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PECULIARITIES OF SPORADIC VARIATIONS IN DENSITY AND ANISOTROPY OF GALACTIC COSMIC RAYS IN SOLAR CYCLE 24

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Abstract. In this work, we have processed data from the global network of neutron monitors and muon telescopes by the global survey method to study variations in the density and anisotropy of galactic cosmic rays during Forbush decreases observed in solar cycle 24. The simultaneous use of two different type detectors made it possible to examine the temporal dynamics of the angular distribution of cosmic rays in two different energy intervals. Besides, we have used measurements of the Yakutsk cosmic ray spectrograph after A.I. Kuzmin to assess the energy spectrum index during large disturbances of the interplanetary medium in this cycle. Analysis of the results obtained confirms our early statements that solar activity cycle 24 features an increased level of turbulence in the interplanetary magnetic field.

Keywords: cosmic rays, solar activity, Forbush decreases, energy spectra.

INTRODUCTION

Solar activity (SA) cycle 24 saw a low number of sunspots and weak manifestations of interplanetary and geomagnetic disturbances compared to previous cycles 19–23 [Bazilevskaya et al., 2021]. Our earlier estimate [Grigoryev et al., 2014] of the energy spectrum of Forbush decreases (FD) has shown that a softer energy spectrum was observed during the ascending phase of solar cycle 24 than during the previous one. This indicates that, unlike cycle 23, at the beginning of cycle 24 the interplanetary magnetic field (IMF) was more turbulent, hence the role of the diffusion mechanism must have prevailed in the FD formation during that period [Krymsky et al., 1981].

In this paper, by processing data from the worldwide network of neutron monitors (NM) and muon telescopes (MT), using the global survey method [Altukhov et al., 1970; Nagashima, 1971; Belov et al., 1974; Dvornikov et al., 1983], we examine variations in the density and anisotropy of galactic cosmic rays (CR) during FD events in solar cycle 24. The global survey method [Altukhov et al., 1970], developed at ShICRA SB RAS, makes it possible to use Earth with the existing worldwide NM network as a single instrument oriented in many directions at each measured moment. Recently, we have modified this method [Gololobov et al., 2021]. It can now provide information on CR distribution from the MT network data. The paper relies on the results of calculations of the first angular momentum of the CR distribution function, obtained by processing data from the Neutron Monitor Database (NMDB) [https://www.nmdb.eu] and the Global Muon Detector Network (GMDN) [http://cosray.shinshu-u.ac.jp/crest/DB/Public/Archives/GMDN.php] by the global survey method for 2012–2017. Taking into account CR trajectories in the geomagnetic field and their interaction with Earth's atmosphere allows us to theoretically estimate the relationship between primary CR intensity variations outside the magnetosphere and the intensity directly recorded by a ground-based detector. In the global survey method, such an estimate is made by introducing the so-called receiving vectors [Krymsky et al., 1981], expressed by the components x_n^m, y_n^m. In this case, the CR intensity I^j, recorded by the j-th ground-based detector is determined by the following expression:

$$I^j = \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(a_n^m x_n^{m,j} + b_n^m y_n^{m,j} \right) K_n^j, \qquad (1)$$

where a_n^m, b_n^m are the components of spherical harmonics of CR angular distribution, K_n^j is the normalizing factor necessary to take into account the difference in energy sensitivity of each detector; a_n^m, b_n^m are found by solving system of equations (1), using a sufficient number of independent and multidirectional ground-based CR detectors.

This approach involving CR detectors of different types allows us to simultaneously track the temporal dynamics of CR density and anisotropy parameters in different energy ranges. For example, the mean CR energies recorded by the NM network are ~15 GeV, while the MT network detects CRs with energies of ~50 GeV. This method provides us with the CR anisotropy parameters that indirectly indicate CR modulation processes in a large-scale perturbed structure.

It is also of interest to further investigate FD energy spectra, using a technique based on data from the Yakutsk spectrograph equipped with NM and an underground MT complex at 0, 7, 20, and 40 m of water equivalent (w.e.) [Shafer et al., 1967]. This technique considers the ratio of expected and observed readings of detectors located in the same geographical location, so the perturbing effect of various atmospheric and geomagnetic factors is minimized.

