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Density Variations of Galactic Cosmic Rays in Magnetic Clouds

A. V. Belov, A. A. Abunin, M. A. Abunina, E. A. Eroshenko, V. A. Oleneva, and V. G. Yanke

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow oblast, 142190 Russia

e-mail: abelov@izmiran.ru

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Abstract—Galactic cosmic ray behavior features in events when magnetic clouds that have been observed in interplanetary disturbances near the Earth are investigated. It is shown in most cases (but not in all) that the cosmic ray density behavior in the magnetic cloud near the Earth can be described by a simple parabolic distance dependence measured in gyroradii. Most magnetic clouds modulate cosmic rays by reducing their density, but there is a group of events (about 1/5) in which the cosmic ray density in the magnetic cloud increases. The extremum (minimum or maximum) of the cosmic ray density is often located closer to the cloud center rather than its edges. A number of factors that contribute to the model description are considered, and the contributions are estimated.

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1. INTRODUCTION

A magnetic cloud (MC) (Burlaga et al., 1981; 2002) comes to the Earth retaining solar fiber structural elements. As has been shown, for example, in (Zhang et al., 2013; Xie et al., 2013), all interplanetary coronal mass ejections (ICME) contain flux rope structures that determine the MC. However, such quasi-cylindrical structure cannot be reliably recorded in all events. If the Earth crosses the ejection in its peripheral part (as is the case with the majority of events), MCs are usually not observed (Yashiro et al., 2013). The second reason why there may be no MC in the ICME involves the interaction of two or more interplanetary disturbances that destroy the structure of the MC. MC self-destruction is impossible (Zhang et al., 2013), but interaction with the background solar wind compresses this structure without changing the topology of the magnetic field lines. Thus, when observing the MC, we almost see the fiber structure that was on the Sun and which stands out against the background of the conventional solar wind. The *Bz* component is most often large in an MC. Thus, a significant proportion of large geomagnetic storms occur during the passage of an MC, and the indices of geomagnetic activity during these periods (*Dst*, *Kp*) tend to be the highest. In (Richardson and Cane, 2010), the most complete CME-ICME list at present was made with the identification of MCs. It was also shown there that ejections with MCs are more geoeffective than other transient events: 43% of storms occurred in presence of an MC, and only 18% of them were generated by ICME without an MC.

The main properties of an interplanetary disturbance including an MC are reflected in Fig. 1, in which the MC region is marked by two vertical lines. According to various sources, the following changes of interplanetary parameters that are characteristic of an MC can be identified (Kim et al., 2013):

(1) Increased intensity of the interplanetary magnetic field (IMF).

(2) Reduction in the the variation of the magnetic field (MF).

(3) Abnormally low proton temperature (*T*).

(4) Solar wind velocity trend (decline).

(5) Decreasing plasma density.

(6) Increased Fe/O ratio.

(7) Bidirectional electron flow.

These features do not necessarily occur all at once, but the presence of two to three of them allocates the MC structure from the surrounding solar wind (e.g., Gosling, 1990).

MCs are closely associated with the Forbush decrease (FD) of cosmic rays (CR) (Barnden, 1973; Belov et al., 1976). Since Forbush decreases occur when partially closed magnetic structures in the solar wind extend (Lockwood, 1971; Cane, 1993; Belov et al., 1997; Belov, 2009; Richardson and Cane, 2010) and an MC is the most obvious example of this structure, it is only natural to expect the most profound decrease in the CR density inside MCs. The two-stage FD concept (Barnden, 1973; Wibberenz et al., 1998), in which the second, deeper density decrease is associated with an MC, is based on this.

The MC impact on galactic CR was considered in a number of studies (Badruddin et al., 1986; Zhang and Burlaga, 1988; Lockwood et al., 1991; Cane, 1993; Singh and Badruddin, 2007; Abunin et al., 2013) that obtained mixed results. This paper differs from previous ones in that the density data on a CR of certain rigidity outside the atmosphere and the Earth's

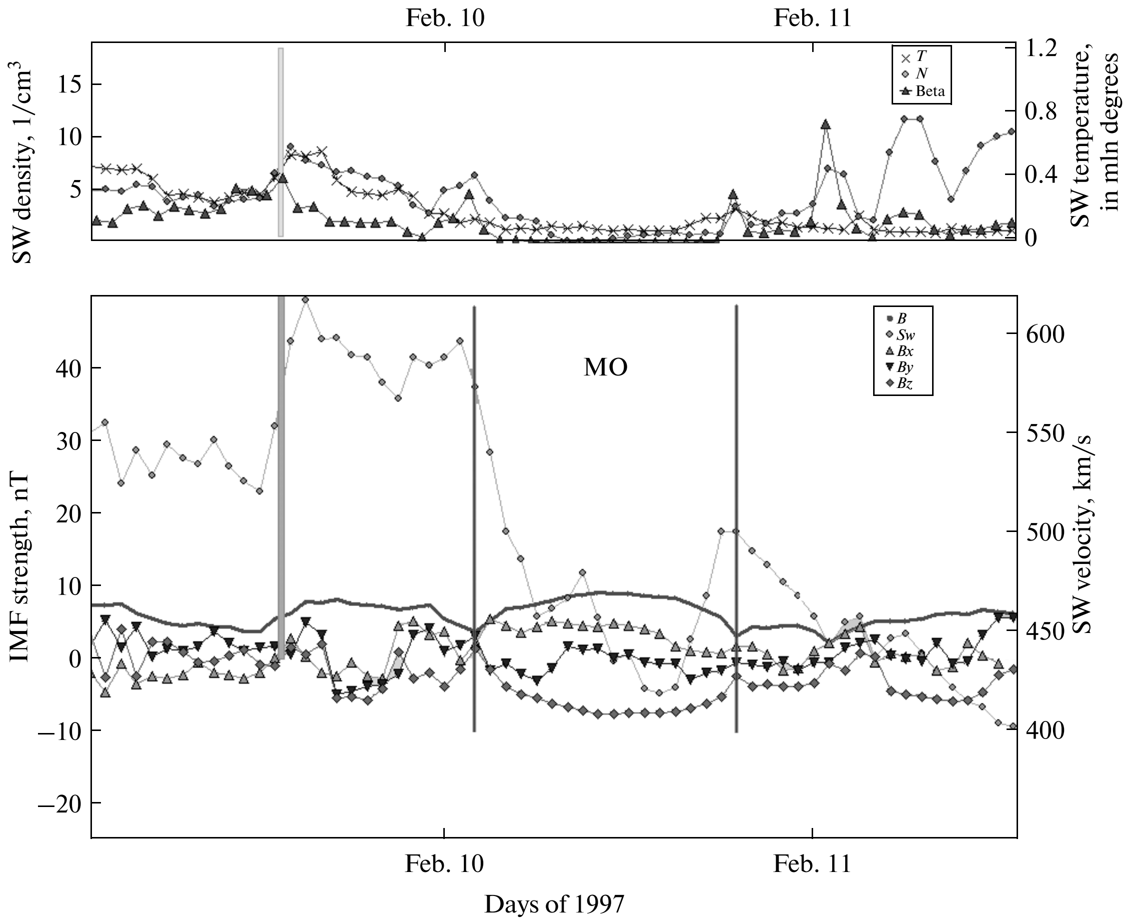

Fig. 1. A magnetic cloud example according to interplanetary measurements in February 1997.

