33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

The impact of magnetic clouds on the density and the first harmonic of the cosmic ray anisotropy

A. ABUNIN[1], M. ABUNINA[1], A. BELOV[1], E. EROSHENKO[1], V. OLENEVA[1], V. YANKE[1], H. MAVROMICHALAKI[2], A. PAPAIOANNOU[2]

[1] *Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, RAS (IZMIRAN)*
[2] *Nuclear and Particle Physics Section, Physics Department, National and Kapodistrian University of Athens*

abunin@izmiran.ru

Abstract: It is known more than 20 years that magnetic clouds affect the galactic cosmic rays. They are able to change the density of cosmic rays, creating a two-step structure of the Forbush-decreases, and significantly increase the second harmonic of the cosmic ray anisotropy. In this paper the variation of cosmic rays by the global survey method obtained from the world wide neutron monitor network, were studied for 99 events, identified with magnetic clouds. It is shown that the interplanetary disturbances with magnetic clouds modulate cosmic rays stronger than the disturbances with similar characteristics of solar wind, but without the magnetic clouds. Many examples of cosmic ray density decreases in the magnetic clouds revealed a good agreement with the cylindrical symmetry. However, there are some events in which a maximum of the cosmic ray density in the cloud is observed instead of the minimum. In several cases variations of the cosmic ray density have complicated character, with alternating local minima and maxima, possibly reflecting the toroidal structure of the cloud. One can see that galactic cosmic rays not only react to the magnetic cloud in common, but also can display the internal structure of its magnetic field. In many cases one can identify the boundaries of the magnetic cloud by to the data on density and anisotropy of the cosmic rays.

Keywords: magnetic cloud, Forbush effect, cosmic ray anisotropy.

1 Introduction

Magnetic clouds (MCs) [1] are closely related to the Forbush decrease (FDs) of cosmic rays (CRs) [2, 3]. As FDs arise during the expansion of partially closed magnetic structures in the solar wind [4, 5, 6, 7], and MCs is the most obvious example of such a structure, it is natural to expect the deepest decrease in the CR density exactly in MCs. The concept of two-step FDs is based on this fact [2, 8], in which a second, deeper density decrease is associated with the MC. The impact of MCs on the galactic CRs was considered in a number of papers (eg, [9, 10, 11, 12, 13]), but obtained results were ambiguous.

In this paper we have used the ICME catalog [14], in combinating with our database on FDs [15, 7], to investigate the features of the CR anisotropy and density in the events when MCs were observed in the interplanetary disturbances near Earth.

2 Data and methods

In the ICME catalog [14] the basic properties of interplanetary disturbances, their solar sources and the relevant geomagnetic effects are presented for 1996 - 2009. We selected those ICMEs, which entered the list of magnetic clouds WIND (`http://wind.nasa.gov/mfi/mag_cloud_pub1.html`) and/or are listed in [16]. Created in IZMIRAN, the database on Forbush effects and correspondingly interplanetary disturbances, is based on the variation of density and anisotropy of the CR with rigidity of 10 GV. These parameters are received by the global survey method (GSM) (eg. [17, 18]) using data from the neutron monitor network. Apart from CR parameters, this database includes various data of the interplanetary disturbances, indices of geomagnetic activity and solar parameters.

One of the problems in studying the effect of MCs on CRs is the magnetospheric variations of CRs. During the passage of a magnetic cloud, geomagnetic storms are often observed at Earth, which in turn may influence CR density variations defined by GSM.

To avoid this undesirable effect, we estimated the possible magnetospheric variations, and as an example, picked up the events in which the magnetospheric variations were either small or changed unsignificantly in the magnetic cloud.

3 Discussion

Into the group of ICMEs with MCs, observed at the Earth, 99 events the 23^{rd} and 24^{th} solar cycles were selected [14]. The presence of MCs underlines the common group of these events, but both the MCs and FDs in the group - are very variable. Among them are the short and long-term disturbances, very fast ICMEs with the solar wind velocity at the Earth $> 1000 km/s$ and the slow ones - with velocity $< 400 km/s$, with a very large and modest increase of the interplanetary magnetic field. Magnetic clouds - are the structures with enhanced interplanetary magnetic field, but this enhancement used to be very high (up to 57 nT), and small (up to 8 nT). Not all events (only 62 of 99) have begun with the arrival of an interplanetary shock, which we define by the SSC.