The FD formation mechanism was studied in [Krymsky et al., 1981], where a CR decrease was assumed to be due to a high degree of IMF irregularity and the presence of magnetic inhomogeneities in the solar wind. This mechanism was called diffusion and led to the formation of a power-law spectrum with an index equal to –1. In the same paper, the dynamics of the diurnal CR anisotropy expected from the diffusion mechanism of FD formation was calculated. It was shown that the arrival of the perturbed structure at Earth would have been accompanied by an anisotropic CR flux directed from the Sun to Earth and arising due to convective CR outflow. Thus, the experimental observation of CR anisotropy with corresponding direction during FD events may be considered an additional indication to the diffusion mechanism of FD formation.

Our paper experimentally determines peculiarities of variations in density and anisotropy of galactic CRs during large-scale solar wind disturbances in solar cycle 24, using data from ground-based CR detectors, and calculates the FD energy spectrum from the Yakutsk CR spectrograph data.

VARIATIONS IN THE DIURNAL CR ANISOTROPY VECTOR DURING FORBUSH DECREASES

We have analyzed ten cases of manifestations of significant FD events (>4 % in FD amplitude at the Yakutsk CR spectrograph's NM) in solar cycle 24: March 9, 2012 (11.2 %), July 15, 2012 (7 %), April 15, 2013 (4.3 %), June 24, 2013 (4.4 %), September 12, 2014 (5 %), December 23, 2014 (6.4 %), March 17, 2015 (4.7 %), June 23, 2015 (8.6 %), July 16, 2017 (6.6 %), September 8, 2017 (8.0 %). The following periods have been included in the analysis: a day before the commencement of disturbances and three subsequent days after. When determining the CR distribution by the global survey method, on average for each event we have used data from about 30 neutron monitors and five multidirectional muon telescopes recording CRs from more than 50 independent directions. This allowed us to isolate with sufficient accuracy the one-hour dynamics of the isotropic part of the CR intensity and CR vector anisotropy parameters. We preprocessed data from each CR detector to take into account distorting factors of instrumental and atmospheric origin.

The analysis shows that in eight of ten cases variations in the behavior of the vector of the first CR distribution harmonic during FD events are consistent with the diffusion mechanism of formation of these disturbances. The azimuthal direction of CR anisotropy before the arrival of the shock wave changes to the sunward radial one, which indicates an increase in IMF turbulence during cycle 24 as compared to cycles 22 and 23. As an example we show isotropic parts of the CR intensity and the behavior of the diurnal anisotropy vectors $\vec{A}_{11}$, obtained by the global survey method for the FD events observed in March 2012 (Figure 1) and September 2014 (Figure 2).

Analysis of these figures suggests that the behavior of the vector $\vec{A}_{11}$, determined from MT measurements is noticeably more stable in value and direction than that from NM data. This is due to the lower sensitivity of CRs, recorded by MT, to the small-scale structure of solar wind disturbances. Nevertheless, the anisotropy behavior, according to the data from the above detectors, is, on average, fairly consistent. At the same time, owing to the more bounded energy range of particle detection, the modulation depth of intensity of CRs detected by MT during the disturbances was much less than that calculated from the NM network's data.

FD ENERGY SPECTRUM

The FD energy spectrum has been treated by many authors [Kuzmin, 1968; Sakakibara et al., 1987; Despotashvili et al., 1999; Wawrzynczak, Alania, 2011]. They found and analyzed the dependence of the rigidity (or energy) spectrum of Forbush effects on the SA level and phase, as well as on the polarity sign of the general solar magnetic field. At the same time, the generally accepted shape of the energy spectrum is a power-law spectrum with the index γ [Dorman, 1963; Krymsky et al., 1981; Cane, 2000]. The choice of the spectrum of this type is due to its simplicity and satisfactory agreement with experimental data. According to some studies, the FD energy spectrum might have a more complex shape. For example, in [Kojima et al., 2013; Alania, Wawrzynczak, 2012] it was noted that the FD spectrum, according to NM data, might be harder than that according to MT data.