magnetosphere obtained by a global survey (GSM) (Belov et al., 2005) were used for the research; significantly more CME/ICME events than in previous studies were investigated, which made it possible to carry out statistical analysis. Finally, there are some methodological differences that will be discussed below.

The study of the MC can help in the prediction of the development of solar wind disturbances and their geoeffectiveness. It is possible to try to predict *Bz* component behavior, which is crucial for the development of a geomagnetic storm. This was attempted in (Bothmer and Schwenn, 1998) with an investigation of MC structure with the use of cylindrical models. If we had a good MC model, it could be possible to predict MC development by its start. Hence, the development of such models are important.

Apparently, a significant part of MCs that are observed near the Earth have quasi-cylindrical geometry. This is consistent with modern concepts stating that the internal part of the ejection is originally solar fiber arranged as a long, cylindrical, flux rope. It is also in line with observations of solar wind disturbances near the Earth and successful attempts to simulate MCs as cylindrical structures. Certainly, not the whole cloud is involved but its small, near-Earth part. It is possible to represent it as a quasi-cylinder and use this model, which includes predictions of further disturbance development. Such models are successfully used to describe the behavior of cosmic rays in an MC (Kuwabara et al., 2009). It is assumed that the impact of the selected limited near-Earth part of the ICME on CRs can be singled out from the general modulation created by the whole interplanetary disturbance.

Our goal was to test the applicability of the simplest parabolic model to the description of the CR density behavior in a large number of MCs and to obtain as exhaustive information as possible about the impact of MCs on cosmic rays. When modeling in this paper, we considered the behavior of only the isotropic part of the CR variation, i.e., the CR density. In the simplest case, the CR density minimum should be observed near the MC center, while toward the edges the density should increase. A parabola is a function that represent this distribution. In theoretical models the solution is represented by more complicated functions, but it can be shown that in the first fairly good approximation they coincide with the parabola. Note that the parabolic representation does not require cylindrical geometry and is good (at least in the first approximation) for any dependence with one minimum.

When the Earth is inside an MC, very often a geomagnetic storm can be observed on it, and there are so-called magnetospheric variations in CR variations recorded by ground-based detectors (Dorman, 2010). The main part of magnetospheric variation is caused by changes in the geomagnetic cutoff rigidity at observation points. In this case, a variable count rate increment occurs; it depends on the geomagnetic activity level, which may cause undesirable effects in the construction of the model of the MC impact on CR variations and should be taken into account. In this paper, we investigated the contribution of different factors in the model, as well as the features of the CR density distribution within an MC.

2. DATA AND METHODS

The main ICME list (Richardson and Cane, 2010) was used for the analysis of events for 1996–2009 (the most complete list of interplanetary disturbances over these years). It has data on the main parameters of the interplanetary disturbances, their solar sources, and related geomagnetic effects. Richardson and Cane made their list using a list of MCs observed by the satellite WIND (http://wind.nasa.gov/mfi/mag_cloud_publ.html) and other lists (Gosling, 1990; Huttunen et al., 2005). Note that there are other lists that may be useful in statistical studies of MCs, such as the list (Ermolaev et al., 2009) available on the website (ftp://ftp.iki.rssi.ru/pub/omni).

We selected the events from Forbush effects from our database, which are coincided with the events with an MCs in the catalogues mentioned above. Thus, our sample included 99 events. Variations of density and anisotropy of CR with a rigidity of 10 GV obtained by the global survey method (GSM) (e.g., Belov et al., 2005) according to the worldwide network of neutron monitors were used as data on cosmic rays. Variations of the CR density and anisotropy outside the atmosphere and the Earth's magnetosphere obtained by the GSM-method are more efficient for the study of heliospheric processes than the data from any single CR detector. IZMIRAN developed a database of Forbush decreases and interplanetary disturbances based on these data that includes characteristics of CRs and interplanetary disturbances, as well as geomagnetic activity indices and parameters of solar sources for almost 6500 events. The database has been widely used by us for a long time, and we have used it for this paper. However, it is not yet in the public domain.

3. RESULTS AND DISCUSSION

The sample of ICMEs with an MC observed near the Earth in solar cycles 23–24 includes 99 events. They are united by the presence of MCs, but they are all very different. Among them there are short and long disturbances, very fast ejections at a velocity of the solar wind near the Earth of >1000 km/s, and slow ones with a rate of <400 km/s with a very large and very modest strengthening of the interplanetary magnetic field. MCs are structures with a reinforced interplanetary magnetic field, but this gain can be quite significant (up to 57 nT) or almost imperceptible (up to 8 nT). Not all of the selected events (only 62 out of 99) began with the arrival of the interplanetary shock waves, which was estimated by *SC* data.

The events caused by the ICME also significantly differ. Together with exceptionally large magnetic storms, this list also includes a dozen of events in which the *Kp*-index did not rise even to the level 4. The corresponding CR variations are also varied. The sample included the largest Forbush decrease (FD) in history with a value of $A_F = 28\%$ and a few small FDs with a value of not more than 0.5% (all of the characteristics of CR variations are given for a rigidity of 10 GV). The averaged characteristics for the 99 events with an MC show that these are large FDs ($A_F = 3.4 \pm 0.4\%$) that on average were accompanied by a moderate magnetic storm ($Ap_{\max} = 98 \pm 9$ (2 nT) and $Dst_{\min} = -103 \pm 8$ nT). In order to understand how the CR modulation depends on the presence of MCs, we compared the discussed sample (with an MC) with a control sample. It included events from the same period (1996–2009) with similar interplanetary characteristics (products of maximum values of the IMF module and the solar wind velocity) but without an MC. The comparison of the average characteristics of the master (with the MC) and control (without the MC) samples shows that the ICME with the MC modulates CRs much more effectively and creates deeper FDs with a more rapid density decrease and with greater CR anisotropy magnitude. Such difference in samples also takes place in the case of geomagnetic activity but to a lesser extent.