Also phenomena caused by ICMEs are significantly different. Together with exclusively big magnetic storms, a dozen of events with the Kp-index $\leq$4- turned out to be in this list. The corresponding CR variations are also variable. The sample includes the biggest in the history of FDs with a magnitude of A_F = 28% (all the characteristics of CR variations are calculated for 10 GV rigidity) and a few small FDs with a value of not more than 0.5%. If for the sample of 99 events with a MC, we calculate the average characteristics, it turns out that on average these are large enough FDs ($A_F = 3.4 \pm 0.4\%$), which were accompanied, again on average, by moderate magnetic storm ($Ap_{max} = 98 \pm 9(2nT)$, and $Dst_{min} = -103 \pm 8nT$).

To understand how the CR modulation depends on the presence of MCs, we compared the sample with the MC being discussed, with the control sample (see Table 1). The control subset includes the events of the same period (1996-2009 years) with similar interplanetary characteristics (close products of maximum values of IMF intensity and the solar wind velocity). Comparison of the average characteristics of these two groups shows that the ICMEs with MCs more effectively modulate cosmic rays, creating deeper FDs with a more rapid decrease in the density and with greater amplitude of the CR anisotropy. The differences of samples reveals also for geomagnetic activity, but to a lesser extent.

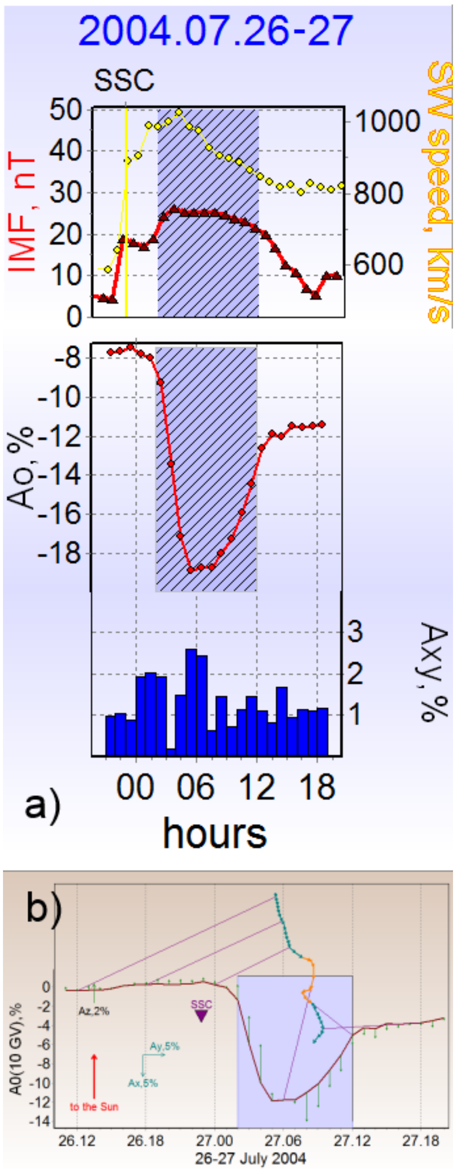

Fig. 1: Example of event with strongly pronounced minimum in the CR density inside the MC (26-27 July 2004).

	Mean (with MC)	Mean (without MC)
Magnitude (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
B_{max}	20.21 ± 1.07	18.01 ± 0.33
V_{max}	551.5 ± 16.5	652.2 ± 9.1
$V_{max}B_{max}$	6.05 ± 0.54	5.79 ± 0.07

Table 1: Different mean characteristics of Forbush decreases with and without MC. Description of table: Magnitude (A_F) - FD magnitude (%) in CR density; Axy_{max} – maximum of equatorial component of vector CR anisotropy (%); Az_{range} – range of changes of north-south component of vector CR anisotropy (%); D_{min} – maximum of hourly decrement of CR density; Ap_{max} (2nT) and Dst_{min}(nT) – maximum of Ap-index and minimum of Dst-index in related geomagnetic disturbance; B_{max} (nT) and V_{max} (km/s) – maximal IMF intensity and solar wind velocity for parent interplanetary disturbance, $V_{max}B_{max}$ – normalized product of B_{max} and V_{max}.

For the control subset we have selected events with simular interplanetary conditions (i.e. $V_{max}B_{max}$ – approximately equal for the control and main subsets) and separated by 36 hours before and 48 hours after other FDs.

