Open Access Online Journal on Astronomy and Astrophysics

Acta Astrophysica Taurica

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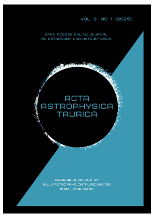

Acta Astrophys. Tau. 6(1), 35–39 (2025)

Analysis of data on cosmic ray variations during periods of interplanetary disturbances and geomagnetic storms

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Received 29 September 2024

ABSTRACT

The paper presents the results of the method developed by the authors for analyzing data on cosmic ray variations during interplanetary disturbances and geomagnetic storms. The method was tested on the data from neutron monitors at high-latitude and polar stations. Numerical implementation of the method allows obtaining the result of the cosmic ray flux state assessment as the neutron monitor data enter the processing system. The efficiency of the method was confirmed based on statistical modeling performed using both natural and model data. The results showed that at the rate of data recording in the processing system ($\Delta t = 1$ sec), application of the developed method allows us to detect anomalous changes, which precede and accompany magnetospheric disturbances of varying intensity, in the cosmic ray flux.

Key words: cosmic rays, Forbush effects, space weather, natural data analysis

1 Introduction

Cosmic rays (CRs) were first discovered over a hundred years ago. However, the research related to this physical phenomenon becomes more and more relevant every year (Kuznetsov, 2014; Mandrikova, 2024). The interest to the study of cosmic rays is due to a number of factors, for example, the study of the fundamental properties of the matter, the search for astrophysical objects in which a cosmic ray spectrum is generated, the study of the processes that form this spectrum, etc. (Berezhko, 2007; Murzin, 2007). In recent years, due to the active development of communications, information and computer technologies, space weather problems have become especially important. Cosmic rays are a significant factor in space weather (Kuznetsov, 2014). Nowadays, scientists from different fields of knowledge and countries actively study anomalous manifestations of cosmic rays (Forbush effects and ground level enhancement events, GLE events), developing and improving their methods (Krymsky et al., 1966; Veselovskii, Yakovchuk, 2011; Belov et al., 2018b; Mandrikova, 2024; Real Time Data Base for the Measurements of High-Resolution Neutron Monitor). One of the successful physical methods for detecting Forbush effects based on the data from a neutron monitor network is the global survey method (Belov et al., 2018b). This method originates in the 1960s (Krymsky et al., 1966) and has been actively developed by a group of scientists (Belov et al., 2018b) up to this day. The global survey method is complex. This method includes the method of cosmic ray variation coupling functions, particle trajectory calculations, and spherical analysis to identify significant spherical harmonics. A disadvantage of this approach is the high computational complexity of the calculations. As a result, it is difficult to automate the global survey method, and it is of little use for the operational forecast of Forbush effects. Another method used to forecast major cosmic ray anomalies (GLE events) is the threshold GLE Alert method (Real Time Data Base for the Measurements of High-Resolution Neutron Monitor). This method provides an answer in the mode of data receipt in the processing system, but has low efficiency (Veselovskii, Yakovchuk, 2011). Recently, digital signal processing, time decomposition of data, machine learning and artificial intelligence have also been used to obtain information from cosmic ray variation data. For example, a group of scientists from different countries (Peraza et al., 2013) proposed to use a wavelet analysis for the task of forecasting the increases in cosmic rays intensity. Using Morlet wavelets, the authors classified the periodicities of cosmic rays of the three main GLE groups and identified periodicities consistent with the changes in solar activity. For the problem of rapid transit time forecasting of coronal mass ejections (CME) directed to the Earth, Minta et al. (2023) proposed to use a cascade feed-forward neural network (CFNN). The studies of Minta et al. (2023) demonstrated the efficiency of the constructed neural network model and the possibility of its application for rapid forecasting of the arrival time of CME. The authors estimated that the model forecast error ranges from −2.43 to +23.75 h, which is a good result compared to wider variations from the authors' previous studies. Thus, the problems associated with the study of cosmic rays currently require improvement and creation of more effective methods and approaches.