The table shows the average values of the obtained parameters for both groups of events for a more vivid comparison.

Let us consider some examples of various ICMEs with the MC and their manifestations.

Figure 2a–2d shows the behavior of IMF (left scale, triangles) and solar wind (SW) velocity (right scale, circles). In the lower panels *A*0 is the CR density variation (left scale, tight circles) and *Axy* is the equatorial component of CR anisotropy (right scale, columns). In all of the panels (Fig. 2a–d), the shaded area indicates the time during which the Earth was in the MC.

On July 26–27, 2004 (Fig. 2a), the Earth was in a fast ICME with a strong (about 25 nT) IMF. The maximum field strength was observed in the MC. In this event a deep minimum in CR density with the MC near its center can be clearly seen, and it can be attributed to a two-step Forbush decrease. In this case, the

Average parameters of CRs, interplanetary space, and geomagnetic activity for distrubances with an MC and without an MC

Parameter	Average for the sample with an MC	Average for the control sample (without an MC)
A_F	3.36 ± 0.37	1.91 ± 0.16
*Axy*_max	2.03 ± 0.13	1.38 ± 0.08
*Az*_range	2.04 ± 0.10	1.36 ± 0.06
*D*min	–0.93 ± 0.11	–0.44 ± 0.03
*Ap*max	97.87 ± 8.65	56.64 ± 3.51
*Dst*_min	–102.6 ± 8.2	–56.5 ± 3.8
Bm	20.21 ± 1.07	18.01 ± 0.33
Vm	551.5 ± 16.5	652.2 ± 9.1
VmBm	6.05 ± 0.54	5.79 ± 0.07

Here A_F is value of the Forbush decrease (%), *Axy*_max is the maximum equatorial component of the CR anisotropy vector (%), *Az*_range is the variation range of the north–south component of the CR anisotropy vector (%), *D*min is the maximum hourly CR density decrement, *VmBm* is the normalized product which is the most effective characteristic of the interplanetary disturbance for the consideration of its correlations with different parameters. Parameter *VmBm* was normalized as follows:

$$VmBm = \frac{V_{\max}}{V_0}\frac{B_{\max}}{B_0}, \qquad (1)$$

where V_0 and B_0 are parameters of the undisturbed interplanetary medium (usually $V_0 = 400$ km/s and $B_0 = 5$ nT are used, and $B_{\max}$ (nT) and $V_{\max}$ (km/s) are the maximum IMF strength and solar wind velocity in the disturbance).

second step (caused by the MC) can be expressed much better than the first.

A similar CR density behavior was observed on October 3, 2000 (Fig. 2b), and it was associated with a relatively slow CME. There are many similar examples of such behavior of the CR. The FD with the two-step structure and with the main minimum of density in the MC are fairly typical. However, the presence of the MC does not guarantee a two-step structure of the FD. In our sample, the primary CR density minimum was inside the MC only in 67 of 99 cases.

The density minimum was located even more rarely at the MC center. Moreover, there were events in which not the minimum but the maximum CR density

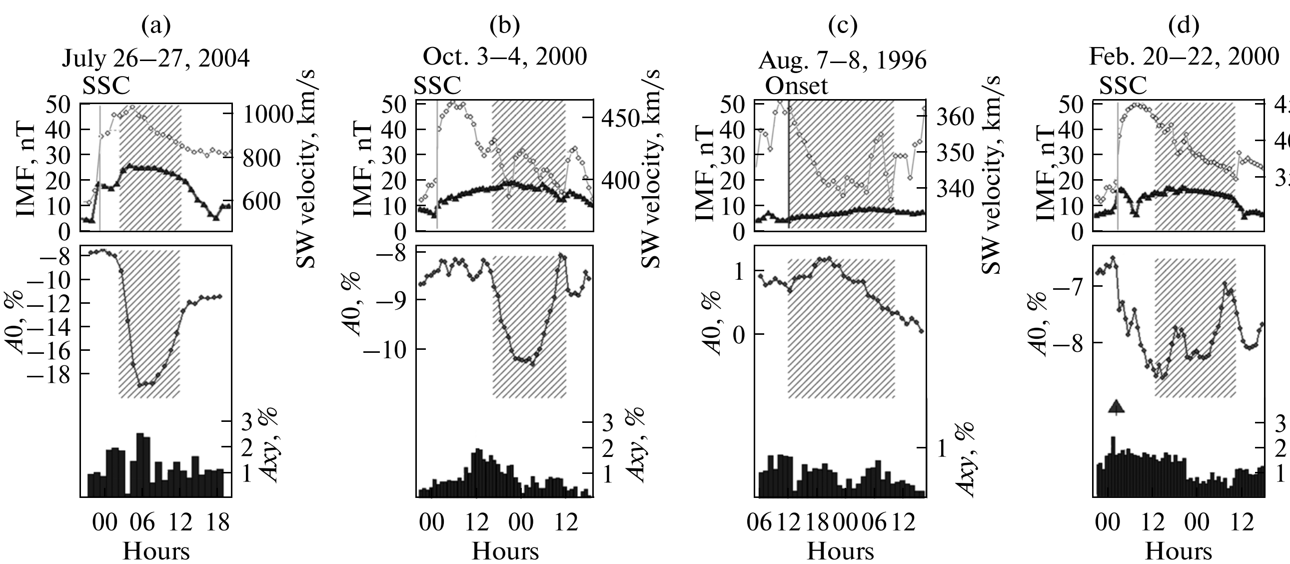

Fig. 2. Examples of events with a pronounced minimum of the CR density inside the MC (July 26–27, 2004, and October 3, 2000 (a, b)), with an increase in density inside the MC (August 7, 1996 (c)), and events with a complex structure of the MC (February 20, 2000 (d)). IMF is the interplanetary magnetic field strength, *A*0 is the CR density with the rigidity of 10 GV, *Axy* is the equatorial component of the first harmonic of the CR anisotropy with the rigidity of 10 GV.

was observed in the central part of the MC. One such example is shown in Fig. 2c. As in this example, the IMF strength inside the cloud is not usually high in such abnormal cases.

In some cases, a more complex CR density behavior inside the MC can be observed with alternating local maxima and minima (Fig. 2d). These examples show that the CR density behavior not only reflects the MC as a whole but also features of its structure.

