Transparency of a magnetic cloud boundary for cosmic rays

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Abstract. We have suggested a model of magnetic cloud presented as a torus with magnetic flux rope structure situated inside the interplanetary corona mass ejecta expanding radially away from the Sun through the interplanetary medium. The magnetic field of the torus changing during its propagation has been obtained. The magnetic cloud — solar wind boundary transparency for cosmic rays with different energies depending on the cloud orientation and properties of the torus magnetic field has been determined by means of calculation of the particle trajectories at the boundary.

1. Introduction

The interplanetary counterpart of a Coronal Mass Ejection (ICME) exerts on the greatest impact on condition of the near-Earth space and causes the most powerful geomagnetic storms. In general ICME has a complicated structure: 1) the shock front is outer boundary of disturbance, 2) the compressed solar wind located behind the shock front, 3) CME, 4) a magnetic cloud (MC) is an important part of the CME. MC exerts the most intense impact on the Earth’s magnetosphere and on the spatial distribution of the cosmic rays (CRs) due to the special structure of the magnetic field (magnetic flux rope — MFR). At present, usually only one part of the disturbance is accounted for in study of effect of the ICME on the CRs. Krymsky et al. [1] developed a model of Forbush–decrease of CRs, in which a particle stream coming into the volume of the ICME is determined by increased magnetic field at the shock front. Munakata et al. [2] developed a model of Forbush–decrease of the CRs, in which this flux is determined by the cross–field diffusion particles across the MC boundary.

The magnetic field in the MC has a number of free parameters for its description. It is still unknown how these parameters affect on the flow of the incoming CRs. This paper presents the first results of calculation of this CR flux based on kinetic model.

2. Model

There is no generally accepted model of the MC dynamics in the interplanetary space. We propose to use as one a kinematic model, because: 1) the effect of force-free magnetic field is weak \( \vec{j} \times \vec{B} \sim (\vec{\nabla} \times \vec{B}) \times \vec{B} \ll 1 \), 2) the kinetic energy of the flow is much higher than thermal energy \( M^2 = \frac{U^2}{c_{sw}^2} \gg 1 \). Here \( \vec{j} \), \( \vec{B} \) are current and magnetic field strength; \( U \), \( c_{sw} \) are velocities of the flow and sound; \( M \) is sound Mach number. The kinematic approximation is used to describe the nonstationary flows of the solar wind [3]. In the kinematic approximation velocity of the flow of Lagrangian particles is conserved.
the torus border to a distance

front of the torus is given by the radius vector beginning from the center of the torus and continuing from

Lagrangian particles is distributed linearly from

West-North direction of magnetic field inside MC); the torus moves into the radial flow; the velocity of

of the torus cross-section equal

respect to the heliocentric spherical coordinate system.

distance;

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B

field at the torus axis equals

expands radially with constant speed

the location of the particle source relative to the boundary and on the energy of the CRs.

to the total intensity define the probabilities of these events waiting of CRs. The probabilities depend on

boundary and intersecting border. The ratios of these group particle intensities integrated on solid angle

passing by the MC, 2) CRs coming to the MC boundary and reflecting from it, 3) CRs coming to the MC

on the overall solid angle. The calculation of the CR beam trajectories divides CRs into 3 groups: 1) CRs

the solar wind. The CR intensity is presented by a set of the particle beams of equal intensity distributed

It is assumed, that the omnidirectional CR intensity is given as particle source placed in front of the MC in

The location of the radius vector is given by the angle counted from the plane of the solar equator.

In this case, the determination of the Lagrangian particle velocity distribution at any time allows us to obtain

the change of their relative positions both in the past and in subsequent times. Depending on

the adopted distribution intersection of the trajectories of some Lagrangian particles will be possible

meaning a violation of approximation. Then as amendment to the approximation it may be taken into

account, for example, the presence of the magnetic pressure, which will increase, in dependence from

approach these particles preventing the intersection of their trajectories.

To determine the magnetic field of a MC we assume that the MC has the shape of a torus and at

initial time the magnetic field corresponds to the solution [4]. At subsequent times the magnetic field is
determined by condition of frozen–in represented in the form of the magnetic flux conservation through

the area associated with the Lagrangian particles. The proposed model may be used for description of

the MC dynamics in the interplanetary space only. It is not able to determine the CME move from the

solar corona to the interplanetary medium when strongest changes of the CME structure occur.