This work continues the research of Mandrikova (2024) and Mandrikova, Mandrikova (2024) and is devoted to the development of methods for analyzing cosmic ray variation data and detecting anomalies. The paper presents the results of the method developed by the authors for analyzing cosmic ray variation data during interplanetary disturbances and geomagnetic storms. The method was tested on neutron monitor data from high-latitude and polar stations. Numerical implementation of the method allows us to detect anomalous changes in neutron monitor data and estimate their parameters (duration, intensity, and sign) at the rate of data receipt in the processing system ($\Delta t = 1$ sec). The efficiency of the method was confirmed based on statistical modeling performed using both natural and model data. The study showed that the dynamics of the cosmic ray flux (according to the data from ground-based neutron monitor stations) is determined by the type and strength of an interplanetary disturbance and the magnetosphere state. Anomalous changes in the CR flux according to the data from different neutron monitor stations have pronounced general dynamics.

2 Method

The method includes the following operations:

2.1 Operation 1

Using a set of bases $D = U_{\lambda\in\Lambda}B_\lambda$ (Mallat, 1999), we perform decomposition into wavelet packets $W_j^0 = \bigoplus_{j=0}^{J} W_j^p, \{\Psi_j^p(2^j t - m)\}_{m\in\mathbb{N}}$ (Mallat, 1999; Chui, 1992) and determine the information components: base $B_j^p = \{\Psi_j^p(2^j t - m)\}_{m\in\mathbb{N}}$ of space W_j^p is the basis

$$B_{j_i}^{p_i} = \begin{cases} \overset{\left\{\Psi_{j_i}^{p_i}(2^{j_i}t-m)\right\}_{m\in\mathbb{N}}}{} \\ if \sum\limits_{m\in I^{p_i}} \left|\left\langle f, \Psi_{j_i,m}^{p_i}\right\rangle\right|^2 \geq \sum\limits_{m\in I^{2p_i}} \left|\left\langle f, \Psi_{j_i+1,m}^{2p_i}\right\rangle\right|^2 + \sum\limits_{m\in I^{2p_i+1}} \left|\left\langle f, \Psi_{j_i+1,m}^{2p_i+1}\right\rangle\right|^2, \\ \overset{\left\{\Psi_{j_i+1}^{2p_i}\right\}_{m\in\mathbb{N}} \cup \left\{\Psi_{j_i+1}^{2p_i+1}\right\}_{m\in\mathbb{N}}}{} \\ if \sum\limits_{m\in I^{p_i}} \left|\left\langle f, \Psi_{j_i,m}^{p_i}\right\rangle\right|^2 < \sum\limits_{m\in I^{2p_i}} \left|\left\langle f, \Psi_{j_i+1,m}^{2p_i}\right\rangle\right|^2 + \sum\limits_{m\in I^{2p_i+1}} \left|\left\langle f, \Psi_{j_i+1,m}^{2p_i+1}\right\rangle\right|^2, \end{cases}$$

where $I^l, l = p, 2p, 2p+1, m \in I^l, if\left|\left\langle f(t), \psi_{j,m}^p\right\rangle\right| \geq T_{j,\alpha}^p$, $T_{j,\alpha}^p = t_{1-\frac{\alpha}{2},N-1}\widehat{\sigma}_{p,j}$.

2.2 Operation 2

We perform a wavelet reconstruction of the components obtained in Operation 1 and estimate the approximation error

$$\tilde{f}_{\mathcal{B}\lambda}(t) = {}^{J}_{j=0}\sum{}^{M}_{m=1}\sum T_{j,a}^{P}(\langle f, \psi_{j,m}^p\rangle)\psi_{j,m}^p(t),$$

$$\mathfrak{R}_{B_{best}} = \min_{B_\lambda} \|f(t) - \tilde{F}_{B_\lambda}(t)\|^2,$$

where M is the signal length, and J is the largest scale.

