

RELATIONSHIP BETWEEN GEOMAGNETIC THRESHOLDS OF GALACTIC COSMIC RAYS AND HELIOSPHERIC PARAMETERS DURING THE MAY 10–12, 2024 STORM

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Abstract. Galactic cosmic rays (CRs) are charged energetic particle fluxes that penetrate interplanetary space. Under the influence of the geomagnetic field, charged cosmic ray particles change their trajectories. Some of these particles, with rigidity below the threshold value characteristic of the measurement site (called the geomagnetic cutoff rigidity, or geomagnetic threshold, R), do not reach the Earth surface.

In this study, geomagnetic thresholds R as well as their changes relative to quiet conditions (ΔR) for six stations at different latitudes have been calculated using two methods: 1) a method in which cosmic ray particle trajectories are calculated numerically in a model magnetic field of the magnetosphere (R_{eff}); 2) a spectrographic global survey based on observational data from cosmic ray recordings by a global network of stations (R_{sgs}) during a very strong magnetic storm on May 10–12, 2024.

The obtained results were compared. It was found that the changes in cosmic ray geomagnetic thresholds for this storm, calculated by both methods, correlate

well with each other. The most geoeffective components are the vertical component of the interplanetary magnetic field B_z and its full scalar value B , whereas the B_y component of the field has virtually no effect on changes in threshold rigidities for all stations. ΔR also correlates well with the geomagnetic indices Dst and K_p , with the electric field parameter E_y , and with the solar wind's dynamic parameters (density and pressure), while no significant correlation is observed with solar wind speed. Analysis has shown that the response of ΔR to the controlling electromagnetic parameters and geomagnetic activity indices remains virtually unchanged with the latitude of the observation station for the given storm.

Keywords: cosmic rays, geomagnetic threshold, cosmic ray cutoff rigidity, interplanetary magnetic field, geomagnetic activity.

INTRODUCTION

The magnetic storm on May 10–12, 2024, caused by a series of X-ray solar flares and related coronal mass ejections (CME), was one of the strongest storms in solar cycle 25. Those days, Earth's magnetosphere experienced the severest disturbance in the last twenty years, called the Gannon Storm in foreign literature (in honor of Dr. Jennifer Gannon, a leading expert in space weather research, who died a week before this event) [Lawrence et al., 2025].

This storm was associated with a large active region AR13664, located in the center of the solar disk just below the equator, which on May 7 (its coordinates on that day: S21°, E05°) rapidly grew in size (up to 15 Earth diameters across; it became close in size to the famous Carrington sunspot, which in 1859 generated the strongest magnetic storm ever recorded) and acquired a complex magnetic structure that facilitated the formation of X- and M-class X-ray flares. From May 8 to May 11, AR13664 produced six X-class flares: X1.0, X1.0, X2.2, X1.1, X3.9, X5.8, which launched CMEs with speeds from 530 to 1614 km/s [Hayakawa et al.,

2025]. It was these CMEs that caused the magnetic storm on May 10–12, 2024.

There are two generally accepted independent classifications of magnetic storms:

- According to the three-hour planetary geomagnetic activity index K_p [Bartels et al., 1939], which measures geomagnetic disturbances and covers the solar wind effect on Earth's magnetosphere at high latitudes.
- According to the disturbance storm time index Dst [Loewe, Prölss, 1997], which measures the effect of the global westward ring current causing a decrease in the geomagnetic field H component during the magnetic storm main phase at low latitudes.

Table 1 presents the classification of magnetic storms from [Loewe, Prölss, 1997].

Note that the storm classification by the Dst index is underestimated in intensity relative to K_p .

This magnetic storm belongs to extreme geomagnetic storms ($Dst < -350$ nT), which are generally driven by transient events — CMEs and related interplanetary structures: corotating interaction regions, compression regions in front of interplanetary CMEs, magnetic clouds,

Table 1

Classification of magnetic storms

K_p	Class	Storm type	Dst
$K_p=5$	G1	weak	$Dst < -30$ nT
$K_p=6$	G2	moderate	$Dst < -50$ nT
$K_p=7$	G3	strong	$Dst < -100$ nT
$K_p=8$	G4	very strong	$Dst < -200$ nT
$K_p=9$	G5	extreme	$Dst < -350$ nT

and magnetic “pistons” [Gosling, 1993; Gonzalez et al., 1999; Yermolaev et al., 2013; Richardson, 2018]. Moreover, this storm belongs to the class of storms with sudden commencements (SSC), which are preceded by an abrupt change in the geomagnetic field accompanied by a marked change in Dst and K_p .