The upper panels of the figures 1a, 2a, 3 and 4 show the behavior of IMF (left scale, red triangles) and solar wind speed (right scale, yellow circles); the bottom panels show the change in the CR density (left scale, red circles) and Axy-component of CR anisotropy (right scale, blue bars). The solid curve in Figure 1b and 2b corresponds to profile of the isotropic part of the CR variation (CR density) with rigidity of 10 GV; vector diagram represents the hourly values of the vector of the equatorial component of cosmic ray anisotropy; vertical vectors show a change of north-south component of CR anisotropy; thin lines connect the same points of time at vector diagram and at the CR density curve every 6 hours. In all figures (1-4) the time that the MC is passing by Earth is being marked.

Let's consider the behavior of the CR density and the anisotropy in different events with MCs.

On 26-27 July 2004 (Fig. 1) the Earth was inside the fast ICME characterized by a strong IMF, and the maximum of the field intensity was observed within the magnetic cloud. In this event a deep minimum in the CR density is clearly visible close to the central of the MC, and this example can be attributed to the two-step Forbush effects. In this case, the second step, which was due to the MC, is expressed much clearly than the first one.

Similar behavior of the CR density was observed on 3 October 2000 (Fig. 2), and was associated with a relatively slow CME. There are a lot of examples of such behavior of the cosmic ray density. Forbush effects, with two-step structure and with the main minimum of density in the MC, are typical. However, the presence of a magnetic cloud does not guarantee a two-step structure of the FD at all [19].

In our sample, the main minimum of the CR density was inside the magnetic cloud only in 67 of 99 cases.

Even more seldom, a minimum density was located at the center of the MC. Moreover, there were some events when in the central part of the MC not minimum but on the contrary a maximum of CR density was observed. One such example is shown in Fig. 3. Typically, as in this example, in the abnormal events the IMF intensity not so strong inside the cloud.

In some cases, inside the magnetic cloud we see a more complex behavior of the CR density with alternation of local maxima and minima (Fig. 4). These examples show that the behavior of the CR density reflects not only the magnetic cloud in a whole but the features in its structure as well.

Even stronger, MCs affect the behavior of the first harmonic of CR anisotropy. As a rule, at the entrance to the MC and/or at the exit the magnitude and direction of anisotropy change significantly. It is revealed in variations

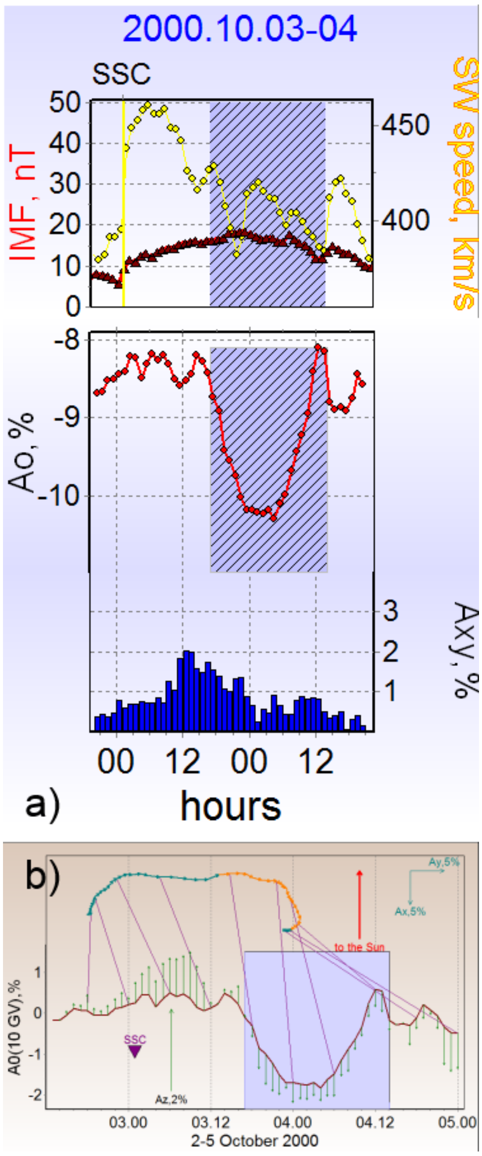

Fig. 2: Example of event with strongly pronounced minimum in the the CR density inside the magnetic cloud and the relatively low velocity of solar wind (3-4 October 2000).