2.3 Operation 3

To detect anomalies, we map the function $\tilde{F}_{B_\lambda(t)}$ into wavelet space and apply thresholds:

$$\hat{A}_\psi(t) = \sum_k \sum_{n=1}^{N} P_{T_{a,k,n}}(C_{k,n})\psi_{k,n}(t),$$

where $\psi_{k,n}(t) = 2^{\frac{k}{2}}\psi(2^k t - n)$ are the basis wavelets, $C_{k,n} = \left\langle \tilde{f}_{B_{best}}(t), \psi_{k,n}\right\rangle$,

$P_{T_{a,k,n}}(C_{k,n}) = \begin{cases} C_{k,n}, if\ |C_{k,n}| \geq T_{a,k,n} \\ 0, if\ |C_{k,n}| < T_{a,k,n} \end{cases}$ are the thresholds.

2.4 Operation 4

Based on the decision statistic, E_n calculates the intensity of the anomaly detected based on *Operation 3:*

$$E_n = \sum_{k=0}^{K} P_{T_{a,k,n}}(C_{k,n}).$$

2.5 Operation 5

A conclusion about the presence (absence) of an anomaly is formulated according to the rule that there is an anomaly in the data at time $t = n$ and its intensity is equal to E_n, if $\Phi_{T_{ap}}(E_n) > 0$,

$$\Phi_{T_{ap}}(E_n) = \begin{cases} E_n, |E_n| \geq T_{ap}, \\ 0, |E_n| < T_{ap}, \end{cases}$$

T_{ap} is the threshold.

Note. The thresholds T_{ap} for each neutron monitor station were estimated by minimizing the a posteriori risk (Chui, 1992). The threshold T_{ap} divides the space E_n into two nonintersecting regions: region $E_0 : E_n < T_{ap}$ (hypothesis Γ_0, data state s_0) and region $E_1 : E_n \geq T_{ap}$ (hypothesis Γ_1, data state s_1). The average losses are defined as

$$J_j = \sum_{j\neq i} P\{s_j/E_n \in E^i\},$$

where $P\{H_j/E_n \in E^i\}$ is the a posteriori probability of the data state s_j. The thresholds T_{ap} were selected to ensure $J = \min(J_0 + J_1)$.

3 Results of the method and discussion

The data from ground-based neutron monitor stations were used. When selecting the stations, their geographic coordinates were considered. Taking into account the opinion of the specialists in the applied field[1], data from the neutron monitor stations located at high and polar latitudes were used. As it was indicated in Solar-Terrestrial Physics, Forbush effects are more pronounced when cosmic ray intensity is measured at high latitudes. In addition, we used the data that did not contain outliers characteristic of hardware errors and did not

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[1] Solar-Terrestrial Physics

have long gaps. If the data contained small (up to 10 counts) gaps, they would be filled with median values. When generating data samples, in order to obtain reliable results, their representativeness was also taken into account. Data were selected for the periods in which measurement results from several stations (at least three) were available. The scientific value of neutron monitor measurement results is known to increase significantly when data from several stations are analyzed jointly (Moraal et al., 2000).

The data were taken from the Real Time Data Base for the Measurements of High-Resolution Neutron Monitor, which provides access to good-quality neutron monitor data (Mavromichalaki et al., 2011). Therefore, in the absence of large gaps and outliers in the data, they were accepted as correct.

When choosing periods for the analysis, the magnetosphere state was taken into account. The Dst index was used to determine the magnetosphere state. The data were analyzed for the periods of magnetic storms, two days (or more) before the onset of which the magnetosphere state was calm (the Dst index varied around zero).

High-latitude and polar stations are more informative for the analysis of secondary CR dynamics (Belov et al., 2018a; Solar-Terrestrial Physics); thus, the data from the Apatity (Coord.: 67.5704, 33.3935), Inuvik (Coord.: 68.36, -133.72), Oulu (Coord.: 65.0544, 25.4681), and South Pole (Coord.: -90, 0) stations were under analysis (Real Time Data Base for the Measurements of High-Resolution Neutron Monitor).