Nowadays, strong geomagnetic disturbances pose a serious threat to a technology-dependent society. Geomagnetically induced currents flowing in ground systems during periods of increased geomagnetic activity can damage electric grids [Boteler et al., 1989; Pulkkinen et al., 2001; Rodger et al., 2017], railways [Liu et al., 2016; Love et al., 2019; Patterson et al., 2023], oil and gas pipelines [Khanal et al., 2019; Ingham et al., 2022; Oliveira et al., 2024], and submarine cables [Chakraborty et al., 2022; Boteler et al., 2024]. Extreme space weather events can also wreak havoc on satellite navigation by distorting or delaying signal transmission through the ionosphere [Roy, Paul, 2013; Hapgood, 2017; Demyanov, Yasyukevich, 2021; Pilipenko et al., 2023].

The effects of the storm in May 2024 have been summarized in several publications: Parker, Linares [2024] describe how geomagnetic disturbances during the event affected trajectories of low-Earth orbit satellites; Schennetten et al. [2024] deal with the effect of the event on radiation fields at altitudes used in aviation.

After two decades of mostly mild geomagnetic conditions, solar cycle 25 has brought an increase in the rate of occurrence of solar flares, which is likely to trigger further geomagnetic storms and potentially severe space weather. Thus, studying information about extreme events such as the May 10–12, 2024 storm is important to understand their true impact on both a global and local scale. Continuous observations and follow-up studies of solar activity, propagation of CMEs in interplanetary space, and their associated space and terrestrial effects are needed to improve prediction capabilities in order to reduce the impact of extreme geomagnetic storms in the future [Lawrence et al., 2025].

Variations in CR fluxes on Earth during magnetic storms are caused by variations in geomagnetic thresholds, or threshold geomagnetic cutoff rigidity of CRs (ΔR). These values depend on the screening properties of the geomagnetic field. Geomagnetic screening decreases during storms, as the magnetic field inside the magnetosphere weakens due to the formation and strengthening of global current systems. As a result, cosmic particles can penetrate to lower latitudes. In turn, the dynamics of current systems depends on the dynamics of the solar wind (SW) electromagnetic parameters in near-Earth space.

The response of geomagnetic screening to changes in electromagnetic conditions, SW, and the interplanetary magnetic field (IMF) during magnetic storms is

little understood, despite a number of studies in this area involving theoretical and experimental approaches [Kanekal et al., 1998; Belov et al., 2005; Kress et al., 2010; Adriani et al., 2016]. Nonetheless, an unambiguous answer to the question as to which parameters of near space control the CR transportation during disturbances has yet to be found. In order to draw generalized conclusions about changes in geomagnetic screening during interplanetary and geomagnetic disturbances, at least a fairly extensive database of relevant data is needed for geomagnetic storms of various types and intensities generated by different sources on the Sun and in interplanetary space and, moreover, occurring during different solar cycle phases. We have previously calculated (see [Ptitsyna et al., 2019; Danilova et al., 2023, 2025] and references therein) variations in geomagnetic thresholds and their correlations with helio- and geospheric parameters for one moderate and eight strong geomagnetic storms of solar cycles 23, 24, and 25. Most of the storms were recorded during decline phases and at solar minima. In this paper, to further expand our data archive, we examine ΔR during the extreme superstorm in May 2024 near the maximum of cycle 25, which has other causes and a different evolution than the storms considered in our previous works. This article is sequel to [Danilova et al., 2025].

The purpose of this work is to determine geomagnetic thresholds R , calculated by two different methods during the extreme storm on May 10–12, 2024, analyze the dependence of their variations ΔR on SW electromagnetic parameters, and find the most geoeffective parameters for this storm.

