Modeling the behavior of the cosmic ray density in magnetic clouds

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Abstract. Our study focuses on the behavior of the density of cosmic ray particles at 10 GV rigidity in a magnetic cloud at Earth. It is shown that it can be mostly described by a simple parabolic dependence over distance from the centre of the cloud, when measured in gyroradii. The majority of magnetic clouds modulate cosmic rays, decreasing their density. However, there is a group of events (about 1/5 part of the total sample) during which the cosmic ray density increases within the magnetic cloud. The factors that contribute to the model description are considered, and estimates of their influence are carried out and discussed.

1. Introduction

In this work we considered only those solar wind (SW) disturbances (Interplanetary Coronal Mass Ejections - ICMEs) in which magnetic clouds (MCs) are observed. It should be noted that such disturbances with well identified magnetic clouds make only a small part of the disturbances capable to cause Forbush effect (FE).

Magnetic clouds encounter the Earth, keeping the elements of the solar filament structure [1]. As it was shown, for example, in [2], all ICMEs that reach the Earth, have a "flux rope" structure, but it cannot be completely observed in all events. There is a geometrical selective effect and the "observed manifestation" of a magnetic cloud strongly depended on the passage of the observing satellite through the ICME structure [3]. Having MC observations, we practically witness filaments which lay on the Sun – with a large regular magnetic field, which significantly differs from the field in usual SW. Most of MCs show a large Bz component at Earth. It is well known the role of this component in strong magnetospheric responses. Therefore the main part of geomagnetic storms are initiated while passing of MCs, and as result, indices of geomagnetic activity (Dst, Kp etc.) during these periods have the high values.

Richardson and Cane [4] made the Coronal Mass Ejections (CMEs)-ICMEs catalog over the time period 1996 to 2009, with an identification of MCs, which is the most complete at present. They showed that CMEs with MCs are more geoeffective, than other transient events. Apparently, considerable part of the MCs observed at Earth, have quasi-cylindrical geometry. This is supported by
current ideas that the internal part of the CMEs is the original solar filament arranged as the long cylinder with “flux rope” structure [5]. This also agrees with observations of the SW disturbances at Earth, and with successful attempts to model MCs as cylindrical formations [6]. Small near-Earth part of a MC can be presented in the form of a quasi cylinder. In this work we consider only the isotropic part of the CR variations, i.e. CR density variations, inside the regions where the MC model is applicable.

It is natural to assume that exactly within a MC (owing to its expansion and relative isolation) the mechanism leading to Forbush decreases (FDs), is especially effective. However, it should be noted that FEs are created in the whole disturbance, and in many FEs associated to the MC, the CR minimum may appear inside and also outside of cloud, e.g., between the driven shock and MC nose [e.g., 4, 14]. We consider only the part of FEs which is directly related to the MC. In the simplest case this part of disturbance can be presented in the quasi cylinder form. Accordingly, the minimum of the CR density is expected to be observed near the central axis of this structure, while the CR density is expected to increase close to the surface of the quasi-cylinder. A simple function, capable to display such a distribution is the parabola. This parabolic function will be suitable not only for cylindrical, but for any distribution of CR with one extreme inside or even out of a MC. In the theoretical models the decision is given by more complex functions, but it is possible to show that in the first approximation they can be described with a parabola.

2. Data and Methods
To select the events for analysis we used the catalog of ICMEs [4] for the time period 1996 to 2009 – (the only complete catalog of interplanetary disturbances for these years). It includes key parameters of interplanetary disturbances, their solar sources and the accompanying geomagnetic effects. We selected those ICMEs which were included in the list of magnetic clouds of WIND (http://wind.nasa.gov/mfi/mag_cloud_pub1.html) and/or are listed in [7] and/or [8]. The CR parameters (variations of CR density and anisotropy) on the chosen events were taken from databases created in IZMIRAN. In the first database on “CR variations”, hourly values of the CR density and anisotropy above the Earth atmosphere and magnetosphere, specially calculated for 10GV rigidity by the Global Survey Method (GSM) [9] using data from world network of neutron monitors (www.nmdb.eu; http://cr0.izmiran.ru/mosc), are combined with solar, interplanetary and geomagnetic data [10] (http://omniweb.gsfc.nasa.gov/ow.html; ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc; http://www.swpc.noaa.gov/). The second database “on interplanetary disturbances and Forbush effects (FEs)” contains characteristics of FEs on more than 6000 events, and parameters of associated with FEs, solar wind disturbances, indices of geomagnetic activity and information on solar sources [8, 13]. The information on SW is derived from the OMNI database (http://omniweb.gsfc.nasa.gov/). In this work the influence of the variations of the magnetosphere on the CR density is investigated during geomagnetic storms. Furthermore, the contribution to the model of various coefficients and features leading to the density distribution of CRs in a MC is being discussed.