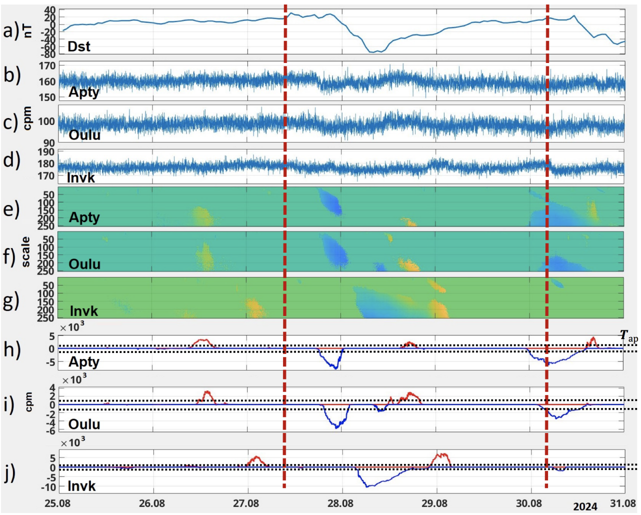

Fig. 1. Processing results: (a) geomagnetic activity Dst index; (b–d) NM data; (e–j) results of the method.

During the analyzed period (Fig. 1), two magnetic storms occurred on August 27 and 30, 2024. Both events were caused by the arrival of a high-speed stream from coronal mass ejections (CME on August 22–23 and CME on August 26). According to space weather data (Moraal et al., 2000), on August 25 and 26, the solar wind speed (SWS) varied in the range of 300–250 km/sec, and the southern component fluctuated from $Bz = -4nT$ to $Bz = +3nT$. The results of the method (operations 3–5) for the data of all analyzed stations show anomalous changes in CR variations (Fig. 1, b–d) both on the eve and during the events (Fig. 1, e–j). On the eve of the moderate magnetic storm on August 27, a weak anomalous increase in CR intensity is observed with a delay of several hours at different stations. On August 27 at 07:00 UTC, a high-speed stream (CME from August 22 and 23) arrived, marked in the figure by the red vertical line (Moraal et al., 2000). Fluctuations of the southern component increased to $Bz = -13nT$; the SWS began to increase and by 13:00 UTC on August 27 reached a value of 330 km/sec. The results of the method (Fig. 1, e–j) show a sharp anomalous decrease in CR intensity (Forbush decrease) during the event at all analyzed stations lasting for about 7 hours. According to Moraal et al. (2000), on August 28, the Dst index reached a value of −76 (Fig. 1a; Mavromichalaki et al., 2011). During the recovery phase of the magnetic storm, an increase in the CR flux intensity occurred. It reached the maximum values at the end of the day on August 28.

Furthermore, the results of the CR variation data processing (Fig. 1, e–j) show a sharp anomalous decrease in CR intensity (Forbush effect) at all analyzed stations from the beginning of the day on August 30, lasting for about 14 hours at the Apatity station and 8 hours at the Oulu station. According to Moraal et al. (2000), on August 30, the Dst index reached a value of −54 (Fig. 1a), and a weak magnetic storm occurred.

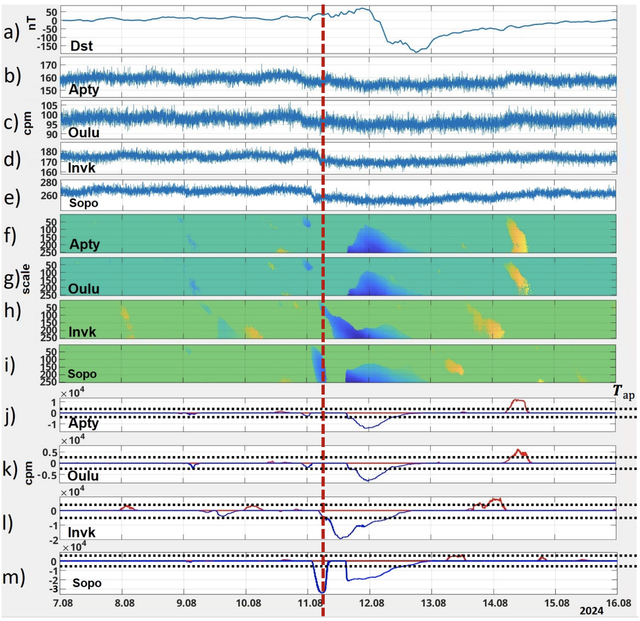

Fig. 2. Processing results: (a) geomagnetic activity Dst index; (b–e) NM data; (f–m) results of the method.