1. METHODS AND DATA

The geomagnetic thresholds R have been obtained by two independent methods:

1. R_{eff} (model thresholds), by a trajectory calculation method that consists in numerically integrating CR trajectories [Shea et al., 1965] in the magnetic field of the disturbed magnetosphere by the Tsyganenko model Ts01 (see [Tsyganenko et al., 2003] and references therein). Sources of the magnetospheric magnetic field in this model are the main current systems: Chapman—Ferraro currents, which keep the geomagnetic field inside the boundary of the magnetosphere; symmetrical and partial volume ring currents, a system of magnetotail currents, field-aligned currents, and currents at the magnetopause. Parameterization of the current systems was carried out using satellite data measured during 37 geomagnetic storms with $Dst \leq -65$ nT [Tsyganenko et al., 2003]. In order to limit the field inside the magnetosphere, a block was included which described the interaction field, which is the effect of IMF penetration into the magnetosphere. The interaction field is represented as a uniform magnetic field that is proportional to the transverse component and directed along it. To calculate the magnetic field from internal sources, we use a representation of the main geomagnetic field in the form of series expansion in spherical harmonic functions up to $n=10$. The Ts01 model utilizes Dst , the SW dynamic parameters — density N and velocity V , as well as the IMF components B_y and B_z as input parameters.

2. R_{sgs} (observational thresholds), by the spectrographic global survey (SGS) method [Kovalev et al., 2022]. This method provides information on the distribution of primary CRs by energy and pitch angles in IMF, as well as on changes in the planetary system of geomagnetic thresholds for each moment of observations, from ground-based observations of CRs at a global network of stations.

Geomagnetic threshold variations ΔR have been determined for six cosmic ray stations, located in such a way that under quiet conditions they covered the main range of threshold rigidities R_c affected by the geomagnetic field (Table 2). R_c is the minimum rigidity or energy that a charged cosmic ray particle must possess in order to penetrate through the geomagnetic field and be detected by a specific ground-based detector (a neutron monitor or a muon telescope).

The values of ΔR were obtained for each hour as the difference between R calculated for the period May 10–12, 2024 and on the quiet day of May 8, 2024.

Then, correlation coefficients k and standard errors s (derived by analyzing regression equations) were calculated between geomagnetic thresholds (ΔR_{sgs} and ΔR_{eff}) at the listed stations and the SW, IMF parameters, and geomagnetic activity indices. The K_p and Dst indices and parameters of IMF (B , B_z , B_y), electromagnetic field (azimuthal component E_y), and SW (N , V , P , and plasma β) were taken from the website [<https://omniweb.gsfc.nasa.gov/form/dx1.html>]. (Plasma β is the ratio of plasma pressure to magnetic pressure (the β parameter is equal to the ratio of thermal pressure to magnetic pressure: $\beta = NkT/(B^2/(8\pi))$) during the development of geomagnetic storms.)

2. DISCUSSION

2.1. Changes in heliospheric parameters and geomagnetic thresholds during the May 10–12, 2024 magnetic storm

As already noted, the speed of the CME, which was one of the drivers of the geomagnetic storm on May 10–12, 2024, proved to be almost twice as high as usual; the sunspot's magnetic field, six times; and the direction of the ejection's magnetic field was also suitable for the onset of the magnetic storm, hence the first impact on Earth's magnetosphere occurred in the evening on May 10.

According to data from the IKIR FEB RAS Observatory, the storm began on May 10 (DOY=131) at 17:06 UT and immediately exceeded the G4 level. After midnight on May 11, the storm intensified to the maximum G5 level. During the day on May 11, the level of disturbance was at least G4, periodically rising to G5.

As Earth fell into the CME distribution sector, space weather experts predicted a magnetic storm of the highest class. In reality, due to the superposition of effects from six CMEs, the rate of increase in disturbance level and its average level exceeded all predictions.

The auroras spread to the entire territory of Russia, up to the Caucasus. Figure 1 presents images of an aurora in the vicinity of Saint Petersburg. Northern lights were observed by residents from all over Europe, to its southern regions — Italy, France and Spain, as well as in the USA, Mexico, and New Zealand. For the first time since 1859 and 1921, residents of Puerto Rico saw an aurora.

Table 2

Cosmic ray stations

Station name	International code	Geographic latitude	Geographic longitude	R_c , GV
Kingston (Australia)	KGSN	42.99° S	147.29° E	1.9
Moscow (Russia)	MOSC	55.47° N	37.32° E	2.08
Irkutsk (Russia)	IRKT	52.47° N	104.03° E	3.13
Almaty (Kazakhstan)	AATB	43.25° N	76.92° E	5.21
Rome (Italy)	ROME	41.90° N	12.52° E	6.11
Emilio Segre Observatory (Israel)	ESOI	33.30° N	35.80° E	10.73



Figure 1. Aurora on May 10–11, 2024 at night (from 23:30 to 23:50 LT) in the Leningrad Region (the images were taken by A. Koval on the Murmansk highway, 60 km from St. Petersburg)

A decline in geomagnetic activity began on May 12, but since large solar flares occurred on May 10 and 11, there were grounds to expect that they would have an impact on geomagnetic conditions. Nonetheless, plasma ejections from these flares, although they approached Earth on May 12, deviated during their propagation in the interplanetary medium and interacted with Earth's magnetosphere tangentially. The level of geomagnetic disturbances on May 12–13 did not exceed G2–G3, and this recurrent geomagnetic storm ended by noon on May 13.

