of ΔR_{eff} and ΔR_{SGS} with the SW parameters *P*, *V*, and *N*, the IMF components *Bz* and *By*, and the *Dst* index of geomagnetic activity were calculated. The coefficients *k* were obtained from analysis of the regression equations for a sample of observations throughout a storm. The analysis showed that the *k* values at the listed stations do not differ much from each other, so they are not given in this article.

At the last stage of the study, we averaged the *k* values over all stations; the resulting average *k* values were further analyzed and compared for observational and model ΔR.

3. RESULTS

3.1. Correlation between the Observational and Model Cutoff Variations

As mentioned above, at the first stage of the study, the cutoff variations were calculated by two methods. Since ΔR_{SGS} and ΔR_{eff} are the basis for further calculations, we analyzed how closely they correlate with each

Table 2. Correlation coefficients between ΔR_{SGS} and ΔR_{eff}

Station	1997	2003	2004 I	2004 II	2005	2012	2015
Tokyo	0.02	0.81	0.76	0.05	0.25		
ESOI						0.51	0.54
Almaty	0.24	0.92	0.92	0.70	0.71	0.65	0.79
Rome	0.28	0.92	0.93	0.78	0.76	0.72	0.83
Irkutsk	0.48	0.95	0.93	0.81	0.84	0.65	0.87
Moscow	0.47	0.93	0.95	0.82	0.83	0.61	0.87
Hobart	0.46	0.88	0.94	0.75	0.72		
Kingston						0.41	0.87
Average	0.32	0.90	0.90	0.64	0.68	0.59	0.80

other. The correlation of the observational ΔR_{SGS} and model ΔR_{eff} was calculated for all stations during the storms. Table 2 shows the results of the correlation analysis.

Table 2 shows that the correlation between the rigidity variations obtained in two ways is weakest for the moderate storm of 1997. In addition, the correlation values were low at Tokyo station for all storms except for the very large storms of 2003 and 2004 (2004 I). At the remaining stations, ΔR_{SGS} and ΔR_{eff} are in close agreement with each other, and the correlation coefficients for each storm differ little among each other. The last row of Table 2 shows the correlation coefficients *k* between ΔR_{SGS} and ΔR_{eff} averaged over all stations. Their values are within 0.59–0.90 for all storms except for the storm of 1997, in which the coefficient *k* drops to 0.32. The correlation coefficient reaches its highest value for the very intense storms of November 2003 (*Dst* = –373 nT) and November 7–8, 2004 (*Dst* = –472 nT), while the lowest correlation is observed for the storms of 1997 (*Dst* = –78 nT) and 2012 (*Dst* = –143 nT). From this we can conclude that the Ts01 model describes well the magnetospheric field of very strong storms but does not adequately reflect the field of weaker storms. This result is not unexpected, since the Ts01 model was specifically designed for strong magnetospheric disturbances.

3.2. Correlation of the Observational Cutoff Variations with Interplanetary and Geomagnetic Parameters

Table 3 shows the average correlation coefficients *k* between the cutoff rigidity variations (ΔR_{SGS}) obtained from observations at the neutron monitor network and the SW parameters *P*, *V*, and *N*, the IMF components *Bz* and *By*, and the *Dst* index of geomagnetic activity. To illustrate the geoeffectiveness of the heliospheric parameters, the diagram (Fig. 1) shows the correlation coefficients $k \geq 0.46$ for the studied storms.

Table 3 and the diagrams (Fig. 1) show that the moderate storm of January 1997 stands alone in the series of studied storms. During this storm, the correlations of ΔR_{SGS} with interplanetary parameters and geomagnetic activity were very weak (0.01–0.35). During the other storms, the cutoff variations demonstrated various degrees of correlation with the parameters of the heliosphere and geomagnetic activity, often very significant correlations. The greatest correlation of ΔR_{SGS} is found with the *Dst* index of geomagnetic activity. For *Dst*, the correlation coefficient *k* is 0.64–0.92. In this case, the following pattern is observed: for the very intense storms of November 18–24, 2003 (*Dst* = –373 nT) and November 7–8, 2004 (*Dst* = –472 nT), the dependence of ΔR_{SGS} on the SW and IMF parameters is manifested very strongly, while this dependence becomes insignificant for more moderate storms of January 9–15, 1997 (*Dst* = –78 nT) and March 7–11, 2012 (*Dst* = –143 nT). In other words, the higher are the negative values reached by the *Dst* geomagnetic activity index at the storm maximum (i.e., the stronger the storm), the closer is the connection between ΔR_{SGS} and *Dst*.