During the next analyzed period (Fig. 2), a strong magnetic storm occurred on August 11, 2024, caused by the arrival of a high-speed stream from a coronal mass ejection (CME on August 8). According to the space weather data[2], at the beginning of the analyzed period and until 11:00 UTC on August 10, the SWS was within 360–400 km/sec, and the southern component of the interplanetary magnetic field

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[2] Institute of Applied Geophysics

(IMF) fluctuated from $Bz = -6nT$ to $Bz = +5nT$. According to the results of the method (operations 3–5), the state of CR variations was calm during this period (Fig. 2, f–m). On August 10, the SWS began to increase and by 02:00 UTC on August 11 reached a value of 500 km/sec; fluctuations of the southern component increased to $Bz = -18nT$ (Institute of Applied Geophysics).

Against the background of increasing SWS and IMF fluctuations, the anomalous increases and decreases in CR intensity, reaching the upper limit of the background level, are observed at certain moments of time (Fig. 2, f–m). On August 11 at 6:00 UTC, a gradual commencement of the magnetic storm was recorded at the Novosibirsk station. Three-four hours before the storm onset, according to the data from all analyzed stations, an anomalous decrease in CR intensity is observed (Fig. 2, f–m). During the initial phase of the storm, the CR intensity was also anomalously reduced (a prolonged Forbush decrease). Then, on August 11 at 20:00 UTC, a high-speed stream from a coronal mass ejection (CME from August 09) arrived, fluctuations of the southern component increased to $Bz = -20nT$, and the SWS increased to 520 km/sec (Institute of Applied Geophysics). During this period, the Forbush decrease reached its greatest amplitude (Fig. 2, f–m), and its total duration was about a day. According to the data from Geomagnetic Equatorial Dst Index, on August 12, the Dst index reached a value of –188 (Fig. 2a). During the recovery phase of the magnetic storm, the intensity of the CR flux began to increase and reached the characteristic values in the middle of the day on August 14.

Statistical modeling was performed to evaluate the efficiency of the proposed method. Model data were constructed based on the similarity of natural data. About 1500 model signals were formed. Additive correlated (pink) and white noises with different signal-to-noise ratios were added to the model signals. To assess the sensitivity of the method and test its stability, model data with different signal-to-noise ratios were constructed, and anomalies of different amplitudes and durations were used. Figure 3 shows an example of neutron monitor data (Oulu station) for the period from July 15 to 20, 2017 (Fig. 3a) and a model signal constructed based on its similarity (Fig. 3c).

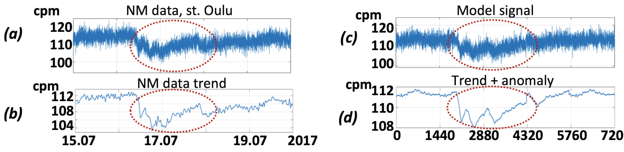

Fig. 3. Data: (a) NM signal at the Oulu station; (b) trend of NM signal; (c) the model signal; (d) trend of the model signal.

Figure 4 shows the examples of the constructed model signals, a long-term negative anomaly (Fig. 4b), and a short-term low-amplitude anomaly (Fig. 4d).

The graphs of anomaly detection probabilities based on statistical modeling, depending on the anomaly amplitude (signal-to-noise ratio) and anomaly duration, are illustrated in Fig. 5. The analysis of the results shows that the detection probability for the anomaly, having the duration of 20 counts, is more than 80% for a signal-to-noise ratio of 1.5 (at the false alarm rate $\alpha = 0.05$). When the anomaly is more than 60 counts, the detection probability is close to 90% for a signal-to-noise ratio of 1.3. The results for the problem solved are satisfactory.

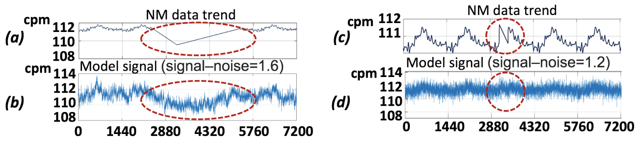

Fig. 4. Data: (a, c) trend of the model signal; (b, c) the model signal.