Figure 2 represents geo- and heliospheric parameters during the geomagnetic storm on May 10–12, 2024. Curves (from top to bottom) correspond to total scalar IMF B and its component B_z , electric field azimuthal component E_y , plasma parameter β , SW velocity V , density N , pressure P , as well as the geomagnetic activity indices K_p and Dst . Referring to Figure 2, the main phase began on May 10 around 17:00 UT, when Dst started to drop sharply. On May 11 at 02:00 UT, Dst reached a minimum (−406 nT).

It is believed that negative B_z for a long time (≥ 3 hrs) is a necessary condition for the occurrence of a magnetic storm [Gonzalez, Tsurutani, 1987]. A characteristic feature of this storm is that during the main phase B_z dramatically changed not only its value, but also its sign many times (see Figure 2). Variations in E_y were similar to those in B_z , but in reverse orientation, and reached a peak value of 26.2 two hours before the

storm maximum. Three-hour K_p remained unchanged (~ 8 – 9) for almost a day and a half, from 15:00 UT on May 10 to 0:00 UT on May 12, and only after that it began to gradually decrease. The plasma β parameter stayed almost the same during the storm main phase, remaining close to zero, as it did later in the recovery phase. Figure 2 demonstrates a similar behavior of most parameters.

Figure 3 shows calculated geomagnetic threshold variations ΔR_{eff} (a) and ΔR_{sgs} (b) for all stations in use during the May 10–12, 2024 storm. The ΔR_{eff} curves are arranged from top to bottom in descending order of threshold rigidities R_c (increasing station latitude, except for KGSN located in the Southern Hemisphere). To illustrate the relationship between the dynamics of geomagnetic thresholds and evolution of the storm, Figure 3 also depicts variations in SW pressure (panel b) and Dst (panel d). Figure 3, a, b demonstrates a nonstandard behavior of thresholds during this storm. Figure 3, a indicates that ΔR_{eff} is minimum not only during the storm maximum (Dst minimum), but also several hours later. The difference from other storms is that the maximum decrease in $\Delta R_{\text{eff}} \sim -1.4$ GV is first observed at the lowest-latitude ESOI station in the main phase on May 10 at 02:00 UT, during the storm maximum ($Dst = -406$ nT); an hour later, at the higher-latitude MOSC station; and four hours later, at the mid-latitude IRKT station.

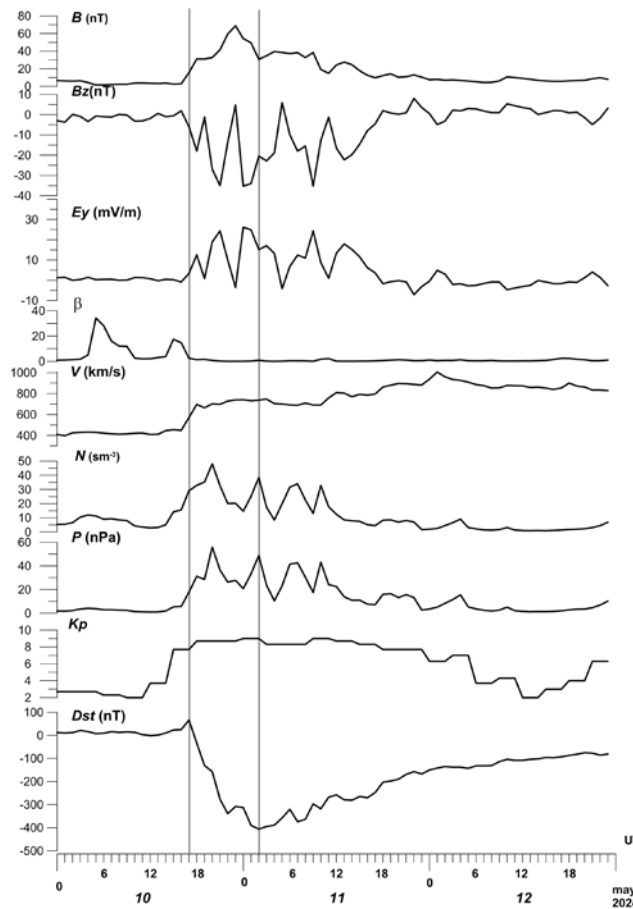


Figure 2. IMF and SW parameters, as well as geomagnetic activity indices during the storm on May 10–12, 2024 (from top to bottom). Vertical lines denote boundaries of the storm main phase