3. Discussion of the results
The selection of ICMEs with MCs observed at Earth within solar cycles 23-24 resulted at 99 events all of which are grouped by the presence of MCs, but all of them being very different.

As it was mentioned above, the simplest function, capable to model the distribution of the CR density variations in the quasi-cylindrical structure of the MC, is a parabola. Discrepancy of real distribution with a parabola is possible, but other circumstances which we consider below, are even more essential when modeling the behavior of the CR density in the MC.

1. We use data of the CR density variations obtained in each hour by the GSM. As the plasma from ICMEs extend almost radially, we assume almost a radial section (to define more precisely: a puncture) when studying the CR density hourly data. This puncture can pass through a cloud differently, but it doesn't limit the applicability of the parabolic representation of the CR density. Nonetheless, when modeling hourly averaged data, it is necessary to
remember that Earth, when crossing the interplanetary disturbance, passes for an hour different distance according to the speed of this part of the disturbance. For charged particles the distance is better expressed neither in kilometers (km) nor in astronomical units (AU), but in Larmor radii (gyroradii) \( \rho \), which depends on the rigidity of particles \( R \) and on the hourly intensity \( B \) of the interplanetary magnetic field. It is possible to write down that for an hour the observer passes in the interplanetary disturbance (in particular, in a MC) a distance of 

\[
X_\rho = \frac{cVB}{R}
\]

gyroradii (this is equation of conversion of time into distance), where \( V \) is the radial speed of the SW. Upon transition from the linear sizes to gyroradii it is possible to expect more symmetric changes of the CR density in the cloud. This is confirmed in figure 1.

![Figure 1](image)

**Figure 1.** Example of the MC effect in cosmic rays: CR density variations \( A_0 \) plotted versus time (top panel) and depending on the gyroradii (low panel) for particles of 10 GV rigidity. Shaded area shows the MC period in this event (2006.12.15). Triangle (SSC) marks the beginning of the geomagnetic storm.

2. The second important fact which should be considered when studying the influence of MCs on the CR, using the ground level neutron monitor data, is the magnetospheric variations during the magnetic storms [11]. The main part of these variations is caused by the change of the geomagnetic cut off rigidity at the points of observation, thus it is variable, depending on the level of geomagnetic activity, resulting in an increase of the NM count rate. This magnetospheric variation partially remains in the changes of CR density obtained by the GSM. It was repeatedly noted [11] that variations of cut off rigidity and the corresponding variations of CR counting rate are closely correlated with changes of the Dst-index of the geomagnetic activity. This correlation seems to be extended also on the variation of CR density obtained by the GSM. Thus, the expected variation of the CR density in a MC can be written as:
A0 = a + b_1 X + b_2 X^2 + b_d Dst  \tag{1}

where $a$ is a constant, $b_1$ – trend coefficient, $b_2$ content the main part of the influence of MC on the CR, $b_d$ defines a contribution of the magnetosphere. $X$ is a distance in giro-radii from the onset of disturbance. Dst is the index of geomagnetic activity.

We applied this simple model to all 99 events of our selection, each time determining parameters $a$, $b_1$, $b_2$, $b_d$ by the RMS method. So, we have a set of these parameters for 99 events. An example of the model simulation of the CR density variations (A0) in a MC is presented in Figure 2, where a good agreement between of the calculated and experimental data is clearly seen. Correlation coefficient for this event is 0.996, $b_2$ is 0.058 ± 0.006%/gyroradii.

![Figure 2](image)

**Figure 2.** Example of modeling of the CR density in the MC in the event of 2004.07.26. Dependence of the CR density variations (A0) in the magnetic cloud on the gyroradii of particles with rigidity 10 GV: triangles — observable CR density variations obtained by GSM, points — model results of the CR density distribution in this event.