Even stronger MCs affect the behavior of the fundamental CR anisotropy. As a rule, at the entrance of the MC and/or when leaving it, the magnitude and direction of anisotropy change significantly. Inside the MC there are usually observed systematic changes in the anisotropy. For the *Axy* component inside the cloud, it is characterized by rotation, often in one direction but every so often with the change of rotation direction. The north–south component *Az* of the cloud usually varies in a regular manner. It often changes the sign at the cloud center.

A large variety of MCs with high and low speed, high and low IMF voltage, and different lifetimes causes a different depth and profile of Forbush decrease. Figures 3–4 show examples of CR behavior during the passage of MCs with different properties: fast, slow, with complex configuration, and demonstrating an increase of CRs in the middle of the cloud.

The abnormal behavior of CRs, in which an increase is observed instead of a minimum density in the MC central part (Fig. 4), can be explained as follows. In some MCs, it is possible that the magnetic field weakens and eventually ceases to create an effective quasi-trap for CRs, but the regular structure of the cloud's magnetic field facilitates the penetration of charged particles of cosmic rays from distant eastern areas of the heliosphere unaffected by FD into the central part.

The presence of the MC in the interplanetary disturbance significantly increases the ability of this disturbance to modulate cosmic rays. There are several possible explanations of this fact, and they complement each other. When there is an MC in the ICME, the chances of the Earth entering it are higher when the cloud is larger and the CME is the closer to the solar disk center. Both of these factors increase FD depth (Abunina et al., 2013) (1a). Inside the MC we are closer to the center of the mechanism that produces FD (1b). If there is no MC in this solar wind disturbance, it could mean that the source of the disturbance is not the ejection but the coronal hole, which does not as effectively influence CRs (2a), or the MC existed initially but as a result of the interaction with the other structures it lost its main properties, in particular, its field became more irregular (2b). A regular, well-organized field more strongly affects CRs than a random field of the same magnitude.

Even in events with a distinct MC observed near the Earth, the FD structure is not always two-step.

The CR behavior inside the MC reflects it as a whole and as features of its structure. It can be clearly seen in the behavior of density and vector anisotropy of CRs obtained from data of the worldwide network of neutron monitors by the global survey method (Fig. 3). In a significant number of events, changes in the CR density within the cloud give an almost symmetrical pattern with a minimum density at the cloud center, making it possible to assume its quasi-cylindrical structure. Events in which the CR density behavior remains regular but becomes more complex with alternating of areas with high and low density within the cloud are also quite frequent. It may be a manifestation of some quasi-toroidal structure of some MCs.

3.1. Simulation of Cosmic Ray Density in MCs

As was mentioned above, the simplest function that is able to represent the CR density distribution in the MC quasi-cylindrical structure is a parabola. A discrepancy between the actual distribution and the parabola is possible, but other circumstances that need to be taken into account when simulating the CR density behavior in the MC are even more important.

1. Let us use data on the CR density changes obtained for each hour by the global survey method. Since ICME plasma extends practically radially, we obtain an almost radial section, more precisely, a puncture. Hourly average CR density measurements along the "puncture" disturbance movement can generally be located arbitrarily in the cloud, but it does not limit the applicability of the parabolic representation of the CR density behavior. However, when simulating hourly average data, it is necessary to remember that the interplanetary disturbance that crosses the Earth's orbit passes different distance each hour according to the speed of this part of the disturbance. It is equally important to take into account the specifics of cosmic rays. For charged particles it is advisable to express the distance not in kilometers or astronomical units but in Larmor radii (gyroradii) ρ, which are determined by the particle rigidity R and the strength of the interplanetary magnetic field B. An extended MC with a weak magnetic field can affect cosmic rays more strongly than a cloud with a strong but narrow field. It is possible to note that the observer passes $X_\rho = cVB/R$ gyroradii, where V is the solar wind radial velocity, in the interplanetary disturbance (in particular in the MC). As is evident from Fig. 5, in the transition from linear dimensions to gyroradii, it is possible to expect more symmetric distributions of the CR density in the MC.

2. The second important factor that should be taken into account by studying the effect of the MC on CRs by ground data is magnetospheric CR variations (Dorman, 2010) during magnetic storms, when the Earth is in the MC. The majority of them is caused by the change in geomagnetic cutoff rigidity at observation points. In this case, a variable depending on the