The most geoeffective interplanetary parameter for variations in the observational geomagnetic thresholds was the SW speed *V*. The anticorrelation of ΔR_{SGS} and *V* can be traced for almost all storms, reaching the highest value (–0.82) for the first storm of 2004. The correlation with *Bz*, conversely, is weakly expressed. Only for the storms of 2003 and 2004 (I), during which *Bz* reached gigantic values of ≈ –50 nT, does the correlation coefficient reach 0.42 and 0.61, respectively. The IMF *By* component shows practically no connection with ΔR_{SGS}. According to Table 3, the dynamic pressure *P* also has almost no effect on cutoff varia-

Table 3. Correlation coefficients of the variations of cutoff rigidity ΔR_{SGS} with parameters of the SW, IMF, and geomagnetic activity

Parameter	1997	2003	2004 I	2004 II	2005	2012	2015
Dst	0.35	0.80	0.92	0.67	0.75	0.64	0.83
Bz	0.29	0.42	0.61	0.10	–0.13	0.33	0.21
By	0.01	0.37	–0.24	–0.06	–0.07	–0.27	–0.21
N	0.29	–0.49	0.66	0.01	0.28	0.23	0.26
V	–0.04	0.14	–0.82	–0.53	–0.49	–0.37	–0.62
P	0.29	–0.46	0.46	–0.20	0.12	–0.10	–0.10

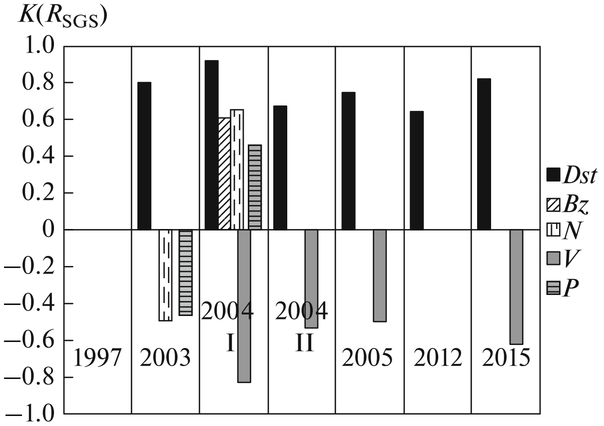

Fig. 1. SW and geomagnetic activity parameters showing the strongest correlation ($k > 0.46$) with the variations in the observational cutoff rigidity ΔR_{SGS} for the studied magnetic storms.

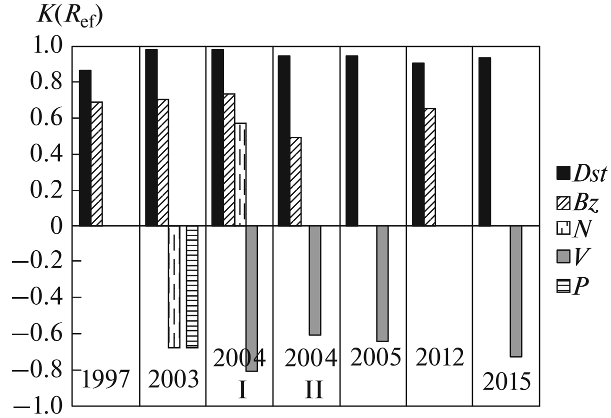

Fig. 2. SW and geomagnetic activity parameters showing the strongest correlation ($k > 0.5$) with the variations in the model cutoff rigidity ΔR_{eff} for the studied magnetic storms.

tions. Only for the storms of 2003 and 2004 (2004 I) does the correlation coefficient between ΔR_{SGS} and P approach 0.5; however, these storms have different signs of correlation. The correlation of ΔR_{SGS} and N for the same two storms is more pronounced ($k = -0.49$ and $k = 0.66$, respectively). It should be noted that the correlation with density N for these two storms, like the correlation with the pressure P, has different signs (positive for the 2004 storm (I) and negative for the 2003 storm).