Nonetheless, it is of interest, in order to expand our earlier works ([Gerasimova et al., 2000; Grigoryev et al., 2014]), to apply the data from NMs and underground MTs of the Yakutsk spectrograph to determine γ with the assumed power-law spectrum of Forbush effects. If the expected Forbush decrease spectrum is represented as a simple power-law function $a_0 E^{-\gamma}$, where a_0 is an unknown constant, $E^{-\gamma}$ is the energy spectrum, its amplitude A (or variations in CR intensity $\delta I/I$ observed by a device) is determined by the expression

$$A = \frac{\delta I}{I} = \int_{E_{\min}}^{\infty} a_0 E^{-\gamma} W(E)\, dE.$$

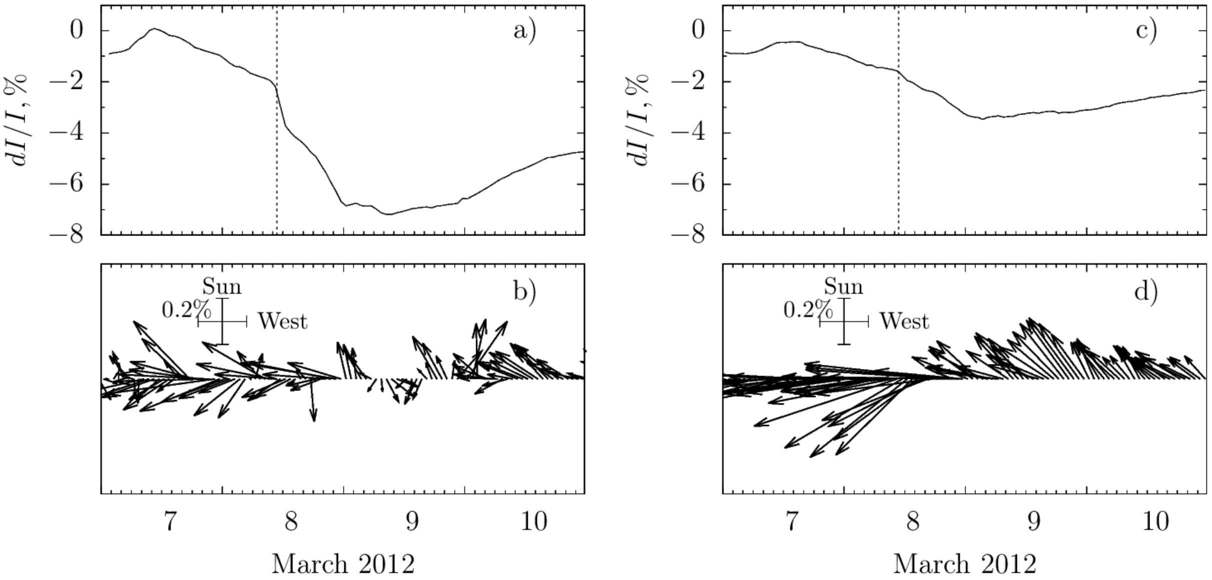

Figure 1. Isotropic parts of CR intensity *dI/I* and the behavior of diurnal CR anisotropy variation vectors $\vec{A}_{11}$ according to NM (*a*, *b*) and MT (*c*, *d*) data during the FD event in March 2012. Vertical dotted lines indicate the moments of shock wave arrival determined from spacecraft measurements [https://omniweb.gsfc.nasa.gov/form/dx1.html]