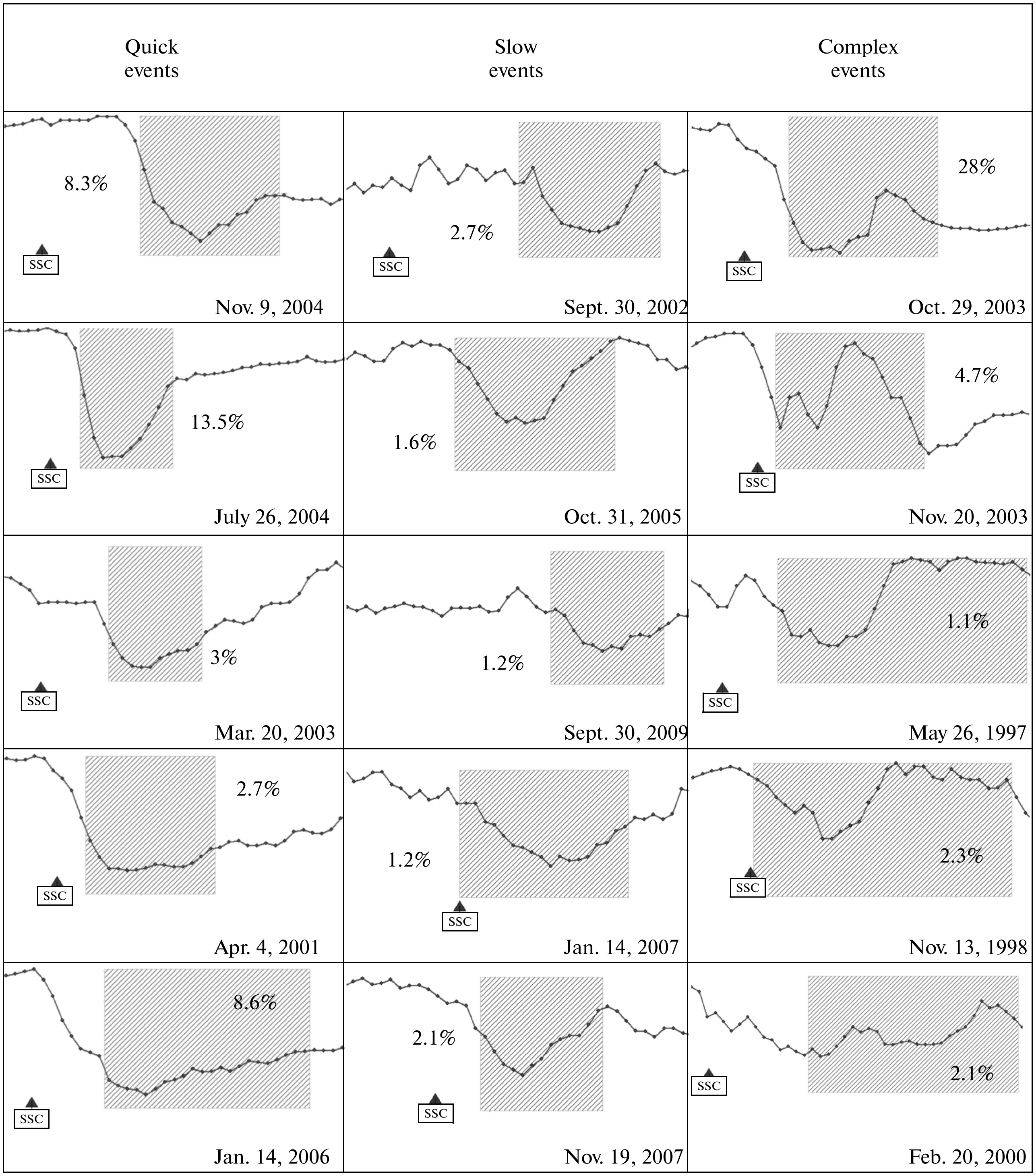

Fig. 3. Examples of profiles of Forbush effects caused by rapid, slow, and complex ICMEs with magnetic clouds. Numerals indicate the FD maximum value, as well as the event date; triangles mark the moments that the shock wave arrived at the Earth (SC). The shaded area corresponds to the time that the Earth was in the cloud.

geomagnetic activity count rate level increment appears. This magnetospheric variation partly also remains in changes of the CR density obtained by the global survey method. It was repeatedly noted that variations of the cutoff rigidity and corresponding variations of the CR counting rate are closely correlated with changes of the *Dst*-index of geomagnetic activity. We made sure that this correlation applies to density variations of CRs obtained by GSM (e.g., Belov et al., 2005).

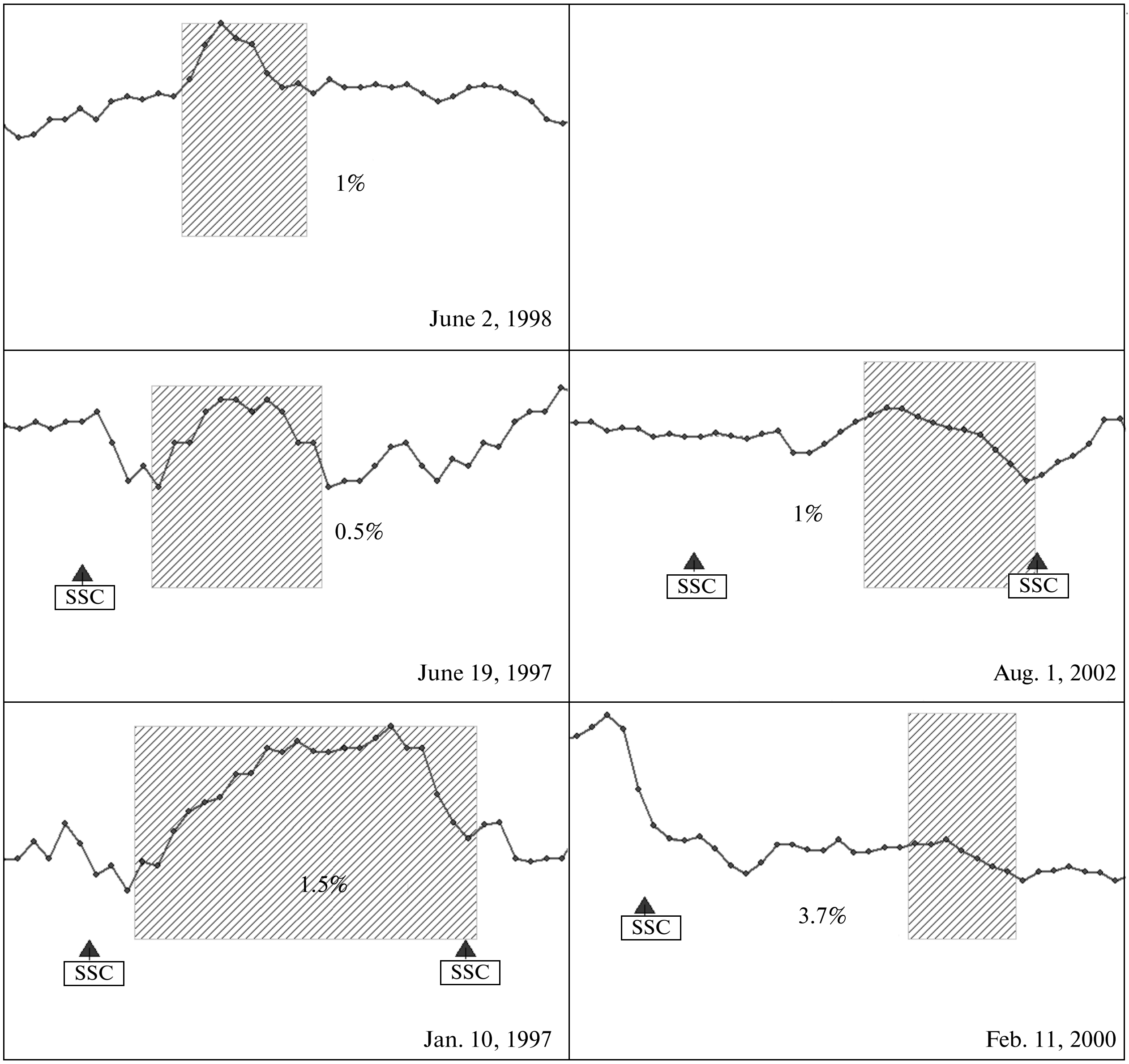

Fig. 4. Examples of the positive effect on CRs within the magnetic cloud. Each panel shows the event date and the magnitude of the maximum change of the CR density inside the MC. Triangles indicate shock wave arrivals to the Earth. The shaded area corresponds to the time that the Earth was in the cloud.

