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MONITORING OF GEOMAGNETIC DISTURBANCES USING THE GLOBAL SURVEY METHOD IN REAL TIME

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Abstract. A method for forecasting geomagnetic storms using the realization of the global survey method in real time is presented. The method is based on data from the worldwide network of neutron monitors NMDB. Using this method, we analyze the behavior of components of three-dimensional angular distribution of cosmic rays in the interplanetary medium, which were due to the first two spherical harmonics, over the period from 2013 to 2018. We have established that the main parameters that respond to the arrival of geoeffective disturbances of the interplanetary medium at Earth are changes in amplitudes of zonal (north-south) components of cosmic ray distribution. In order to select effective criteria for identifying predictors of geomagnetic disturbances and their possible temporal variations, we have made a retrospective analysis of the relationship between behaviors of the above components and geomagnetic disturbances occurring during the period of interest.

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

INTRODUCTION

One of the most important and topical areas of modern research into cosmic ray (CR) intensity variations is the forecast of geoeffective disturbances of the solar wind (SW). The earlier studies [Dvornikov et al., 1988, 1995; Dvornikov, Sdobnov, 1995] of CR rigidity spectrum variations have shown the possibility of long-term forecasting of sporadic geoeffective SW disturbances. From further works [Munakata et al., 2000; Belov et al., 2001; Dorman et al., 2003; Munakata et al., 2005] it follows that most intense geomagnetic storms ($K_p>7$) have obvious precursors in the behavior of galactic CR intensity and angular distribution according to data from both neutron monitors and muon telescopes. Currently there are already methods for forecasting interplanetary medium disturbances from the CR anisotropy analysis relying on data from a limited number of stations [http://neutronm. bartol.udel.edu/spaceweather; http://cr0.izmiran.rssi.ru/ AnisotropyCR/mainhtm; http://www.mustang.uni-greifswald. de/spaceweather.htm]. Since 2008, SHICRA SB RAS has continuously monitored parameters of CR diurnal anisotropy in real-time mode, using hourly data from only one station — the Yakutsk CR spectrograph after A.I. Kuzmin — in order to explore the possibility of forecasting terrestrial effects of space weather [Grigoryev et al., 2008; http://www.ysn.ru/~starodub/SpaceWeather/currents_ real_time.html]. The analysis of the monitoring results has shown that with a probability of ~0.7 the appearance of the stable negative radial component of diurnal anisotropy $A<-0.4$ % simultaneously in data from a neutron monitor and ground muon telescope, which have different sensitivities to the energy of detected CR, is associated with the approach of a disturbed SW region to Earth.

The global survey method developed in SHICRA SB RAS in the late 1960s – early 1970s based on measurements of the worldwide network of neutron monitors [Krymsky et al., 1981] allows us to determine high- and low-frequency parts of isotropic intensity, as well as eight components of the first two harmonics of CR angular distribution for each observation hour. It is important to emphasize that in this case all ground-based CR detectors having its own characteristics (geomagnetic cutoff rigidities, reception cones, etc.) act as a single multidirectional device. Using the results obtained by this method, we have examined the behavior of the CR diurnal anisotropy vector $\vec{A}_{11}$ before onsets of geomagnetic storms with $Dst\leq-50$ nT, observed in 2012–2013 [Grigoryev, Starodubtsev, 2015]. We have established that over a period from several hours to days before onsets of most geomagnetic storms, $\vec{A}_{11}$ exhibits characteristic variations, which are not observed during periods of quiet SW. The use of these A_{11} variations as precursors has, however, a serious drawback — they also appear during SW disturbances that occur without geomagnetic storms. The relationship between SW disturbances and subsequent observations of storms has been considered in detail in [Shadrina et al., 2012a, b, 2014; Plotnikov et al., 2014], and to enhance its understanding the authors proposed the so-called Forbush-storm classification of events.

The international database of neutron monitors NMDB [http://www.nmdb.eu] established in 2007 made it possible to use the global survey method in real-time mode. This, in turn, allowed us to implement the method of short-term (from several hours to ~1 day) forecasting of geomagnetic storms in real time [http://www.ysn.ru/~starodub/SpaceWeather/global_survey_ real_time.html]. Our studies have shown that the main parameters of CR distribution responding effectively to the approach of geoeffective disturbances of the interplanetary medium to Earth are changes in amplitudes of zonal (north-south) components of the high-frequency part of isotropic intensity C_{00} and the ftableirst two harmonics of the CR angular distribution C_{10} and C_{20} [Grigoryev et al., 2016; Grigoryev et al., 2017]. These changes differ in dynamics, but we can identify certain critical levels whose excess for any of the said three components is likely to be a geomagnetic storm precursor.