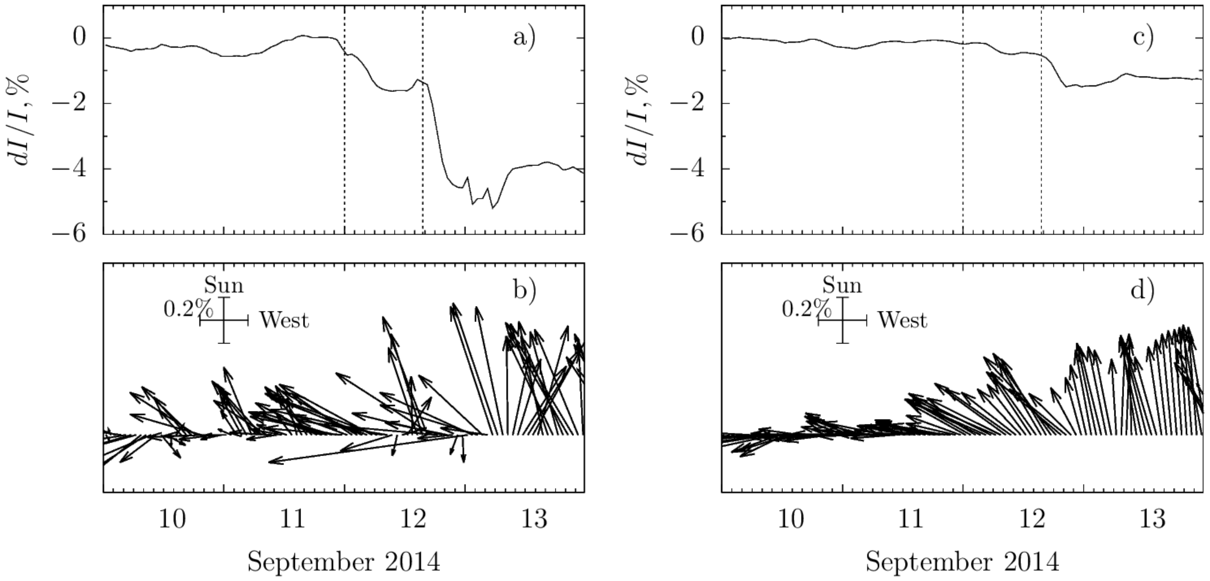

Figure 2. The same as in Figure 1 for September 2014

Here $E_{\min}$ is the minimum energy that this device can detect; *W*(*E*) are coupling coefficients [Dorman, 1963].

Gerasimova et al. [2000] have analyzed the energy spectrum of the Forbush decreases observed in 1965–1994, using CR intensity data from the worldwide NM network’s stations and MT of the Yakutsk spectrograph. They showed that the FD energy spectrum index γ depends on the solar cycle phase and there is a significant correlation with the level of IMF turbulence. At the same time, it is noted that variations in the IMF turbulence level may be one of the main factors determining the dynamics of the FD energy spectrum. Later in [Grigoriev, Starodubtsev, 2011; Grigoryev et al., 2014], the period considered was extended to 2012 and included the ascending phase of solar cycle 24. According to the measurement data from the Yakutsk CR spectrograph, using the above method, we further estimate the energy spectrum index γ of the Forbush decreases observed in solar cycle 24. This period features a low level of SA and a small number of FD events, which were experimentally observed at all recording levels of the spectrograph. In this case, we select those events that appeared in the data from all levels of the underground MT complex (7, 20, and 40 m w.e.), which in the above method is a selection criterion for the events that provide the most accurate estimate of the spectrum index. Table lists dates, amplitudes, and values of the energy spectrum index for nine FD events that occurred in solar cycle 24 and met the above criterion, except for those we analyzed earlier. Table indicates that the amplitude at the level of 40 m w.e. is basically comparable with the value of the statistical observational error (~0.4 %).

FD amplitudes according to the NM and MT data from the Yakutsk CR spectrograph for the events under study. The corresponding values of the spectrum index γ and the errors in its determination σ are given