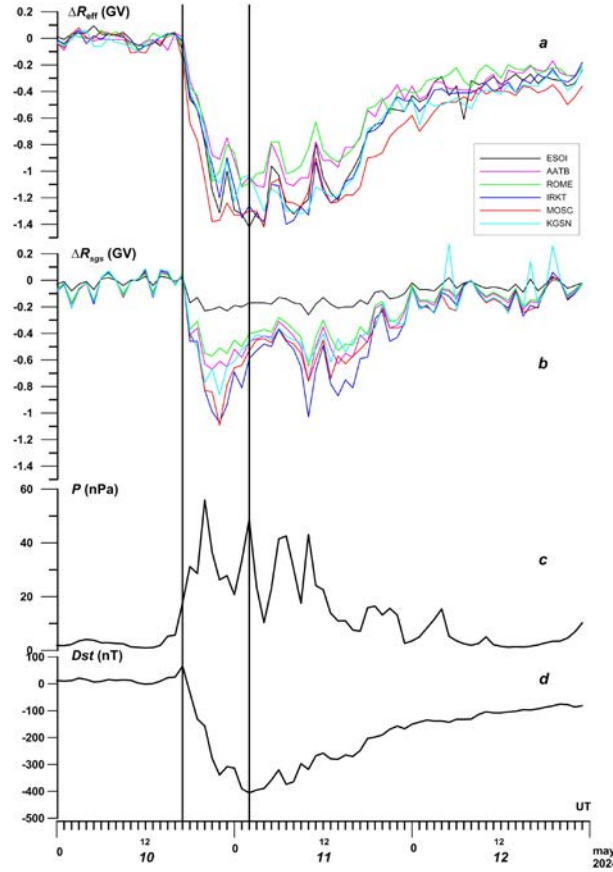


Figure 3. Variations in geomagnetic thresholds ΔR_{eff} (a) and ΔR_{sgs} (b), SW pressure P (c), and Dst (d) during the May 2024 storm. Vertical lines denote boundaries of the storm main phase.

Figure 3, b indicates that ΔR_{sgs} decreases sharply in the main phase and reaches its maximum drop (–1.1 GV) on 10 May at 22:00 UT, 4 hours before the storm maximum, at the mid-latitude MOSC and IRKT stations. In addition, IRKT ΔR_{sgs} has a second pronounced minimum of –1.0 GV during the recovery phase on May 11 at 10:00 UT.

Our result confirms the previously obtained data that geomagnetic cutoff rigidities are most strongly depressed at the maximum of the storm main phase when Dst reaches a minimum. The response of geomagnetic screening to changes in SW conditions outside the main phase is much less understood so far.

In general, as can be seen in Figure 3, the ΔR curves fit Dst variations well, having similar rises and falls, and show that the storm intensity began to decrease only by May 13.

By analyzing observations and calculations, Kress et al. [2004] have revealed that an increase in the SW dynamic pressure P depresses geomagnetic cutoff rigidities during SSC of the November 24, 2001 storm. It follows from [Flückiger et al., 1990; Belov et al., 2005] that geomagnetic thresholds, on the contrary, increase at the beginning of a storm relative to the level of the quiet field due to the formation of currents at the magnetopause. Kress et al. [2010, 2015] indicate that an increase in P can cause both an increase and a decrease in rigidities, depending on SW conditions and local time. For this storm, we can see (Figure 3) that a rise in P entails a fall in ΔR .

2.2. Correlation analysis

Time curves (see Figure 3) show that both ΔR_{eff} and ΔR_{sgs} change with changes in SW, IMF, and geomagnetic activity parameters, i.e. with the evolution of the storm. In order to quantify the relationship between variations in geomagnetic thresholds and the parameters under study, we calculated correlation coefficients k and standard errors s , presented in Tables 3 and 4.

