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FORECAST OF GEOMAGNETIC STORMS IN APRIL–NOVEMBER 2024 BASED ON COSMIC RAY MONITORING RESULTS

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Abstract. Since 2013, continuous monitoring of spatial-angular distribution of CRs for each hour of measurements has been carried out at SHICRA SB RAS, using data from the international neutron monitor database NMDB and the method of real-time global survey. For this purpose, nine parameters of the CR distribution are automatically calculated which result from the first two angular moments of the spatial distribution function of particles in interplanetary space. Our earlier studies have shown that before the onset of most geomagnetic storms with the amplitude of the geomagnetic activity *Dst* index lower than –50 nT there is a sharp increase in amplitudes of north-south components of CR distribution. This can serve as a predictor of the onset of geomagnetic disturbances with a lead time from several hours to 1–2 days. This paper presents the results of forecasting of geomagnetic storms with a *Dst* amplitude <–50 nT, observed in April–November 2024. It is also shown that the appearance of false predictors is associated with Earth's entry into large-scale SW disturbances without geomagnetic effects.

Keywords: cosmic rays, neutron monitor, global survey, geomagnetic storms, zonal components, predictors.

INTRODUCTION

Forecasting Earth's entry into intense geoeffective solar wind (SW) disturbances is an urgent problem in studying space weather. As has been shown (see, e.g., [Dvornikov et al., 1988; Munakata et al., 2000; Belov et al., 2001; Dorman et al., 2003]), most geomagnetic storms have predictors in angular distribution of cosmic rays (CRs). Since 2013, using data from the international neutron monitor database NMDB [https://www.nmdb.eu] and the global survey method developed at SHICRA SB RAS [Altukhov et al., 1970], we have continuously monitored the spatial-angular distribution of CRs in real time for each measurement hour. At the same time, the entire network of CR stations acts as a single multidirectional instrument. To determine the CR distribution, a system of linear equations is solved [Altukhov et al., 1970] which in the matrix representation has the form

$$\boldsymbol{I}=\boldsymbol{MA},$$

where $\boldsymbol{I}$ is the matrix of observational data; $\boldsymbol{M}$ is the matrix of receiving vectors of stations whose data is used; $\boldsymbol{A}$ is the matrix of CR distribution. The system of equations is solved by the least square method in the assumption that the expansion of CR distribution into a series of spherical functions converges rapidly. As a result, nine parameters defined by the first two harmonics of spatial distribution of CRs in interplanetary space are calculated. Our studies of the behavior of these parameters in time have shown that before the onset of most geomagnetic storms with *Dst*<–50 nT there is a sharp increase (above the empirically established critical values) in amplitudes of zonal (north-south) components of CR distribution [Grigoryev, Starodubtsev, 2015], which can serve as a predictor of the onset of geomagnetic disturbances with a lead time from a few hours to a day and a half. The abnormally large amplitude of CR anisotropy is also a predictor of such disturbances. The appearance of predictors before geomagnetic disturbances with this approach is observed in at least 70 % of the total number of cases we have examined since 2013. The time period from April to November 2024 under study was characterized by increased geomagnetic disturbance, which, in turn, led to various manifestations of space weather on Earth. The paper presents the results of the use of data from the international neutron monitor network, obtained when monitoring CRs at SHICRA SB RAS, to predict intense geomagnetic storms observed during the maximum of solar cycle 25.

EXPERIMENTAL DATA AND THEIR ANALYSIS

As shown in [Grigoryev et al., 2017; Zverev et al., 2020], the main parameters of CR distribution that effectively respond to large-scale interplanetary medium disturbances approaching Earth are changes in amplitudes of zonal (north-south) components of the high-frequency part of the isotropic intensity (C_{00}) and the first two harmonics (C_{10}, C_{20}) of spatial-angular distribution of CRs. An increase in the amplitude of the first harmonic in CR distribution (A_{11}) can also serve as a predictor of a geomagnetic storm. From the long-term experience we have found the critical values of the analyzed CR distribution parameters [Grigoryev et al., 2019]: for the north-south component of the high-frequency part of isotropic variations C_{00} — 0.4 %; for the north-south component of the first harmonic vector C_{10} — 0.6 %; for the north-south component of the second harmonic C_{20} — 0.7 %; for the sum of positive values of these components — 0.9 %; and for daily anisotropy vectors A_{11} — 1.4 %. Their excess was considered as the appearance of a predictor of geomagnetic disturbance, yet the excess of the critical value by any parameter for only one hour was not taken as a predictor. The predictor value was assumed to be 1.5 if any component exceeded the corresponding critical level; and 0 if its value was below the level.