Date	A_{HM}, %	A_{MT0}, %	A_{MT7}, %	A_{MT20}, %	A_{MT40}, %	γ	σ
14.04.2013	4.3	1.5	1.2	0.9	0.6	0.79	0.09
15.12.2013	4.7	1.4	1.2	0.8	0.7	0.79	0.10
09.11.2014	3.7	1.2	0.8	0.5	0.3	1.19	0.11
20.12.2014	6.4	2.5	1.8	1.1	0.8	1.01	0.05
16.03.2015	4.7	1.7	1.2	0.7	0.5	1.10	0.08
21.06.2015	8.6	3.8	2.6	1.7	1.0	1.07	0.04
30.12.2015	4.7	1.5	1.2	0.9	0.7	0.79	0.10
16.07.2017	6.6	2.2	1.6	1.0	0.6	1.06	0.06
08.09.2017	8.0	3.5	2.0	1.3	1.0	1.24	0.04

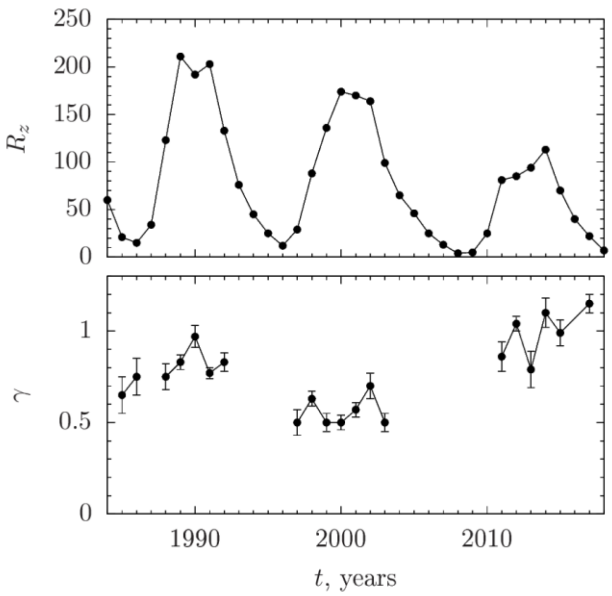

Figure 3. Number of sunspots R_z and the annual average index γ of the FD power-law energy spectrum for 1985–2017

Figure 3 presents the previously determined annual average values of the energy spectrum index γ for 1985–2012 [Grigoriev, Starodubtsev, 2011; Grigoryev et al., 2014] and those recalculated for 2013–2015 and 2017. It can be seen that a softer energy spectrum of FD was observed in cycle 24 than in cycles 22–23. Such a softening of the FD energy spectrum in cycle 24 suggests that the diffusion mechanism of FD formation plays a key role.

CONCLUSION

The sporadic variations in the density and anisotropy of galactic CRs examined using the global survey method and ground-based measurements in solar cycle 24 allow us to state that the diffusion mechanism dominates in the FD formation, which indicates an increased IMF turbulence compared to previous cycles. This is also confirmed by the estimated energy spectrum index of these variations derived from measurements made with instruments of the Yakutsk CR spectrograph after. A.I. Kuzmin.

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REFERENCES

Alania M.V., Wawrzynczak A. Energy dependence of the rigidity spectrum of Forbush decrease of galactic cosmic ray instensity. *Adv. Space Res*. 2012, vol. 50, pp. 725–730.

Altukhov A.M., Krymsky G.F., Kuzmin A.I. The method of “global survey” for investigating cosmic ray modulation. *Proc. 11th International Conference on Cosmic Rays*. Budapest, 1970, vol. 4, pp. 457–460.

Bazilevskaya G.A., Daibog E.I., Logachev Yu.I., Vlasova N.A. Characteristic features of solar cosmic rays in the 21st–24th solar-activity cycles according to data from catalogs of solar proton events. *Geomagnitism and aeronomy.* 2021, vol. 61, no. 1, pp. 6–13. DOI: 10.1134/S0016793221010023.

Belov A.V., Blokh Ya.L., Dorman L.I., Eroshenko E.A., Inozemtseva O.I., Kaminer N.S. Anisotropy and time dependent changes in the spectrum of cosmic-ray intensity variations during August, 1972. *Izv. AN SSSR. Ser. fiz.* [Bull. Academy of Sciences of USSR. Physics]. 1974, vol. 38, pp. 1867–1875.

Cane H.V. Coronal mass ejections and Forbush decrease. *Space Sci. Rev*. 2000, vol. 93, pp. 55–77.