Tables 3 and 4 suggest that the highest correlation is observed between variations in ΔR and Dst , and hence the ring current makes the largest contribution to geomagnetic screening during this storm. At the same time, for ΔR_{eff} , the correlation with Dst is slightly higher than for ΔR_{sgs} . So, for the AATB and IRKT stations, k for ΔR_{eff} is maximum — 0.98 ± 0.10 ; for other stations, their values are almost the same, whereas for ΔR_{sgs} they fluctuate around 0.8. A high but somewhat lower negative correlation is also seen for K_p . Note that the errors in calculating s are small for higher k (with electromagnetic field and geomagnetic activity parameters) and increase for small k , so the largest errors are found for the least geoeffective parameters.

Notice that the correlations of ΔR with all parameters, as calculated for stations at different latitudes by both methods, differ very slightly from each other. Thus, for the storm in question, we do not observe a pronounced latitudinal dependence.

The results obtained by the two different methods are in good agreement. This is confirmed by high correlation

coefficients (above 0.8) between ΔR_{eff} and ΔR_{sgs} (last row of Table 4).

As is evident from Tables 3 and 4, geomagnetic activity (Dst and K_p), E_y , B_z , and the total IMF B , as well as SW dynamic parameters P and N have the greatest

effect on both ΔR_{eff} and ΔR_{sgs} at all stations. At the same time, the IMF B_y component, the SW velocity V , and the plasma β parameter do not have any significant effect on either ΔR_{sgs} or ΔR_{eff} .

Table 3

Correlation coefficients of ΔR_{eff} with geo- and heliospheric parameters

	ESOI	ROME	AATB	IRKT	MOSC	KGSN
Dst	0.97 ± 0.11	0.97 ± 0.10	0.98 ± 0.08	0.98 ± 0.10	0.96 ± 0.13	0.97 ± 0.11
K_p	-0.79 ± 0.29	-0.80 ± 0.22	-0.78 ± 0.23	-0.77 ± 0.29	-0.82 ± 0.27	-0.77 ± 0.28
E_y	-0.71 ± 0.33	-0.72 ± 0.25	-0.69 ± 0.27	-0.69 ± 0.34	-0.67 ± 0.35	-0.65 ± 0.33
B_z	0.70 ± 0.33	0.71 ± 0.26	0.68 ± 0.27	0.67 ± 0.34	0.66 ± 0.36	0.63 ± 0.34
B_y	-0.09 ± 0.47	-0.07 ± 0.36	-0.07 ± 0.37	-0.06 ± 0.47	-0.09 ± 0.47	-0.09 ± 0.44
B	-0.81 ± 0.27	-0.81 ± 0.21	-0.78 ± 0.23	-0.78 ± 0.29	-0.81 ± 0.28	-0.75 ± 0.29
V	-0.39 ± 0.43	-0.39 ± 0.34	-0.40 ± 0.34	-0.40 ± 0.43	-0.47 ± 0.42	-0.43 ± 0.40
N	-0.48 ± 0.41	-0.51 ± 0.31	-0.47 ± 0.33	-0.47 ± 0.41	-0.47 ± 0.42	-0.42 ± 0.40
P	-0.71 ± 0.33	-0.73 ± 0.25	-0.71 ± 0.26	-0.70 ± 0.33	-0.71 ± 0.34	-0.66 ± 0.33
β	0.45 ± 0.42	0.44 ± 0.33	0.43 ± 0.33	0.44 ± 0.42	0.48 ± 0.42	0.44 ± 0.40

Table 4

Correlation coefficients of ΔR_{sgs} with geo- and heliospheric parameters, as well as with ΔR_{eff}