Figures 1 and 2 show by month the *Dst* dynamics [https://omniweb.gsfc.nasa.gov] (straight lines indicate –50 nT), the behavior of predictors (*Pr*) according to the above method, and CR intensity variations (I_{NM}) obtained from 24-NM-64 neutron monitor data at the station Yakutsk from April to November 2024. As follows from the analysis of the figures, thirteen of sixteen geomagnetic disturbances with *Dst* amplitude below –50 nT had predictors. There were ten cases of false predictors associated with Forbush decreases in CR intensity, which were observed in the absence of significant geomagnetic effects. Figure 2, *c* illustrates the dynamics of the *Dst* index, predictors, and isotropic CR intensity in October 2024. Referring to Figure 2, false predictors, which were not followed by a magnetic storm, were detected on October 26 and 27. Their appearance was due to the fact that Earth entered a large-scale SW disturbance, which caused a significant (>7 %) Forbush decrease in the isotropic CR intensity. Figures 1 and 2 also exhibit six false predictors (for example, June 23 and November 21), which are not associated with the noticeable variations in geomagnetic activity and CR intensity.

Table provides information on the geomagnetic storms in 2024 considered, and presents the results of calculations of CR anisotropy parameters by the global survey method. It indicates the date and time of the onset of the disturbance, the *Dst* index [nT], and the time for which the predictor precedes the onset of a magnetic storm ($-\Delta t^h$). In columns C_{00}, C_{10}, C_{20}, and A_{11}, "+" marks the CR distribution components with a sign of a predictor. In the ∑+ column, "+" indicates that the predictor is caused by exceeding the critical value of the sum of positive north-south components. Table shows there is no dependence of the appearance of predictors in certain zonal components on the decrease in *Dst* variations. There is no *Dst* dependence of the time for which the predictor precedes the onset of a magnetic storm either.

№	Onset of a disturbance of *Dst* (UT)	Amplitude of *Dst* (nT)	($-\Delta t^h$)	∑+	C_{00}	C_{10}	C_{20}	A_{11}
1	Apr. 15, 2024/18^h	–65	34	–	–	–	+	–
2	Apr. 19, 2024/08^h	–117	–	–	–	–	–	–
3	Apr. 26, 2024/05^h	–51	–	–	–	–	–	–
4	May 02, 2024/12^h	–96	28	–	–	–	+	–
5	May 10, 2024/17^h	–412	6	–	+	–	+	–
6	June 27, 2024/19^h	–105	34	–	–	–	+	–
7	July 26, 2024/03^h	–51	18	+	–	–	–	–
8	Aug. 04, 2024/05^h	–101	6	–	–	–	+	–
9	Aug. 11, 2024/24^h	–188	32	–	+	–	–	+
10	Aug. 27, 2024/23^h	–76	12	+	–	–	+	–
11	Aug. 30, 2024/11^h	–72	10	–	+	–	–	–
12	Sep. 12, 2024/07^h	–121	10	–	+	–	–	–
13	Sep. 17, 2024/01^h	–121	5	–	–	+	–	–
14	Oct. 06, 2024/18^h	–148	14	–	–	–	–	+
15	Oct. 10, 2024/17^h	–308	8	+	+	–	–	+
16	Nov. 08, 2024/20^h	–101	–	–	–	–	–	–

Next, we analyze the occurrence of predictors in time and an increase in the radial a_{11}, a_{22}, and azimuthal b_{11}, b_{22} components of the first A_{11} and second A_{22} harmonics of CR distribution. By way of example let us consider two large geomagnetic storms that began on October 6 and 10, 2024. Figure 3 presents the results of calculation of CR anisotropy parameters for the period from October 2 to October 11, 2024. Arrows indicate times of occurrence of predictors, found by analyzing the behavior of north-south components of CR distribution. As Figure 3, *a*, *b* suggests, noticeable increases in amplitudes of variations of both harmonics do not occur before the appearance of predictors of geomagnetic disturbances. At the same time, their maximum changes take place during the magnetic storm main phase.