3. Transparency of the MC border for the CRs

It is assumed, that the omnidirectional CR intensity is given as particle source placed in front of the MC in
the solar wind. The CR intensity is presented by a set of the particle beams of equal intensity distributed
on the overall solid angle. The calculation of the CR beam trajectories divides CRs into 3 groups: 1) CRs
passing by the MC, 2) CRs coming to the MC boundary and reflecting from it, 3) CRs coming to the MC
boundary and intersecting border. The ratios of these group particle intensities integrated on solid angle
to the total intensity define the probabilities of these events waiting of CRs. The probabilities depend on
the location of the particle source relative to the boundary and on the energy of the CRs.

In an illustrative calculation, whose results are shown in Figs. 1.2 it is accepted: the solar wind
expands radially with constant speed 400 km/s; Parker magnetic field: \( B_r = B_{r_0}(r_0/r)^2 \), \( B_\varphi =
−B_\Theta \tan(\Omega r/U) \), \( B_\Theta = 0 \), where \( B_{r_0} = 3.5 \cdot 10^{-5} \) Gs; \( \Omega \) is angular velocity of the Sun; \( r \) is heliocentric
distance; \( r_0 \) is astronomical unit, \( B_r \), \( B_\varphi \), \( B_\Theta \) are components of the interplanetary magnetic field with

respect to the heliocentric spherical coordinate system.

As to the MC, it is accepted that: at the initial moment the MC has the shape of a torus, the radius
of the torus cross-section equal 0.16\( r_0 \); the axis of the torus locates in the plane of the solar equator at
distance 0.41\( r_0 \) from the Sun; the magnetic field components of the torus satisfy solution [4]; magnetic
field at the torus axis equals 20 \( \cdot 10^{-5} \) Gs; the structure of the torus magnetic field is SWN–type (South-
West-North direction of magnetic field inside MC); the torus moves into the radial flow; the velocity of
Lagrangian particles is distributed linearly from 600 km/s to 400 km/s. Location of the CR source in
front of the torus is given by the radius vector beginning from the center of the torus and continuing from
the torus border to a distance 0.5\( R_{L_0} \), where \( R_{L_0} \) is the Larmor radius of the particle.

The location of the radius vector is given by the angle counted from the plane of the solar equator.

Figure 1. Probabilities of different events for the CRs with different energies ( a) \( \varepsilon = 10 \) GeV; b) \( \varepsilon = 20
GeV; c) \( \varepsilon = 30 \) GeV; d) \( \varepsilon = 50 \) GeV), located near the MC being at the initial state. Black dots is the
probability for CRs passing by MC; the red squares is one for CRs coming to the MC and going across
its border; green diamonds is the probability for CRs coming to the MC border and reflecting from it.

Figure 2. As same in Fig. 1 for moving MC. a) initial state, b) 6 hours after the start, c) 12 hours after the start, e) 18 hours after the start.

The point of the torus boundary located closest to the Earth corresponds to $\varphi = 0$. In this problem the solution has a mirror symmetric with respect to the plane of the solar equator, so in Figs. 1, 2 $\varphi$ varies in the range from $0^\circ$ to $180^\circ$. As can be seen from Fig. 1 a probability of CR reflecting from the MC border equals zero. Chance of CR coming into the MC changes along the border having a few differences for the CRs with different energies. For example, for CR with $\varepsilon = 10\; GeV$ probability equals zero at $\varphi > 90^\circ$ and it is equal to 1 at $\varphi > 145^\circ$. The latter quantity is explained by fact that CRs initially moving from the MC back to it due to the magnetic plug of the interplanetary magnetic field located near the Sun. When the CR energy increases the angular size of the region from which the CRs can come into the MC is reduced due to increasing of $R_L$. This result does not mean that the CRs come into the MC interior volume through the back part of the border mainly, because in this case the CRs being before the disturbance must intersect the interplanetary magnetic field.

Fig. 2 shows the results of calculation of the various event probabilities for CRs with $\varepsilon = 10\; GeV$ for moving MC: a) initial state, b) 6 hours after the start, c) 12 hours after the start, e) 18 hours after the start when the MC reaches the Earth. As can be seen from Fig. 2 in this case the probability of the CR coming into the MC varies slightly along the boundary ($0^\circ < \varphi < 90^\circ$) and it reaches 1 at the back side of the boundary ($\varphi > 135^\circ$).

4. Conclusion
The calculation of the event probabilities for CRs with different energies coming to the MC reveals their dependence on the MFR structure of the MC. Subsequent application of the model will allow to determine dependence of the Forbush decrease amplitude on magnetic field structure and orientation of the MC.

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