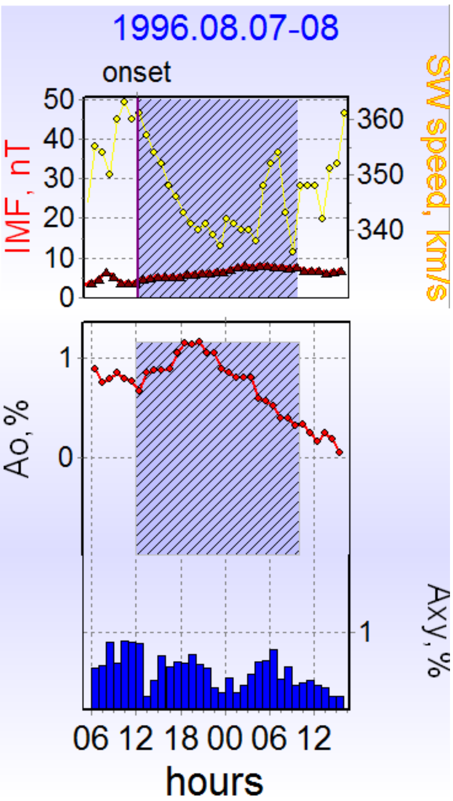

Fig. 3: Example of event with an increase in the CR density in MC (7 August 1996).

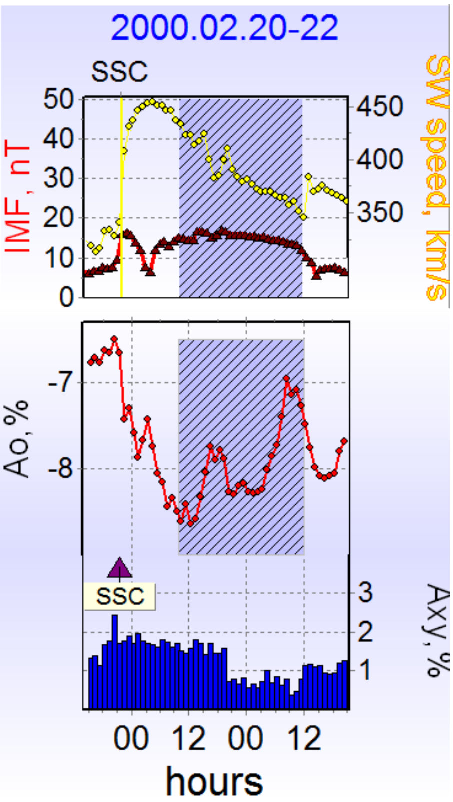

Fig. 4: Example of event with a complex structure of MC (20 February 2000).

of the equatorial Axy (Fig. 1b and 2b) and latitudinal Az (Fig. 1a and 2a of the lower panel) components of the first harmonic of the CR anisotropy in the given examples. Inside the MCs usually systematic changes in anisotropy are observed. For Axy component inside the cloud the rotation, more often in one direction is characteristic (as in Fig. 2b), but sometimes - with a change of the direction of rotation (Fig. 1b). North-south Az component in the cloud typically changes in a regular manner, often changing the sign at the center of the cloud (Fig. 1b).

4 Conclusions

The presence of MCs in the interplanetary disturbances significantly increases the ability of this disturbance to modulate CRs. This can be found several mutually complementary explanations:

- if MC is in the ICME, the bigger magnetic cloud and the closer to the center of solar disk the source of CME the higher chances of the Earth to get into MC, and both these factors increase the depth of the FD [20, 21];
- inside the MC the Earth is closer to the center of the mechanism which generates Forbush decrease.

If in the solar wind disturbance there is no MC, it could mean that:

- the source of this disturbance is not the CME, but coronal hole, which is not so effective in the CR modulation;
- or, the MC initially was present, but it has lost its essential properties in result of interaction with the other structures, particularly its field became more irregular. And regular, well organized field influences CR more strongly, than an irregular field of the same intensity.

Even in the events with well revealed magnetic cloud that observed at the Earth, the structure of FD is not always two-step.

The behavior of cosmic rays inside the magnetic cloud reflects both its properties as a whole and features of its structure. This is clearly seen in behavior of the CR density and the anisotropy vector derived from the data of the worldwide neutron monitor network by the global survey method. The CR density changes inside the clouds give almost symmetrical picture with a minimum of density near the center of the cloud in the majority of events. This allows assuming the quasi-cylindrical structure of clouds, the most favorable for modeling [22]. Rather frequent also are the events in which the behavior of the CR density, remaining a regular becomes more complex, with alternating zones of higher and lower density inside the cloud. This may be a manifestation of some quasi-toroidal structure of magnetic clouds. Finally, a number of events show a maximum of CR density in the central part of MC instead of a minimum. Perhaps in some situations, the regular structure of the magnetic field of the cloud facilitates the penetration of charged particles in its central part from the remote, weakly affected by FD areas of heliosphere.