	ESOI	ROME	AATB	IRKT	MOSC	KGSN
Dst	0.82 ± 0.05	0.82 ± 0.11	0.81 ± 0.13	0.80 ± 0.19	0.80 ± 0.16	0.77 ± 0.16
K_p	-0.74 ± 0.05	-0.75 ± 0.12	-0.75 ± 0.15	-0.74 ± 0.21	-0.74 ± 0.18	-0.71 ± 0.17
E_y	-0.63 ± 0.06	-0.65 ± 0.15	-0.65 ± 0.17	-0.65 ± 0.24	-0.63 ± 0.21	-0.62 ± 0.19
B_z	0.62 ± 0.06	0.64 ± 0.15	0.64 ± 0.17	0.64 ± 0.24	0.62 ± 0.21	0.61 ± 0.20
B_y	-0.10 ± 0.08	-0.11 ± 0.19	-0.12 ± 0.22	-0.15 ± 0.31	-0.13 ± 0.27	-0.10 ± 0.25
B	-0.77 ± 0.05	-0.78 ± 0.12	-0.78 ± 0.14	-0.78 ± 0.20	-0.81 ± 0.16	-0.79 ± 0.15
V	-0.26 ± 0.08	-0.24 ± 0.19	-0.24 ± 0.22	-0.23 ± 0.31	-0.26 ± 0.26	-0.21 ± 0.24
N	-0.56 ± 0.07	-0.57 ± 0.16	-0.56 ± 0.18	-0.55 ± 0.26	-0.57 ± 0.22	-0.59 ± 0.20
P	-0.73 ± 0.06	-0.73 ± 0.13	-0.73 ± 0.15	-0.71 ± 0.22	-0.72 ± 0.19	-0.73 ± 0.17
β	0.33 ± 0.08	0.33 ± 0.18	0.33 ± 0.21	0.32 ± 0.30	0.34 ± 0.25	0.31 ± 0.23
ΔR_{eff}	0.85 ± 0.04	0.87 ± 0.09	0.85 ± 0.12	0.84 ± 0.17	0.87 ± 0.13	0.80 ± 0.15

3. FINDINGS

The analysis of the relationship between CR threshold rigidities and geo- and heliospheric parameters during the extreme storm on May 10–12, 2024 has revealed the following:

1. Model threshold variations ΔR_{eff} exhibit a maximum drop of ~ -1.4 GV at the lowest-latitude ESOI station (which was a surprise to us) in the main phase; during the storm maximum ($Dst = -406$ nT) an hour later, there is a second drop in ΔR_{eff} to the same level at the higher-latitude MOSC station; and after 4 hours, at the mid-latitude IRKT station.

2. Observed threshold variations ΔR_{sgs} show a sharp decrease during the main phase and a maximum drop (-1.1 GV) 4 hours before the storm maximum at MOSC and IRKT. Furthermore, ΔR_{sgs} have a second pronounced minimum of -1.0 GV during the recovery phase on May 11 at IRKT.

3. The highest correlation between ΔR and Dst suggests that the ring current makes the greatest contribution

to geomagnetic screening.

4. There is a high correlation of ΔR with B , B_z , E_y , as well as SW P , whereas it is much lower with other parameters.

5. ΔR_{eff} and ΔR_{sgs} are almost independent of B_y .

6. The specific response of ΔR to changes in heliospheric and magnetospheric parameters during different magnetic storm phases, as well as the latitude dependence of this response are due to different relative contributions of global magnetospheric current systems during these periods.

However, determining unambiguous dependences of ΔR on a specific current system in each storm phase is a challenging and still unresolved problem, since the interaction between the solar wind and the magnetosphere, which controls ΔR variations, is not yet well understood. Further research is called for to identify spatial features of geomagnetic effects in CR penetration into Earth's magnetosphere and to compare them for different storms.

CONCLUSION

In this paper, we have quantified which geomagnetospheric parameters made the greatest contribution to geomagnetic threshold variations and were most geoeffective during the severe magnetic storm on May 10–12, 2024. To do this, we analyzed correlations of ΔR , calculated by two methods, with geomagnetic activity, SW, and IMF parameters. It was found that the geomagnetic thresholds calculated by both methods correlate most strongly with geomagnetic activity, especially with Dst , which indicates the greatest contribution of the ring current to rigidity variations.