In this paper, to select more effective criteria for identifying geomagnetic storm precursors and their temporal dynamics, we perform a retrospective analysis of the relationship between continuous hour parameters of CR distribution, obtained by the global survey method for 2013–2018, and observed geomagnetic disturbances. Note that the choice of this period of time is due to the presence of the known database of the network of neutron monitors NMDB, including measurements made at most active CR stations.

EXPERIMENTAL DATA AND METHOD

The basic principles of the global survey method developed by SHICRA SB RAS are described in [Krymsky et al., 1981]. Here we give only its brief description. To study CR distribution in interplanetary space, the entire global network of stations equipped with neutron monitors is utilized as a single multidirectional device. The CR intensity observed by each detector is largely determined by receiving characteristics of detector, which represent its geometry, geographic location, and type of observed secondary particles. Devices having different receiving vectors record the intensity I that can be defined as follows:

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

where x_n^m, y_n^m are the components of the multidimensional receiving vector $\vec{R}_n^m$; a_n^m, b_n^m are the components of multidimensional vector of CR distribution $\vec{A}_n^m$. For the data we use a system of linear equations, which in the matrix representation takes the form

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

where $\vec{I}$ is the column matrix of observational data, M is the rectangular matrix of $\vec{R}_n^m$, and $\vec{A}$ is the column matrix of $\vec{A}_n^m$. The system of equations is solved by the least-squares method in the assumption that the expansion of CR distribution into a series of spherical functions converges rapidly. Therefore, in addition to the isotropic component, we usually take into account only the first two harmonics of the distribution, whose effects are observed in the experiment with sufficient confidence. Accordingly, in the vector $\vec{A}_n^m$ we identify the first nine components, including C_{00}, C_{10}, and C_{20}.

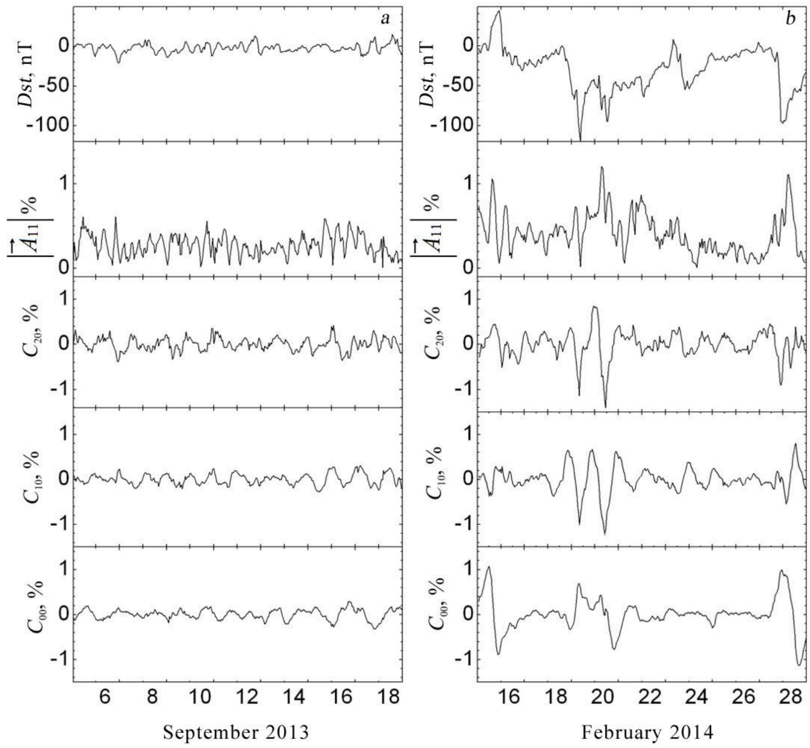

Figure 1. *Dst* index, CR distribution components C_{00}, C_{10}, C_{20}, and amplitudes of the CR diurnal variation $|\vec{A}_{11}|$ in the absence (*a*) and in the presence (*b*) of geomagnetic disturbances

RESULTS

Using calculations made with the global survey method in 2013–2018, we have determined parameters of 3D angular distribution of CR in interplanetary space, which are due to the first two spherical harmonics. For further analysis we used the results of calculations of C_{00}, C_{10}, and C_{20}. We took into account total values with positive $\sum C^{+} = C^{+}_{00} + C^{+}_{10} + C^{+}_{20}$ and negative $\sum C^{-} = C^{-}_{00} + C^{-}_{10} + C^{-}_{20}$ increases in these components, which are additional precursors of the onset of a geomagnetic storm and its main phase. We also used information about the diurnal anisotropy amplitude $|\vec{A}_{11}|$ and low-frequency isotropic CR intensity *I*. Figure 1 shows time dependences of the *Dst* index, which characterizes geomagnetic activity, of CR distribution components C_{00}, C_{10}, C_{20}, and CR intensity variation amplitude $|\vec{A}_{11}|$ in the absence (*a*) and in the presence (*b*) of intense geomagnetic disturbances. Figure 1 shows that in the absence of disturbances the maximum values of these parameters do not exceed 0.5 % in modulus for zonal components and 0.7 % for $|\vec{A}_{11}|$. At the same time, during intense geomagnetic disturbances these values are generally much higher.