Despotashvili M.A., Nachkebia N.A., Shatashvili L.Kh. The energetic spectrum changes of Forbush effects during the different 11-year cycles of solar activity. *Proc. 26th International Conference on Cosmic Rays*. Salt Lake City, 1999, vol. 6, pp. 419–422.

Dorman L.I. *Variatsii kosmicheskikh luchei i issledovanie kosmosa* [Cosmic ray variations and space investigation]. Moscow. 1963, 1028 p. (In Russian).

Dvornikov V.M., Sdobnov V.E., Sergeev A.V. Analysis of cosmic ray pitch-angle anisotropy during the Forbush-effect in June 1972 by the method of spectrographic global survey. *Proc. 18th International Conference on Cosmic Rays*. Bangalore, 1983, vol. 3, pp. 249–252.

Gerasimova S.K., Grigoryev V.G., Krivoshapkin P.A., Skripin G.V., Starodubtsev S.A. Variation of the Forbush-decrease rigidity spectrum with the cycles of solar activity. *Solar System Res.* 2000, vol. 34, no. 3, pp. 262–264.

Gololobov P.Yu., Grigoryev V.G., Starodubtsev S.A., Zverev A.S., Gerasimova S.K. Method of global survey involving data of muon telescope network. *Astroparticle Phys.* 2021, vol. 131, pp. 102586. DOI: 10.1016/j.astropartphys.2021.102586.

Grigoriev V.G., Starodubtsev S.A. Temporal changes in the energy spectrum of Forbush decreases in 20–23 solar activity cycles. *Bull. Russian Academy of Sciences: Physics.* 2011, vol. 75, no. 6, pp. 801–804.

Grigoryev V.G., Starodubtsev S.A., Isakov D.D. The energy spectrum of Forbush decreases during the growth phase of solar cycle 24. *Geomagnetism and Aeronomy*. 2014, vol. 54, no. 3, pp. 282–286. DOI: 10.1134/S0016793214030062.

Kojima H., Shibata S., Oshima A., Hayashi Y. Rigidity dependence of Forbush decrease. *Proc. 33rd International Conference on Cosmic Rays*. Rio de Janeiro, 2013, 135187.

Krymskii G.F., Kuz'min A.I., Krivoshapkin P.A., Samsonov I.S., Skripin G.V., Transky I.A., Chirkov N.P. *Kosmicheskie luchi i solnechniy veter* [Cosmic Rays and Solar Wind]. Novosibirsk: Nauka Publ. [Science], 1981, 224 p. (In Russian).

Kuzmin A.I. *Variatsii kosmicheskikh luchei i solnechnaya aktivnost* [Cosmic rays variation and solar activity]. Moscow. 1968, 157 p. (In Russian).

Nagashima K. Three-dimensional cosmic ray anisotropy in interplanetary space. *Rep. Ionosphere Space Res.* 1971, vol. 25, pp. 189–211.

Sakakibara S., Munakata K., Nagashima K. Rigidity spectrum of Forbush decrease. *Proc. 20th International Conference on Cosmic Rays. Moscow*, 1987, vol. 4, pp. 67–70.

Shafer G.V., Kuz'min A.I., Krymskii G.F., Krivoshapkin P.A. Main characteristics of Forbush decreases during the period of minimum solar activity. *Izv. AN SSSR. Ser. fiz.* [Bull. Academy of Sciences of USSR. Physics]. 1967, vol. 31, no. 8. pp. 1319–1321. (In Russian).

Wawrzynczak A., Alania M.V. Energy dependence of the rigidity spectrum of Forbush decrease of galactic cosmic ray intensity. *Proc. 32nd International Conference on Cosmic Rays*. Beijing, 2011, vol. 10, pp. 288–291.

URL: https://www.nmdb.eu (accessed August 10, 2021).

URL: http://cosray.shinshu-u.ac.jp/crest/DB/Public/Archives/GMDN.php (accessed August 10, 2021).

URL: https://omniweb.gsfc.nasa.gov/form/dx1.html (accessed August 10, 2021).

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