With that said, the expected variation of the CR density in the MC can be written as

$$\delta = A0 = a + b_1 X + b_2 X^2 + b_d Dst, \tag{2}$$

where a is the constant, b_1 is the trend factor, b_2 represents the main part of the effect of MC on CRs, b_d determines the contribution of the magnetosphere, and X is the distance in gyroradii.

We applied this simple model to all 99 events in our sample. Every hour we determined the parameters a, b_1, b_2, and b_d by the method of least squares. An example of the model representation of CR density variations in the MC is shown in Fig. 6.

Here we see a good agreement between the calculated and experimental data (the correlation coefficient is 0.996). It is good or at least satisfactory for most events. However, a match between the model representation and the real density behavior was not always observed, which can occur for many reasons. The main one is that a simplified representation of the MC as a quasi-cylinder is obviously not suitable in some cases. In these cases, the dispersion σ^2 in the least squares method is high, and the correlation coefficient, in contrast, is low. It should be noted that the results cannot always be trusted even in the case of low dispersion. In our sample the number of hours that the Earth spent in MC changes from 6 to 64. It is clear that six hours (six points) are not sufficient for a reliable identification of four model parameters. However, for most events there are enough points, since the average MC lifetime in our sample is 21 ± 1 h.

3.2. Statistical MC Simulation Results

Let us discuss the modeling statistical results and the contribution of different factors in the formula model. We did not consider clouds with a length of <4ρ and cases with large dispersion σ^2 or when σ was >0.3%. These criteria reduced our sample to 74 events, but it turned out that our simple model is applicable to most events.

1. The coefficient b_d determines the contribution of magnetospheric variations in CR density changes. It is not always possible to determine this coefficient exactly, since as a rule CR magnetospheric variations are too small (or change too little in the MC) to determine b_d with sufficient accuracy. The events in which it is possible to do it are summarized in Fig. 7.

Here, the coefficient b_d is shown as the dependence of the minimum *Dst*-index during the hours when the Earth was in the cloud. The average coefficient b_{dm} = 0.0136 ± 0.0016%/nT for these events is shown in Fig. 7 by the solid horizontal line. The region $\pm\sigma_d$ is shaded, where σ_d is the standard deviation of the distribution of coefficients b_d.

It can be seen that the distribution of individual points and errors of individual coefficients are consistent with the standard deviation σ_d. A dependence on the value of the *Dst*-index was not found. The point that drops out refers to the event in February 1998. There were no formal reasons to exclude it from the analysis. However, the MC structure was most likely closer to the toroidal one than to cylindrical in that event, and it was possible to artificially obtain the parabolic dependence by the random correlation of changes in CR density and *Dst*-index. Thus, this ratio (about 0.27%/nT) appears to be unreasonably high and it is better not to take it into consideration.

These results suggest that in all events when the magnetospheric effect is determined relatively accurately, the relationship of magnetospheric variations with changes in the CR density is approximately one and the same and is determined by the above mentioned average coefficient b_{dm}. For magnetospheric CR variations, our sample can be considered random, and the resulting coefficient can apparently be applied not only to variations in MCs but also to variations in CR density with a rigidity of 10 GV obtained by our version of the global survey method in all periods.

2. The coefficient b_2 (Formula 2) is the main one for the parabolic model. The main part of the effect of the MC on CR density is shown in it. The positive coefficient corresponds to a decrease of the CR density in the model. If as a result of the simulated value of the coefficient b_2 is small and comparable to statistical error, it should usually mean that the MC weakly affects CRs around the Earth. At the same time this impact in other parts of the heliosphere can be much stronger, because the Forbush decrease is a large-scale heliospheric phenomena (Belov, 2009). For the analysis we selected 39 events for which $b_2/\sigma_{b2} > 3$ in order to highlight the statistically significant contribution of b_2 in the model.

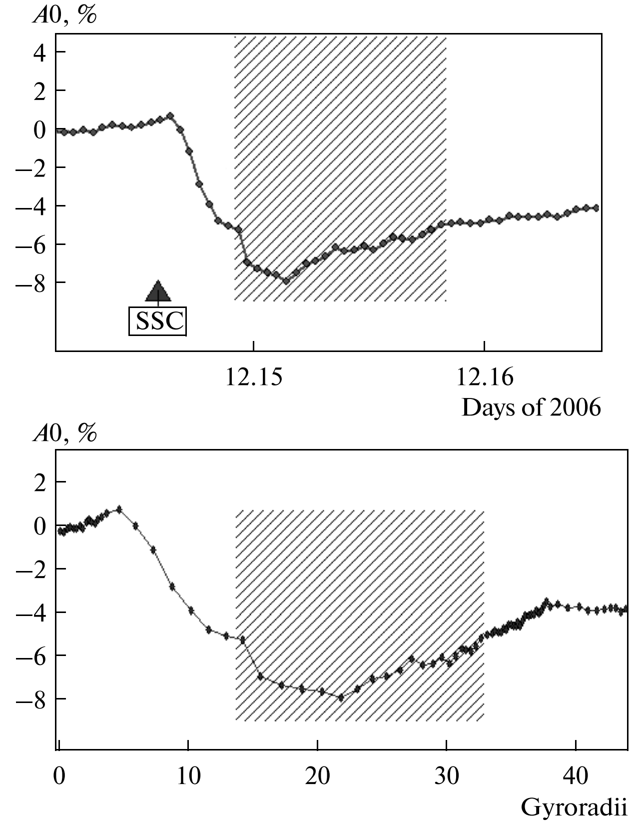

Fig. 5. Example of the magnetic cloud effect in CRs: the CR density distribution (*A*0) in the time base (upper panel) and depending on the gyroradius of particles with the rigidity of 10 GV (bottom panel). The shaded area shows the MC length in this event (December 14, 2006). Triangle marks the beginning of the magnetic storm.

Figure 8 shows the dependence of the coefficient b_2 on B_{max}, which is the maximum IMF strength in the MC, found in 39 events with a parabolic model.