The analysis of geomagnetic storms with *Dst*<–50 nT for the entire period mentioned above allowed us to determine levels of critical values of positive zonal components of CR anisotropy C^{+}_{00}, C^{+}_{10}, C^{+}_{20}, which most effectively manifested themselves before onsets of geomagnetic disturbances. In addition, we established critical levels of a sharp decrease in negative values of these components during the main phase of geomagnetic storms. Note also that the 1.2 % excess of $|\vec{A}_{11}|$ generally corresponds to the entry of Earth into the region of a large-scale SW disturbance, followed by a CR intensity decrease, and can serve as an additional warning about possible approach of a geomagnetic storm.

Table 1 lists new critical values of positive and negative parameters of zonal components of CR distribution and their sums, which are utilized as predictors in the monitoring of geomagnetic disturbances. The Table also shows δ errors in determining these parameters.

From Table 1 it follows that with decreasing level of solar activity, the critical values of the zonal components decreased by ~10 % from 2013 to 2018.

As an example Figure 2 shows *Dst* variations and combined CR distribution parameters used to identify predictors of geomagnetic storms during four disturbances observed in 2013, 2015, 2016, and 2017. Dotted lines indicate critical levels whose excess can be regarded as a warning about a possible disturbance.

Figure 2, *a*, *b* indicates that the predictors of storms were positive sums of C_{10}+ C_{20} and C_{00}+C_{20} respectively. Note that for the geomagnetic storm in October 2016 (Figure 2, *c*) a predictor was the stable abnormally high amplitude of diurnal variation $|\vec{A}_{11}|$>1.2 %. The excess of the critical level for the positive value of only one component C_{20} was a predictor of the magnetic storm in May 2017 (Figure 2, *d*). Figure 2, *a*, *b*, *d* also shows decreases in negative values of zonal components, which correspond to the main phase of the geomagnetic disturbance. Referring to Figure 2, the manifestation of predictors, presented in Table 1, in individual zonal components of CR distribution or their combined sums, as well as in the abnormally high amplitude of the CR diurnal anisotropy A_{11} is observed before onsets of geomagnetic storms with a lead time from several hours to days. Table 2 lists the results of our analysis of manifestations of critical values of positive predictors and their relationship with the level of geomagnetic disturbance or Forbush effects from 2013 to 2018. Table 2 suggests that on average ~80 % of geomagnetic disturbances with *Dst*<–50 nT have, according to the method in use, a predictor in CR before they have an effect on Earth . We have established that all geomagnetic storms with

Table 1

Critical values of positive and negative parameters of zonal components of CR distribution and their sums

Years	$C^{\pm}$	C_{00}, %	C_{10}, %	C_{20}, %	δ,%	$\sum(C_{00}+C_{10}+C_{20})$, %
2013	C^{+}	0.8	0.8	0.8	0.03	1.1
	C^{-}	–0.9	–0.9	–0.9	0.03	–1.3
2014	C^{+}	0.8	0.8	0.8	0.03	1.1
	C^{-}	–0.9	–0.9	–0.9	0.03	–1.3
2015	C^{+}	0.7	0.7	0.7	0.03	0.9
	C^{-}	–0.8	–0.8	–0.8	0.03	–1.2
2016	C^{+}	0.7	0.7	0.7	0.03	0.9
	C^{-}	–0.8	0.8	–0.8	0.03	–1.2
2017	C^{+}	0.7	0.7	0.7	0.03	0.9
	C^{-}	–0.8	–0.8	–0.8	0.03	–1.2
2018	C^{+}	0.7	0.7	0.7	0.03	0.9
	C^{-}	–0.8	–0.8	–0.8	0.03	–1.2