The diagram (Fig. 1) clearly shows the parameters that had the most significant effect on the cutoff rigidity variations for each of the storms. The very strong connection of ΔR_{SGS} with *Dst* is clearly visible. It can be seen that the ΔR_{SGS} values were most sensitive to the heliospheric parameters during the first storm of 2004 (Table 3 and (Fig. 1). For this storm, the correlation of ΔR_{SGS} with almost all parameters (except for the IMF *By* component) is rather high, i.e., all of the SW and IMF parameters were largely geoeffective. In the case of the 2003 storm, the density and pressure turned out to be geoeffective. The remaining storms showed a significant dependence of ΔR_{SGS} on one parameter only, the SW speed.

3.3. Correlation of Model Cutoff Variations with Interplanetary and Geomagnetic Parameters

We further compared the correlations obtained for the observational ΔR_{SGS} with similar correlations for the model ΔR_{eff}. Table 4 shows the correlation coefficients of the model ΔR_{eff} values averaged over all stations with the SW parameters P, V, and N, the *Bz* and *By* components of the IMF, and the *Dst* index of geomagnetic activity.

Table 4 shows that the highest correlation is observed for the *Dst* index: $k = 0.87–0.98$ for all storms. An anticorrelation with V is observed for most storms, reaching $k = -0.81$ for the first storm of 2004. Correlation with N is observed only for the storms of 2003 (−0.68) and the first storm of 2004 (0.57). Correlation with P (0.67) was found only for the 2003 storm. A significant correlation with the IMF *Bz* component is observed for five of the seven studied storms.

To illustrate the geoeffectiveness of the heliospheric parameters, the diagram (Fig. 2) shows the correlation coefficients $k \geq 0.5$ for the studied storms.

A comparison of Tables 3 and 4, as well as Figs. 1 and 2, show that the coefficients of correlation of ΔR_{SGS} and ΔR_{eff} with the interplanetary parameters are

Table 4. Correlation coefficients of the variations of cutoff rigidity ΔR_{eff} with the parameters of the SW, IMF, and geomagnetic activity

Parameter	1997	2003	2004 I	2004 II	2005	2012	2015
Dst	0.87	0.98	0.98	0.95	0.94	0.90	0.93
Bz	0.69	0.70	0.74	0.49	0.18	0.66	0.40
By	0.35	0.15	−0.20	−0.04	−0.24	−0.38	−0.09
N	0.33	−0.68	0.57	0.12	0.21	0.10	0.33
V	−0.16	0.05	−0.81	−0.61	−0.65	−0.36	−0.73
P	0.29	−0.67	0.37	−0.13	−0.07	−0.16	−0.06

generally in close agreement with each other. The signs of the correlation coefficients also coincide. As for the magnitude of the correlation coefficients, they are slightly higher for the model ΔR_{eff} than for the observational ΔR_{SGS}. This result is probably related to the fact that all the SW characteristics, IMF components, and *Dst* values studied in our work are the input parameters of the Ts01 model. Another difference between the correlations of ΔR_{eff} and ΔR_{SGS} with interplanetary parameters is also associated with this. A rather high correlation of *Bz* with the model ΔR_{eff} was obtained for most of the storms, while the correlation of *Bz* with the observable ΔR_{SGS} was found only for two giant storms of 2003 and 2004 (2004 I), during which very large negative values $Bz \approx -50$ nT were reached. This suggests that the model of the magnetospheric magnetic field Ts01 apparently overestimates the influence of *Bz* on the dynamics of the cutoff rigidity to a certain degree.