The predominance of positive b_2 (i.e., events in which there is a local CR density minimum inside the MC) is obvious. Of the 39 events for which the parabolic model is applicable, the influence of the MC on CRs ($b_2/\sigma_{b2} > 3$) is prominent; only in nine cases $b_2 < 0$, which indicates an increase in CR density within the MC. Events in which there is a local CR density maximum inside the MC are in the minority. But they are real. They cannot be explained by bad data or mag-

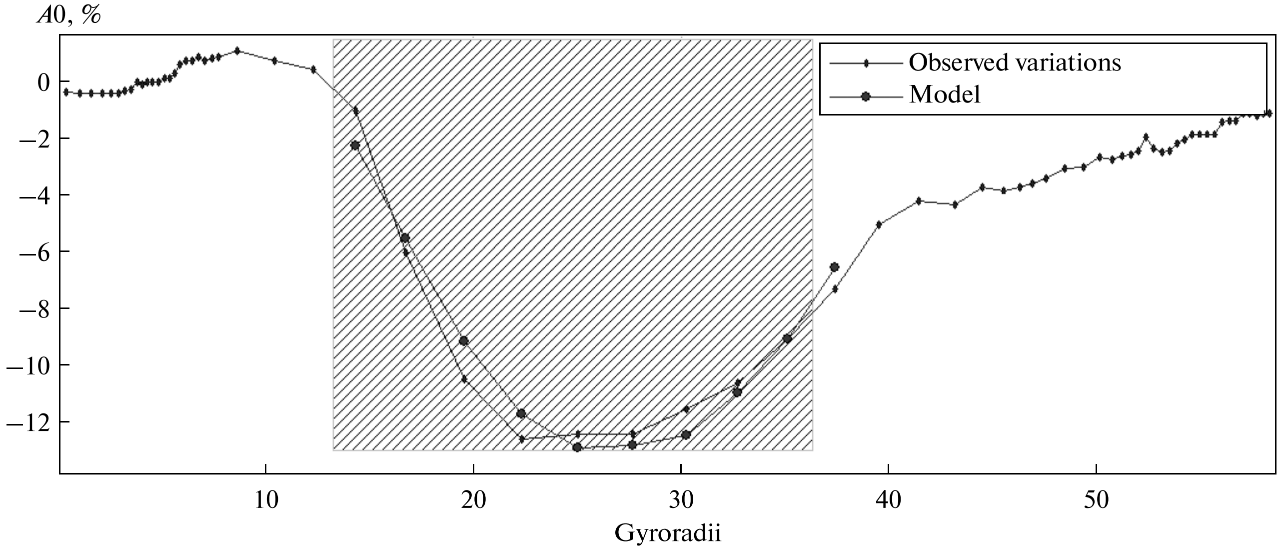

Fig. 6. MC simulation example for the event on June 26, 2004. The dependence of the CR density distribution (*A*0) in the magnetic cloud on the gyroradius of particles with the rigidity of 10 GV: diamonds are the observed CR variations and dots are the model description of the *A*0 distribution in this event.

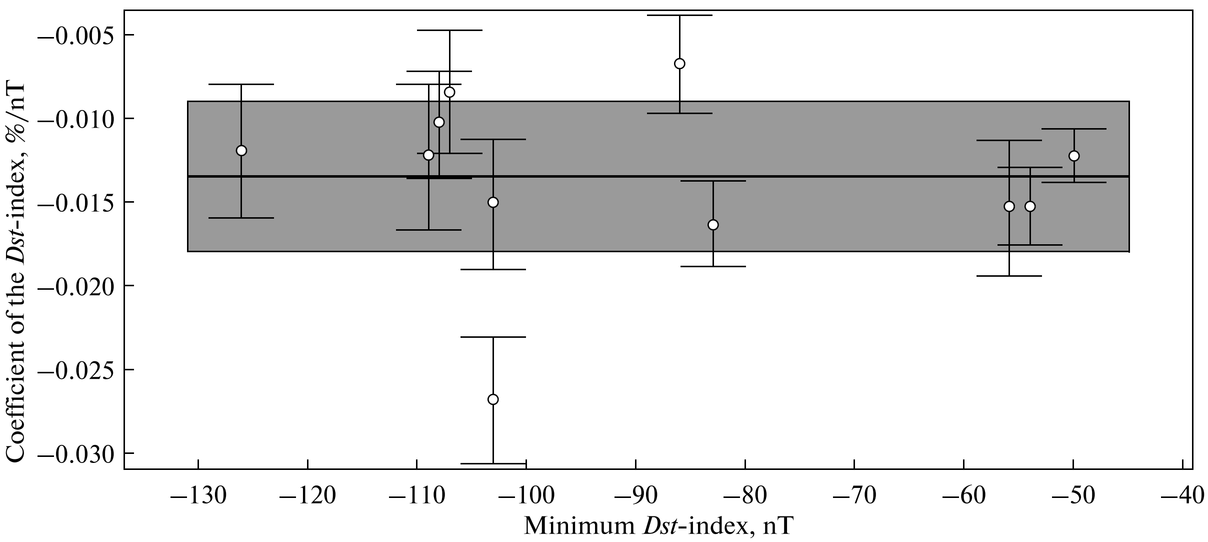

Fig. 7. Dependence of the coefficient b_{dm} on the minimum *Dst*-index in the magnetic cloud.

netospheric effects. These are real increases in the CR density of MCs.

The explicit dependence of b_2 on B_{max} (Fig. 8) is not observed, but it should be noted that all of the negative b_2 were observed in a relatively weak field, and for $B_{max} > 18$ nT all b_2 were positive. That is, in the case of a strong magnetic field, we always have "normal" Forbush decreases with the local CR density minimum inside an MC.

It can be assumed that the value of the effect of the MC on CRs is partly determined by its size (in gyroradii). For 31 events in which density decreases in the MC and the model is fairly adequate, the correlation coefficient between b_2 and the size of the cloud was 0.70.

It should be noted that the effect of most MC on the CR density (10 GV) is small. In 41 of 74 events, this effect was <0.3% and in 50 cases it was <0.5%. It is clear that such small effects are difficult (almost impossible) detect using data from only one CR sensor. It is no surprise that some researchers came to the conclusion that MCs do not affect cosmic rays. We believe that all CME/ICME affect CRs. It cannot be any other way. This is especially true in cases where an MC is observed near the Earth. However, the effects of