Good or, at least, satisfactory consent was present in the majority of the 99 events to what the high coefficient of correlation testifies. However agreement between the model and actual recorded behavior of the CR density was not always satisfactorily. A number of reasons may be accounted for such discrepancies. One of the main reasons is that the simplified representation of MCs in the form of a quasi-cylinder isn’t obviously suitable in some cases. In these cases the dispersion in the rms method appears to be large and the correlation coefficient is small. But it is necessary to point out, that even low dispersion in data not always corresponds to good results. The number of hours the Earth spent within an MC varies in our selection from 6 to 64. Evidently, 6 hours (6 points) aren’t enough to determine the four model parameters reliably. However, the mean duration of the MC is 21 hr with the range 6-64 hr, therefore the number of points is sufficient in most the cases examined in this work.

4. **Statistical results of the MC modelling**

Let’s estimate statistical results of the modelling. We did not consider the MCs of length <4$\rho$ and the cases with large dispersion between observable and calculated values in rms method (root mean square standard deviation) - $\sigma^2$ (when $\sigma$ >0.3%). These criteria reduced our selection to a total of 74 events. The coefficient $b_d$ defining a contribution of the magnetosphere variations in the CR density was not always possible to be determined precisely as the magnetosphere variations of CRs inside the MC are often too small. Those eleven events in which it was defined are plotted in figure 3 where $b_d$ coefficient is presented against the minimum of the Dst-index at those hours when Earth was in the...
MC. An averaged coefficient $b_{dm} = 0.0136 \pm 0.0016 \%$/nT and is plotted in figure 3 by the solid horizontal line. Shaded region is $\pm \sigma_{bd}$ – where $\sigma_{bd}$ is standard statistical error of $b_d$ coefficient.

It is possible to see that the distribution of points in figure 3 and the errors of separate coefficients are within the limits of the standard deviation $\sigma$. There is no dependence of $b_d$ on the value of the Dst-index. The point dropping out at -103 nT, belongs to an event in February, 1998. We had no formal reasons to exclude it from the sample. But, most likely, in that event the structure of the MC was closer to toroidal-shaped, than to cylindrical and the parabolic dependence is an artifact due to casual correlation of CR density changes to the Dst-index. Thus, this coefficient (about 0.27% / nT), apparently is an overestimation and it is better not to consider it, further.

![Figure 3](image-url)  
*Figure 3. Magnitude of $b_d$ coefficient versus the minimum of Dst index in the magnetic cloud.*

Found dependence of CR variations of magnetospheric origin (see section 3, item 2) on Dst index is a magnetospheric effect, its size isn’t related directly with type of interplanetary disturbances, whether it be ICME with MC, ICME without MC or a high-speed stream from coronal hole.

Thus, the obtained results allow one to assume that in all events (or, at least, in their majority) the relation of magnetospheric variations with changes of CR density is approximately the same and is sufficiently defined by the average coefficient of $b_{dm}$ specified here above. In spite of the fact that the magnetic storms associated with MC were very different (long and short, large and small) the $b_d$ coefficient was constant for various type of the storms. It gives promise that the obtained dependence is applicable not only to MC, but also to other structures caused CR variations of a magnetospheric origin.
The coefficient \( b_2 \) (Eq. 1) is the basic for parabolic model. This coefficient displays the main part of a MC influence on the CR density. A positive coefficient corresponds to fall of CR density in model. If the value of coefficient \( b_2 \) is small, comparable with a statistical error, it, as a rule, has to mean that this MC poorly influences CRs near Earth. Since FEs are large scale heliospheric phenomena, this influence can be more effective in other locations in the heliosphere [11, 12].

For further analysis we selected events, for which \( b_2/\sigma_{b_2}>2 \), (where \( \sigma_{b_2} \) is a standard statistical error of \( b_2 \) definition) to provide statistically significant contribution of \( b_2 \) in the model. This criterion reduced our sample to 40 events. In figure 4 the distribution of the coefficient \( b_2 \) obtained from parabolic model by the 40 events, vs the maximum intensity of IMF (\( B_{\text{max}} \)) in the MC, is presented.