Even more explicitly, the magnetic cloud affects the anisotropy than the density of cosmic rays. As a rule, vector anisotropy of CR changes abruptly when the Earth enters and leaves a cloud and changes regularly inside the cloud. These changes (together with the data on the CR density) may provide additional information about the structure of magnetic cloud and its location relatively to the Earth.

Acknowledgment: This work is partly supported by Russian FBR grants 11-02-01478, Program 10 BR of the Presidium RAS ”The fundamental properties of matter and Astrophysics” and Program 22 BR of the Presidium RAS ”Fundamental processes of research and development of the Solar System”. Authors are thankful to all collaborators provided continue monitoring of the CR neutron component: http://cr0.izmiran.ru/ThankYou, http://www.nmdb.eu/.

References

[1] Burlaga L., Sittler E., Mariani F., Schwenn R., Journal of Geophysical Research 86 (1981) 6673-6684 doi:10.1029/JA086iA08p06673.
[2] Barnden L.R., Proc. 13th ICRC 2 (1973) 1277-1282.
[3] Belov A., Dorman L., Eroshenko E., Ivanov K., Inozemtseva O., Kulanina G., Mikerina N., Geomagnetism and Aeronomy 16 (1976) 355-357.
[4] Parker E., New York: Interscience Publishers (1963) 272.
[5] Lockwood J., Space Sci. Revs. 12 (1971) 658-715 doi:10.1007/BF00173346.
[6] Cane H., Space Sci. Rev. 93 (2000) 55-77 doi:10.1023/A:1026532125747.
[7] Belov A., Proc. IAU Symp. 257 (2009) 439-450 doi:10.1017/S1743921309029676.
[8] Wibberenz G., Le Roux J., Potgieter M., Bieber J., Space Sci. Rev. 83 (1998) 309-348.
[9] Sanderson R., Beeck J., Marsden G., Tranquille C., Wenzel K., McKibben B., Smith J., Proc. 21st ICRC 6 (1990) 251-254.
[10] Cane H., J.Geophys.Res. 98 (1993) 3509-3512 doi:10.1029/92JA02479.
[11] Zhang G., Burlaga L., J. Geophys. Res. 93 (1988) 2511-2518 doi:10.1029/JA093iA04p02511.
[12] Lockwood J., Webber W., Debrunner H. J. Geophys. Res. 96 (1991) 11587-11604 doi:10.1029/91JA01012.
[13] Badruddin, Yadav R.S., Yadav N.R., Solar Phys. 105 (1986) 413-428 doi:10.1007/BF00172057.
[14] Richardson I., Cane H., Solar Phys. 264 (2010) 189-237 doi:10.1007/s11207-010-9568-6.
[15] Belov A., Eroshenko E., Yanke V., Proc. 25th ICRC 1 (1997) 437-440.
[16] Huttunen K., Schwenn R., Bothmer V., Koskinen H., Ann. Geophys. 23 (2005) 625-641 doi:10.5194/angeo-23-625-2005.
[17] Krymsky G., Kuzmin A., Krivoshapkin P., Samsonov I., Skripin G., Transky I., Chirkov N., Novosibirsk: Science (1981) 224.
[18] Belov A., Baisultanova L., Eroshenko E., Yanke V., Mavromichalaki H., Plainaki C., Mariatos G., Pchelkin V., Journal of Geophysical Research 110 (2005) doi:10.1029/2005JA011067.
[19] Jordan A. P., Spence,H. E., Blake, J. B.,Shaul, D. N. A., J. Geophys. Res. 116 (2011) A11103, doi:10.1029/2011JA016791.
[20] Belov A., Eroshenko E., Oleneva V., Yanke V., Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 342-350 doi:10.1016/j.jastp.2007.08.021.
[21] Abunina M., Abunin A., Belov A., Eroshenko E., Asipenka A., Oleneva V., Yanke V., Geomagnetism and Aeronomy 53 (2013) 13-21 doi: 10.1134/S0016793213010027.
[22] Kuwabara T., Bieber J., Evenson P., Munakata K., Yasue S., Kato C., Fushishita A., Tokumaru M., Duldig M., Humble J., Silva M., Dal Lago A., Schuch N., Journal of Geophysical Research 114 (2009) doi:10.1029/2008JA013717.