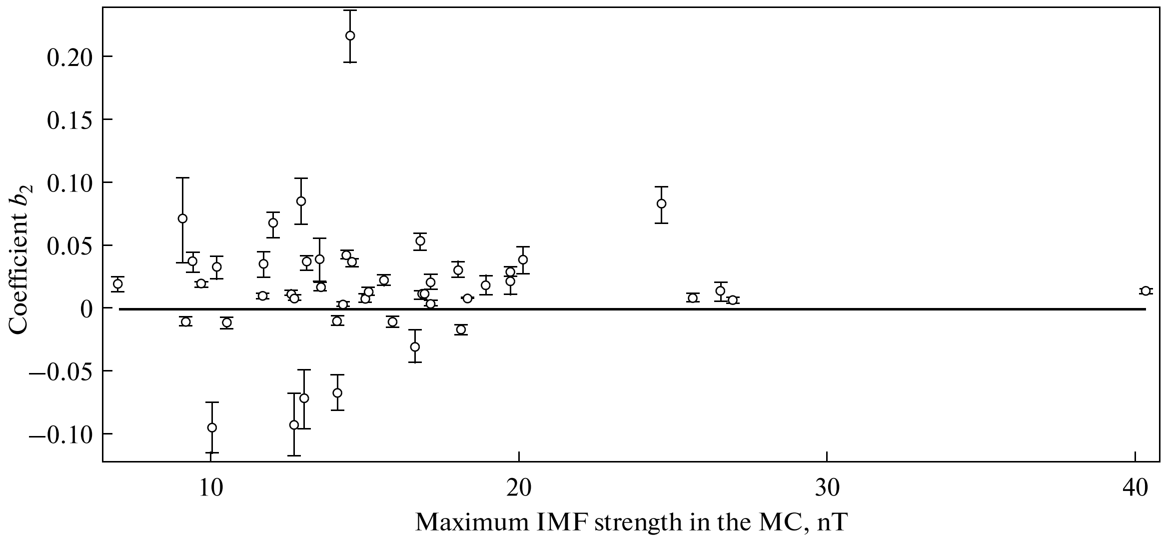

Fig. 8. The dependence b_2 on the magnetic field strength inside the cloud.

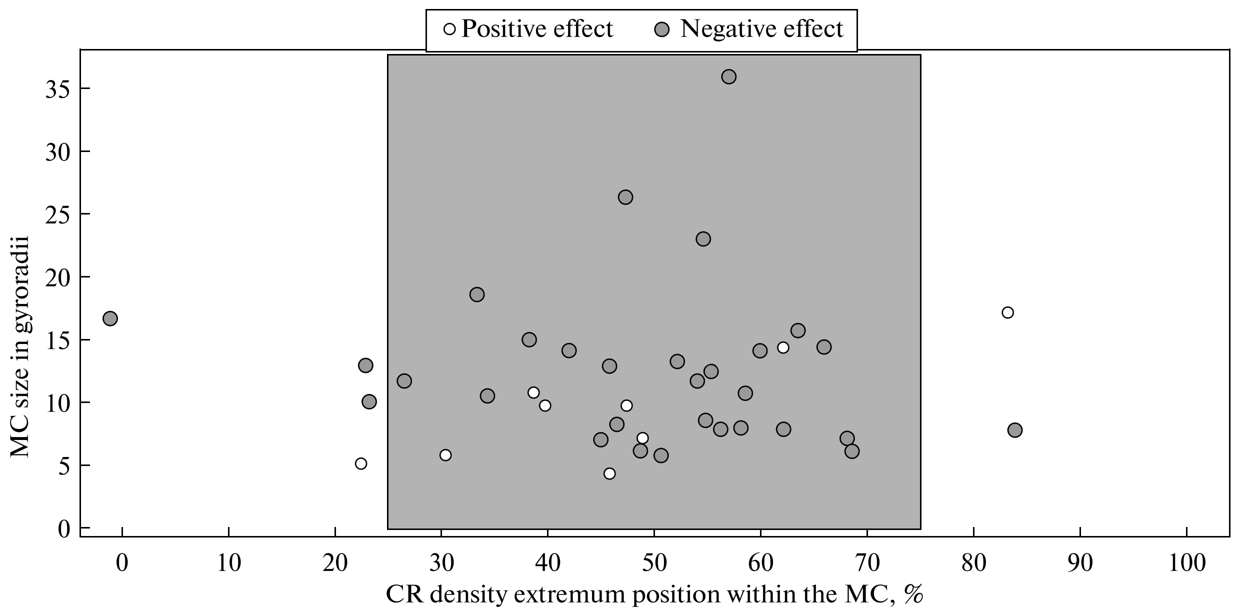

Fig. 9. The position of the extremum in the CR density inside the magnetic cloud.

CME/ICME and MCs are often small and difficult to detect.

The extrema (maximum or minimum) CR density are often located closer to the cloud center, and not on the edges. This can be seen in Fig. 9. In it, the whole cloud is divided into three parts: the central (25–75% of the length) and side parts. Among all of the 39 events, 33 occurred in the central part and only six happened in side parts. Events with a positive effect have a maximum mainly in the leading part of the cloud. In events with a negative effect, the minima are more evenly distributed but tend to be grouped in the rear part of the cloud.

4. KEY FINDINGS

The presence of the MC in the interplanetary disturbance usually enhances the ability of this disturbance to modulate cosmic rays.

In CR behavior the MC is also reflected as a whole and as features of its structure. It can be seen in changes in the density and vector anisotropy of CRs obtained according to the global network of neutron monitors using the global survey method.

In a significant number of events, changes in the CR density inside the MC give an almost symmetrical pattern with a minimum density at the cloud center, suggesting its quasi-cylindrical structure. Events in which the CR density behavior remains regular but becomes more complex with alternating of areas with high and low density within the cloud are also quite frequent. It may be a manifestation of some quasi-toroidal structure of some MCs.

In most cases (but not in all), the CR density behavior in the MC near the Earth can be described by a simple parabolic dependence on distance measured in gyroradii.

Most MCs modulate cosmic rays by changing their density. The CR density in the MC usually decreases, but there is a group of events (about 1/5 of them) in which the CR density increases in the MC.

By the investigation of MCs, it was possible to obtain a quantitative relationship of density variations of CRs of magnetospheric origin defined by the global survey method with changes of the *Dst*-index. It was found in all events that the relationship between magnetospheric variations and CR density changes was approximately the same and was determined by the average coefficient obtained in the paper. Apparently, it can be applied not only to MCs but also to CR density variations with a rigidity of 10 GV, in all periods.

No explicit dependence of CR density variations on $B_{\max}$, or maximum IMF strength measured inside the MC was found. However, it should be noted that all of the positive effects (density increase inside of the MC) were observed in a relatively weak field, and all CR density variations were negative for $B_{\max} > 18$ nT. That is, in the case of a strong magnetic field, we always have "normal" Forbush decreases with the local CR density minimum inside the MC.

The extrema (maximum or minimum) of CR density are often located closer to the cloud center, not on the edges. Events with a positive effect have maximum mainly in the leading part of the cloud. In events with a negative effect, the minima are more evenly distributed but tend to be grouped in the rear part of the cloud.

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