CONCLUSION

1. We have described predictors of geomagnetic disturbances, obtained from the estimated increase in the north-south components of the spatial-angular distribution of CRs.

2. The results of CR monitoring, conducted at SHICRA SB RAS to make a short–term forecast of geo-

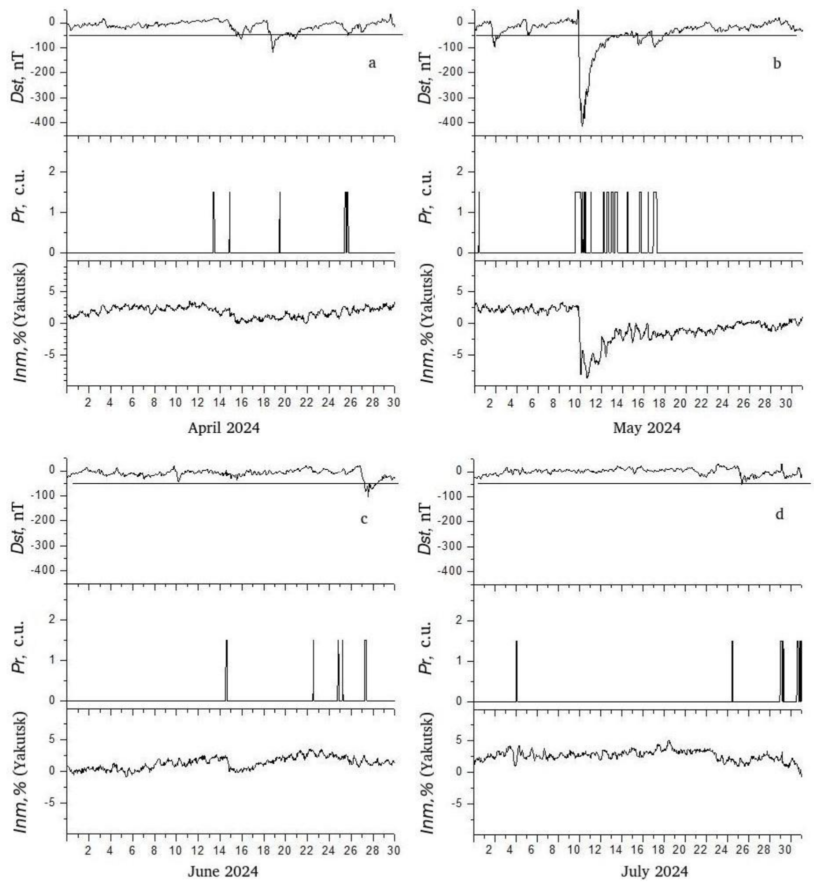

Figure 1. Behavior of the *Dst* index (the straight line indicates –50 nT) and predictors (*Pr*), as well as CR intensity variations (I_{NM}) according to 24-NM-64 neutron monitor data obtained at the station Yakutsk from April to July 2024