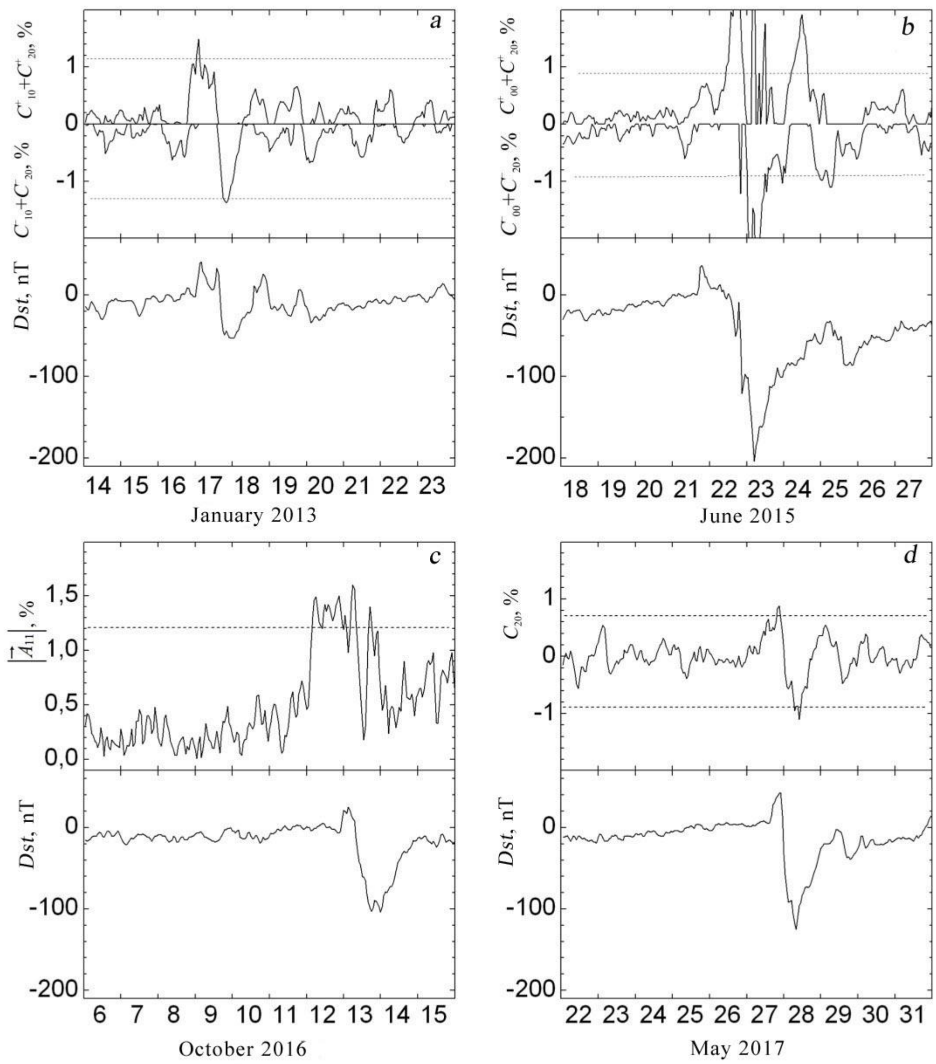

Figure 2. Characteristics of precursors of geomagnetic storms during four geomagnetic disturbances observed in 2013, 2015, 2016, and 2017.

Table 2

Manifestations of precursors of geomagnetic storms by years

	2013	2014	2015	2016	2017	2018
In total, geomagnetic storms with *Dst*<–50 nT have precursors have no precursors	19 11 (58 %) 8	9 8 (88 %) 1	17 15 (82 %) 2	13 11 (88 %) 2	8 8 (100 %) 0	3 2 (66 %) 1
In total, precursors associated with *Dst*>–50 nT	1	7	4	4	4	2
Precursors unrelated to *Dst*-index disturbance	6	5	3	7	1	1
Precursors associated with Forbush effects	5	2	2	6	0	0

Dst < –100 nT have predictors. Note also that the predictors in CR may appear before recording of minor geomagnetic disturbances as well. The false predictors observed during relatively quiet geomagnetic periods are largely associated with solar wind disturbances that cause the CR intensity to decrease.

CONCLUSION

Thus, we can draw the following conclusions.

1. The retrospective analysis of the relationship of CR distribution parameters with geomagnetic disturbances observed in 2013–2018, which was carried out using the global survey method, allowed us to establish a possibility of identifying effective precursors of geomagnetic disturbances with *Dst* < –50 nT.

2. We have found critical values of zonal components of CR distribution, which are effective precursors of geomagnetic disturbances with a lead time from several hours to days.

3. The use of the international database of the worldwide network of neutron monitors NMDB

[http://www01.nmdb.eu] allows us to perform real-time continuous monitoring of geomagnetic disturbances.

4. The monitoring results are available on the website [http://www.ysn.ru/~starodub/SpaceWeather/global_survey_real_time.html].

We thank the team of the NMDB database [http://www01.nmdb.eu], established under the FP7 program of the European Union (contract No. 213007), for providing open access to measurements of the worldwide network of neutron monitors. The work was performed using the Unique Research Facility Russian National Ground-Based Network of Cosmic Ray Stations [http://ckp-rf.ru/usu/433536; http://cr.izmiran.ru/unu.html] and with budgetary funding of RFBR grant No. 18-42-140002-r_a.

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