Prevalence of positive \( b_2 \) (i.e. events with the local minimum of CR density in the MC) is obvious. Among of 40 events for which the parabolic model is applicable and the influence of a MC on CRs is noticeable, only 10 events have \( b_2<0 \). Those are the events, in which within a MC a local maximum
instead of minimum of CR density is revealed (see figure 5), and they are the minority [15]. Those
can't be explained with bad data or magnetospheric effects. These are real increases of CR density in
MCs and, as a rule, they are observed in MCs with relatively weak magnetic field. One of the possible
explanations of such anomalous effect might be the following: while in propagation, in some MCs the
magnetic field weakens, and they stop being an effective quasi trap for high-energy CR. But regular
IMF (fluxrope structure) connects a point of observation to rather remote western areas of a
heliosphere where FEs are weaker and correspondingly the CR density higher.

Accordingly to results in figure 4 an obvious dependence of $b_2$ on $B_{max}$ isn't observed, but it is
possible to note that all negative $b_2$ were observed in relatively weak field, and for $B_{max}\geq 18$ nT
all $b_2$ are positive. Hence, in our selection, in cases of strong magnetic field we always have the normal
effect MC on the CR with a local minimum of the CR density within the MC.

In some works [4, 14] is shown that the FE production seems to be relevant with a duration of the
MC influence. We think that it is possible to assume that the influence of a MC on the CR density is
defined also by its size (in gyro radii). This is confirmed by figure 6 where the magnitude of the
influence of the MCs on the CR density is presented for 31 events within which the MCs led to a
decrease of the CR density. We see that correlation exists but it is not so large (correlation coefficient
$cc = 0.70$) as the size is not the only parameter which influences the FE production. It should be
noted that the influence of the majority of MCs on the CR density variations is insignificant. In 41 out
of the 74 events this influence is <0.3%, and in 50 <0.5%. It is clear that such small effects can't
almost be revealed by the data of a single detector. It is no surprise that some researchers came to a
conclusion that MCs don't influence CRs. However, it seems to us that all CMEs/ICMEs influence
CRs, especially, when MCs are observed at Earth. But effects of ICMEs and MCs often use to be
hidden by the influence of other perturbations, so they are often small and difficult for detection.

The extremes (minimum or maximum) of CR density settle down closer to the cloud centre more
often than to its edges. This is visible in figure 7. Let's divide all MCs into two parts: central (25-75%
of all length) and lateral. Among all 40 events, 34 fall into the central zone and only 6 in lateral. One
can see from figure 7 that events with a positive effect (empty circles) have a maximum, generally in
the leading part of a MC. In the events with a negative effect (full circles) minima density is
distributed more evenly, but tend to be grouped in the tail part of a MC.

5. Conclusions
In large part of events the CR density changes in a magnetic cloud, providing an almost symmetric
picture, with the CR density minimum close to the MC center, allowing one to assume its quasi
cylindrical structure. Events in which the behavior of the CR density, remain regular but becomes more complicated, with alternations within areas of the MC with an increase and/or lower density, are rather frequent also. Those can be manifestations of the quasi-toroidal structure of some MCs.

In most cases (but not in all) the behavior of the CR density within MCs at Earth can be described by a simple parabolic dependence on distance expressed in gyroradii. The majority (but not all) of MCs modulate CRs, decreasing their density, although there is a group of events (about 1/5) in which the CR density increases near the MC center.

![Figure 7. The relative position of extreme CR density within MC. It is defined in a % of all MO: 0% correspond to Earth entrance and 100% -to Earth exit from the cloud](image)

A quantitative relation of Dst index and contribution of a magnetosphere into the CR density variations derived by GSM, was determined via the averaged coefficient $b_d$.

An obvious dependence of a contribution to CR density variations on $B_{max}$ - the maximum intensity of IMF measured in a magnetic cloud isn't observed. But it is possible to note that all positive effects (CR density increases in MCs) were observed in rather weaker field, and for $B_{max}> 18$ nT all variations of CR density are negative, i.e., in cases of a strong magnetic field we always have "normal" FDs with a local minimum of CR density in a MC in our selection.

The extremes (minimum or maximum) of CR density more often settle down closer to the cloud center, than to its edges. Events with a positive effect have a maximum, generally in the leading part of a MC. In the events with a negative effect minima density is distributed more evenly, but tend to be grouped in the tail part of the MC.

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