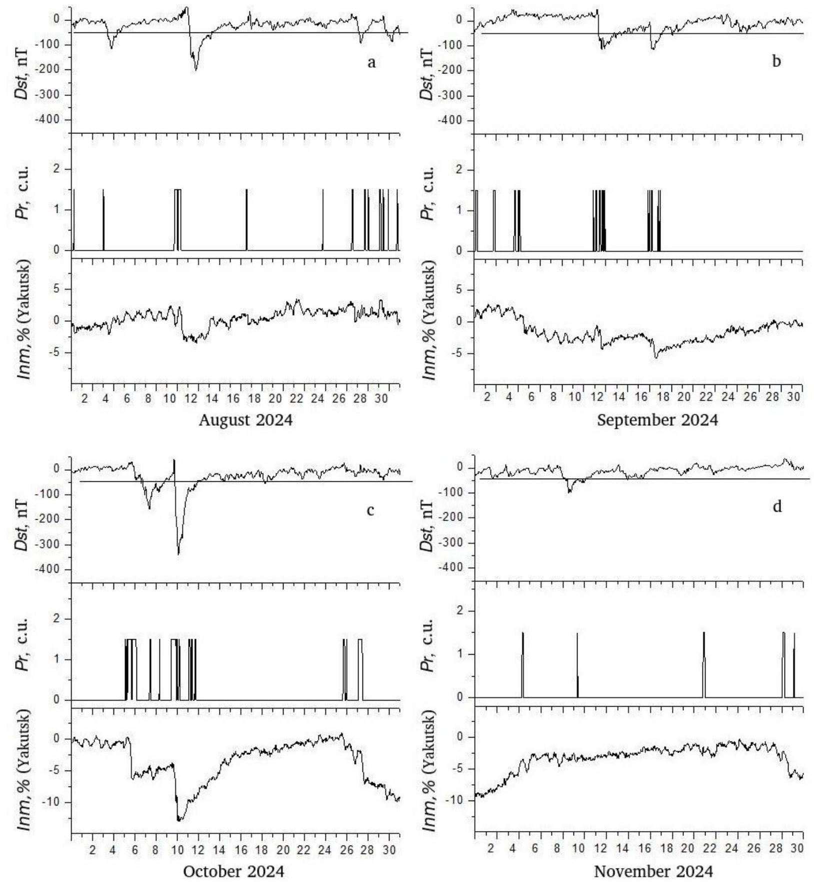

Figure 2. The same as in Figure 1 for the period from August to November 2024

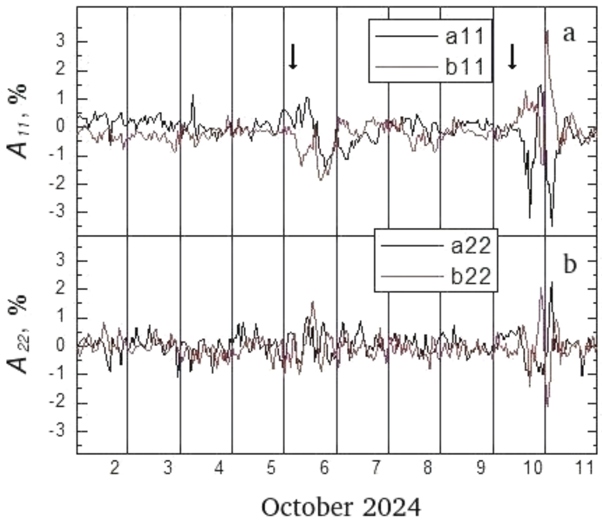

Figure 3. Variations in the components of the first (a_{11}, b_{11}, panel *a*) and second (a_{22}, b_{22}, panel *b*) harmonics of CR distribution in early October 2024. Arrows indicate the beginning of appearance of predictors

magnetic storms for the period April–November 2024, show that 13 of 16 geomagnetic storms (*Dst*<–50 nT) had a predictor, with 30 % of false predictors.

3. After the beginning of a geomagnetic storm, significant changes are recorded in the behavior of the radial and azimuthal components of the first and second harmonics of CR distribution.

4. The appearance of false predictors unrelated to the subsequent magnetic storm is mainly due to Earth's entry into large-scale solar wind disturbances, which are not accompanied by significant variations in geomagnetic activity.

5. The results of our research indicate that in order to maximize the elimination of false predictors of the onset of geomagnetic storms, it is necessary to develop a method for monitoring CRs, using various data from direct measurements of SW parameters on spacecraft in real time.

6. Real-time geomagnetic storm forecast results are available at [https://www.ysn.ru /~starodub/SpaceWeather/global_survey_real_time.html].

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