It may seem obvious that ΔR_{eff} should have a high correlation with input parameters of the magnetospheric field model employed. For the Ts01 model, these are the Dst index, SW density N and velocity V , as well as IMF B_z and B_y components. Note, however, that the dependence of ΔR_{eff} on these input parameters in the semi-empirical Ts01 model is not direct, but indirect, through calculation of particle trajectories in a model magnetic field, which is set by superposition of various current systems. At the same time, these current systems themselves, their relative contribution to the magnetic field of the model and hence to ΔR_{eff} makes this dependence much more complicated. Generally speaking, describing the magnetospheric magnetic field in terms of contributions of different current sources is a fairly common approach. Other magnetospheric models, such as the paraboloid model [Alexeev et al., 2001] or the event-oriented model [Ganushkina et al., 2018], also describe observed field variations, using combinations of various individual sources [Kalegaev et al., 2005]. The ratios that take into account the relative importance of contributions of magnetotail currents and, for example, the ring current under different disturbance conditions in the geomagnetosphere also differ in Tsyganenko models and depend on a specific model [Kalegaev, 2011; Dubyagin et al., 2014; Castillo et al., 2017]. When studying certain storms by Tsyganenko models, we have found that the correlation of ΔR_{eff} with input parameters of the model can be both high and low [Adriani et al., 2016; Ptitsyna et al., 2019; Ptitsyna et al., 2023]. In particular, the analysis carried out in this paper has revealed that for the storm in May 2024 a very high correlation coefficient $k=0.96\text{--}0.98$ is observed for $\Delta R_{\text{eff}}\text{--}Dst$. Moreover, for the relationship between ΔR_{eff} and K_p , which is not an input parameter of the model, $|k|=0.77\text{--}0.82$, i.e. there is a higher correlation than with all other input parameters except for Dst and B (for which $|k|=0.75\text{--}0.81$). A high correlation (~ 0.7) was also obtained for B_z , E_y , and P . On the contrary, k between ΔR_{eff} and the SW parameters V , N , as well as the plasma β parameter is significantly lower: $|k|\leq 0.5$ at all stations. The IMF B_y component has no effect at all ($k<0.1$).

It is believed that the reconnection between the SW magnetic field and the geomagnetosphere, as well as the SW dynamic pressure P , responsible for magnetosphere compression, play a major role in developing magnetospheric disturbances [Dungey, 1961; Akasofu, 1981; Russell, 2000]. Both of these factors weaken geomagnetic screening, reduce the geomagnetic cutoff rigidity, and facilitate SW plasma penetration into Earth's mag-

netosphere and atmosphere. Indeed, when studying correlations of cutoff rigidities with SW and magnetospheric parameters for different intense storms, high correlation coefficients were obtained with both B_z and SW dynamic parameters (see, e.g., [Ptitsyna et al., 2019; Danilova et al., 2023]). For the storm in May 2024, we have found that geomagnetic threshold variations depend on the solar wind pressure P ($k\sim 0.7$) and B_z ($k\sim 0.6\text{--}0.7$), whose change did cause magnetic field lines to reconnect.

The fact that the variation in the geomagnetic thresholds ΔR , calculated by both methods, correlates most strongly with the Dst index suggests that the ring current plays a major role in controlling the dynamics of CR geomagnetic cutoff rigidities in all storm phases. Significant sensitivity to Dst variations is the most typical feature of the interaction between ΔR and the geomagnetosphere, which has previously been noted in [Ptitsyna et al., 2019; Danilova et al., 2023, 2025]. The relationship between ΔR and other parameters (magnetic or dynamic) depends crucially on characteristics of a particular geomagnetic disturbance [Ptitsyna et al., 2024].

Our analysis has shown that the response of both ΔR_{eff} and ΔR_{sgs} to the controlling electromagnetic parameters, as well as to Dst and K_p , hardly changes with latitude of observation station for this storm. In general, the correlation between ΔR_{eff} and ΔR_{sgs} is quite high ($0.8\text{--}0.87$) (see the last row of Table 4). This testifies that both methods quite adequately describe geomagnetic cutoff rigidity variations depending on variations in geomagnetic and interplanetary parameters.

We are grateful for the opportunity to use the OMNI database [<http://omniweb.gsfc.nasa.gov>], as well as the NMDB database [<https://nmdb.eu/>].

The work was financially supported partly by the Ministry of Science and Higher Education of the Russian Federation (Subsidy No. 075-GZ/Ts3569/278). The results for ΔR_{sgs} were obtained using the equipment of the Core Shared Research Facility “Angara” of ISTEP SB RAS [<http://ckp-rf.ru/ckp/3056/>] and the Large-Scale Research Facility “Russian National Ground-Based Network of Cosmic Ray Stations” (CRS network) [<https://ckp-rf.ru/usu/433536>].

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Original Russian version: Danilova O.A., Sdobnov V.E., published in *Solnechno-zemnaya fizika*. 2026, vol. 12, no. 3, pp. 82–91. <https://doi.org/10.12737/szf-123202608>. © 2026 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M).

How to cite this article

Danilova O.A., Sdobnov V.E. Relationship between geomagnetic thresholds of galactic cosmic rays and heliospheric parameters during the May 10–12, 2024 storm. *Sol.-Terr. Phys.* 2026, vol. 12, iss. 3, pp. 72–80. <https://doi.org/10.12737/stp-123202608>.