4. DISCUSSION

Comparative analysis of the sensitivity of the observational values ΔR_{SGS} and model values ΔR_{eff} to interplanetary parameters and geomagnetic activity shows that the sensitivity varies greatly from storm to storm. At the same time, the relation of ΔR to geomagnetic activity demonstrates a clear pattern: the correlation increases with a decrease in *Dst*, i.e., with increasing storm intensity. Conversely, the sensitivity of ΔR to the dynamic and magnetic parameters of the SW shows no clear patterns: not only the magnitude of the correlation coefficients but also their sign changes from storm to storm. A typical example is the storm of 2003 and the first storm of 2004, during which both ΔR_{SGS} and ΔR_{eff} show a different correlation sign with the dynamic parameters of the SW *N*, *P*, and *V* (Tables 2 and 4, Figs. 1 and 2). Apparently, this discrepancy can be understood in light of the results of Adriani et al. (2016), who took direct measurements of cutoff variations at the PAMELA satellite during the 2006 storm. The variations in the cutoff latitude as a function of the cutoff were studied at relatively short time intervals matching the orbital period of the spacecraft (≈94 min). The analysis revealed a weak anticorrelation of ΔR with *N* (–0.12) on the scale of the entire storm and high correlation coefficients of the opposite sign in the initial (−0.74) and the main (0.94) phase. It is possible that the negative correlation of ΔR with *N* and *P* obtained in our study of the 2003 storm and the positive correlation for the 2004 storm depend on the dominance of different phases in these storms. A different mechanism of the influence of the SW parameters on the cutoff rigidity may be involved for different storms and different conditions in the SW, depending on the dominance of various current systems. For example, an increase in SW pressure leads to an increase in the transverse magnetotail currents and magnetopause currents, which have the opposite effect on the cutoff rigidity. Ideally, in order to understand the dependence of the cutoff variations on the SW and IMF parameters, one should study the contribution of each current system to the dynamics of the geomagnetic screen and its relationship with the heliospheric parameters. However, it is not possible ideally to divide the total magnetic field of various current sources into separate constituents.

The pattern of the correlation relationships that vary from storm to storm shows that the effect of the interplanetary medium on ΔR is complex, which reflects the complex and incompletely understood physics of the interaction of the SW with the Earth's magnetosphere during strong disturbances.

It is generally accepted that the main role in the development of magnetospheric disturbances is played by the southern component *Bz* of the interplanetary magnetic field; its growth causes a reconnection of the SW magnetic field and the geomagnetic field, as well as the SW dynamic pressure *P* responsible for the compression of the magnetosphere (Dungey, 1961; Akasofu, 1981; Russell, 2000). Both of these factors weaken the geomagnetic screen and facilitate the penetration of the SW plasma into the magnetosphere and the Earth's atmosphere. From this point of view, our result that the coefficients of correlation of ΔR with the SW density and speed considerably exceeds the coefficients of correlation with the pressure *P* is rather unexpected.

An increase in the density *N* during a magnetic storm was long considered only as an increase in one of the pressure components. However, Fenrich and Luhman (1998), as well as Crooker (2000), expressed the view that pressure is an independent parameter acting on its own. This view is based on the recent understanding that the response of the magnetosphere to the variations in the SW density is a response to the variations in the density of the plasma layer during a storm; the time scale for this process is much longer (approximately 5 h) than for the response to *Bz* (<1 h) (Smith et al., 1999, and references therein). An increase in density leads to an increase in pressure only if the IMF southern component is present at this time (Fenrich and Luhman, 1998). The statistical processing of satellite data (Khabarova and Rudenchik, 2003; Khabarova, 2007) also showed that the SW density *N* is an important independent parameter; it determines the time of the onset of the magnetic storm, which expands the possibilities for the prediction of the disturbed state of the Earth's magnetic field. An increase in *N*, together with a negative *Bz* component, leads to the occurrence of mostly weak and moderate, but sometimes also strong, storms. However, the trigger effect of the density growth is not defined statistically clearly enough, since the delay of the *Dst* minimum with respect to the surge in *N* and the minimum *Bz* varies greatly from storm to storm (Khabarova, 2007).

This is consistent with our result that the response of the geomagnetic screen to variations in the SW parameters is individual for each storm and is associated with specific features of the interaction of the SW and magnetosphere for different storms.