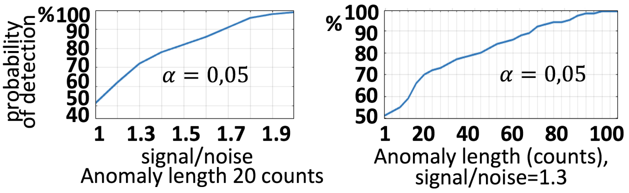

Fig. 5. Graphs of the anomaly detection probabilities.

The considered events show the complex dynamics of galactic cosmic rays (GCRs) during anomalous processes on the Sun and magnetic storms. The analysis of data from different neutron monitor stations indicates a variety of forms of anomalies in CR variations, which is consistent with the results of Aghion et al. (2018) and Andrei et al. (2018). Note that on the eve of events, both an anomalous increase in CR intensity and an anomalous decrease in CR intensity can be observed. This is consistent with the results of earlier studies (Badruddin et al., 2019a; Mandrikova, Mandrikova, 2021), as well as with the works of other authors (Belov et al., 2015; Homola et al., 2020). Due to the variety of anomalies and, in some cases, their possible absence at some stations (Homola et al., 2020), analysis for a network of stations is required for the reliability of the information obtained.

The comparison of the results of different neutron monitors shows a clearly defined general dynamics in cosmic rays, both before and during the events considered. This indicates the reliability of the results of the proposed method. A preliminary increase or decrease in CRs before a magnetic storm allows it to be used as a predictor (e.g., Munakata et al., 2000; Dorman, 2005). Badruddin et al. (2019b) studied the correlation between the variability of GCRs and Dst during the strongly disturbed period of September 4–10, 2017. The results of the authors showed the presence of a delay in Dst by several hours, which is consistent with the results obtained and confirms the importance of taking into account the variability of CRs in space weather.

During the strongest geomagnetic disturbances, according to the results of the study, there was a decrease in variations of CR intensity, and then, during the recovery phase of the storm, it gradually increased and exceeded the intensity before the storm. Similar dynamics in GCRs is described in Gaisser (1974).

The results of the study confirm the need to create effective methods for data analysis capable of detecting anomalies at a low signal-to-noise ratio. Widely used averaging methods (classical methods of time series analysis, neural network approximations, etc.) allow one to study the characteristic changes in GCRs, but they are insensitive to low-amplitude anomalies (Livada et al., 2018). Another disadvantage of averaging methods is the risk of distortion of the information that can result in either an undetected anomaly or a "false" alarm signal. In addition, as indicated in Kudela, Brenkus (2004) and Thomas et al. (2015), anomalies in CRs observed on the Earth may not be associated with magnetic storms. Therefore, the task of forecasting magnetic storms requires further research using different approaches and methods.

4 Conclusions

The research confirmed the complex dynamics of cosmic ray variations during solar and magnetospheric events. The results are consistent with the earlier studies of Mandrikova (2024), Mandrikova, Mandrikova (2024), and the works of other authors (Veselovskii, Yakovchuk, 2011; Peraza et al., 2013; Belov et al., 2018a, b; Minta et al., 2023). Anomalous changes in the CR flux according to the data from different neutron monitor stations have pronounced general dynamics. According to the results of the developed method, anomalies exceeding the background level in amplitude and characterizing the increase in disturbances in the near-Earth space were identified on the eve of the events. At the initial and main stages of the analyzed magnetic storms, prolonged decreases in the level of CR variations were observed. They were recorded at different stations with possible delays of several hours.

The obtained results confirm the importance of taking into account the CR dynamics based on measurements of ground-based neutron monitor stations when forecasting space weather. The study also shows the effectiveness of the developed method for studying CR variations and its ability to detect anomalous changes of varying intensity and duration. The authors plan to continue working in this direction and develop the method with the construction of decision-making rules taking into account the identified general dynamics of the CR on the principles of system analysis.

Acknowledgments. The work was supported by the IKIR FEB RAS state assignment (subject registration No. 124012300245-2).

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