Our result indicates that, for the majority of the studied magnetic storms, the most geoeffective SW parameter with the most significant effect on the cutoff is speed, and this deserves additional consideration. Starting from a historical work (Snyder et al., 1963), in which it was shown that the *Kp* index of geomagnetic activity depends on *V* but that this relationship is not exact and is rather random, there have been many attempts to reveal the role of *V* in the development of a magnetic storm. Gosling et al. (1991) concluded that the SW speed is a key parameter in the development of very intense magnetic storms. Conversely, Tsurutani et al. (1992) concluded that the key factor in the occurrence and development of intense storms is not the speed but the southern component of the magnetic field *Bz*. It was found (Schreiber, 1998) that, in periods when high-speed flows from coronal holes are observed most frequently, the intensity of geomagnetic disturbances depends more on the flow speed than on the southward *Bz* component. The ambiguity of the dependence of the storm generation and development on SW speed is also manifested in the ambiguous connection between ΔR and *V*. While there is a strong dependence of ΔR on *V* for most of the storms studied in our paper, this relationship, for some reason, is broken into two very different cases: the moderate storm of 1997 and the very intense storm of 2003.

5. CONCLUSIONS

We calculated the correlation of variations in the geomagnetic cutoff rigidity ΔR_{SGS} and ΔR_{eff} with interplanetary parameters and the *Dst* index of geomagnetic activity during seven storms of solar cycles 23 and 24. All of them belong to the class of very strong storms, except for the moderate storm of January 1997. The cutoff rigidity variations were obtained by two independent methods: the observational method for ΔR_{SGS} and model method for ΔR_{eff}. The main results of the analysis are as follows.

1. Among all of the parameters, the *Dst* index has the greatest influence on ΔR_{SGS} and ΔR_{eff}. The correlation coefficient *k* between ΔR_{SGS} and *Dst* lies within 0.64–0.92 for all the storms, except for the 1997 storm, for which $k = 0.32$. The correlation coefficient between ΔR_{eff} and *Dst* lies within 0.87–0.98 for all the storms. This confirms the earlier results indicating the dominant role of the ring current in cutoff variations for intense storms. At the same time, the relation of ΔR to geomagnetic activity demonstrates a clear pattern: the correlation increases with a decrease in *Dst*, i.e., with increasing storm intensity.

2. The most geoeffective interplanetary parameter for the majority of the studied storms was the SW speed *V*. The anticorrelation of ΔR_{SGS} and *V* can be traced for almost all storms, reaching the highest value (−0.82) for the first storm of 2004. The same pattern is observed for ΔR_{eff} as well.

3. The correlation of ΔR_{SGS} with *Bz* is weak. Only for the storms of 2003 and 2004 (I), during which *Bz* reached gigantic values of ≈ −50 nT, does the correlation coefficient reach 0.42 and 0.61, respectively. The *By* component and the SW dynamic pressure *P* show almost no connection with ΔR_{SGS}. Only during the 2003 and 2004 (I) storms does the correlation coefficient between ΔR_{SGS} and *P* approach 0.5, but these storms have different signs of correlation.

4. On the whole, the cutoff variations ΔR_{SGS} and ΔR_{eff} are in close agreement with each other. The correlation coefficients of the observational ΔR_{SGS} and model ΔR_{eff} with interplanetary parameters and geomagnetic activity are also generally in agreement. However, the values of the correlation coefficients for the model ΔR_{eff} are slightly higher than those for the observational ΔR_{SGS}. In addition, a rather high correlation of ΔR_{eff} with *Bz* was obtained for five storms, while a connection with *Bz* was found only for two storms in the observational ΔR_{SGS}. From this, it can be concluded that the Ts01 model of the magnetospheric magnetic field apparently overestimates the influence of *Bz* on the dynamics of the cutoff rigidity to a certain degree.

The results presented in this paper show that the sensitivity of the cutoff rigidity variations ΔR to geomagnetic activity parameters and interplanetary medium parameters has a different character. There is a strong correlation between ΔR and the *Dst* index of geomagnetic activity, and this correlation increases with storm intensity. Conversely, the sensitivity of ΔR to the dynamic and magnetic parameters of the interplanetary medium shows no clear pattern: in this case, not only the magnitude of the correlation coefficients but also their sign changes from storm to storm. The picture of correlation relationships shows that the effect of the interplanetary medium on ΔR is complex, which reflects the complex and incompletely understood physics of the interaction of the SW with the Earth's magnetosphere during strong disturbances.

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