INTRODUCTION

Coronal mass ejections (CMEs) are the most powerful large-scale disturbances of the solar wind in interplanetary space. Being a part of a CME, a magnetic cloud (MC), substantially affects the state of the magnetosphere and the intensity of galactic cosmic rays (CR). In other words, it results in a Forbush decrease (FD) in CR intensity, due to the characteristic structure of the magnetic field (magnetic field rope (MFR)).

Cane et al. [1] and Munakata et al. [2] proposed models of FDs in MCs, based on solving the particle transfer equation in a diffuse approximation. The MC in [1] was presented in the form of a constant-radius cylinder traveling in interplanetary space; the model in [2] allowed for expansion of the cylinder. It was shown in [3] that a FD model in which an MC has the form of an expanded cylinder satisfactorily reproduces measurements of CR intensity in some events. Krymsky et al. [4] performed calculations for an FD based on the piston shock generated by an abrupt increase in the velocity of the solar wind. An FD with the hard spectrum observed at solar activity minima was obtained within this model.

In this work, we study the behavior of CRs in an MC under the action of a regular magnetic field.

MAGNETIC CLOUD MODEL

In our calculations, an MC is assumed to be a segment of a torus with a total angular width of 90° at the initial time point. The torus axis lies in the solar equator plane at distance $0.5r_L$ from the surface, where $r_L$ is the Larmor radius. Cross-section radius $0.15r_L$ of the MC lies in the ejected solar plasma, which moves along the radius of heliocentric coordinates. The plasma velocity changes linearly from 600 to 400 km s$^{-1}$ with distance at the torus segment’s cross-section diameter. The ejection continues to expand with inertia. We assume that the MC is surrounded by the solar wind, which blows along the radius with a velocity of 400 km s$^{-1}$, and a Parker magnetic field. Interaction between the ejected matter and the solar wind is ignored.

We assume that the MC has a MFR structure at the initial time point and is described by the solution found in [5]. Further motion of the MC is described on the basis of the kinematic model [6]. The magnetic field is defined by the freezing-in condition. The electric field is found under the condition of perfect conductivity. The magnetic field is considered equal to 20 nT at the torus axis at the initial time point.

The free path along the magnetic field in the MC is $1−2r_L$ for CRs with energies of 10–50 GeV [2]. A relativistic particle crosses this distance in time $T = (5−10) \times 10^2$ s. The CR gyroperiod in the MC $T_{ci} = 2\pi mc/eB = 3$ s. Particle propagation during the time period satisfying condition $kT_{ci} \ll T$ is mainly determined by the regular electromagnetic field; $k$ is the numerical factor. Below, we show that the residence time of most CRs in the MC satisfies this condition.

Calculation Results and Discussion

The behavior of particles inside the MC was studied using the particle trajectory method. Let us represent the particle distribution at a certain time point (conventionally accepted as initial) as a set of particle sources. We consider sources located in an MC cross section that is equidistant from its ends. The source coordinates are specified by the radius and angle. The radius origin coincides with the Largangian coordinate of the cross section’s center at the initial position of the MC; its end is located at distance $0.5r_L$ from the surface, where $r_L$ is the Larmor radius. This choice of the source radius means that we consider particles...
Properties of a Cosmic Ray Flux Propagating to a Distance greater than $0.5r_L$ from the Boundary. The angle is counted from the direction to the Earth. In our calculations, the angles were set uniformly at 6-degree intervals. To specify initial values of the pulse components in each source, the total solid angle ($4\pi$) was divided into equal elements (317 elements were used in our calculations).

The particle trajectories were calculated using the Runge–Kutta method of 4th order accuracy. Each trajectory was calculated during a chosen time period. The course of a trajectory exiting the MC through its side and ends is verified at each time step. The calculations determine the total number of trajectories that remain, escape, and arrive at the ends of the MC. Figure 1 shows the trajectories calculated during the 1st gyroperiod for particles with energies of 5–50 GeV and four MC positions in the interplanetary space. Negative abscissa values denote the times before the leading side of the MC arrives at the Earth’s orbit. The relative number of particle trajectories exiting the torus is shown in Fig. 1a; the number of those remaining in the MO is in Fig. 1b; and the number of those arriving at the MO ends is in Fig. 1c. As can be seen from Fig. 1, a considerable number of the trajectories exit the MO in one period: 90% of the particles with an energy of 50 GeV, 70% of the particles with an energy of 30 GeV, and 55% of the particles with energies of 5–10 GeV. As the MO travels in interplanetary space, the ratio between different types of trajectories changes slightly due to variations in the magnetic fields of the MC and the ambient space.

These results were found for particle sources located in the cross section of an MC equidistant from its ends. We may assume that the above ratios between different types of trajectories generally hold for sources in other cross sections, since the sources’ approach to one end is compensated for by the corresponding motion away from the other end, except for cross sections located close to the MC’s ends, where the number of trajectories arriving at the ends is 50%.

In this work, we restrict ourselves to CR arrival at an MC’s ends. Real MCs are connected to the Sun by magnetic lines, and the effect of this part of an MC on the subsequent behavior of CRs must be studied separately.

Figure 2 shows the density of the relative number of trajectories of particles with energies of 5–100 GeV exiting the MC versus time. These results allow the

![Figure 1](image1.png)

**Fig. 1.** Relative number of trajectories for particles with energies of 5–50 GeV and four positions of the MC in interplanetary space: number of trajectories (a) exiting the MC, (b) remaining in the MO, and (c) arriving at the MO’s ends. Particles with an energy of 5 GeV are shown by the solid curve with dots. Those with 10 GeV are indicated by the dashed curve with squares; those with 30 GeV, by the dashed curve with diamonds; and those with 50 GeV, by the dashed-and-dotted curve with triangles.

![Figure 2](image2.png)

**Fig. 2.** Time dependence of the density of the relative number of trajectories of particles with energies of 5–100 GeV that escape from the MC. Particles with an energy of 5 GeV are shown by the bold solid curve; those with 10 GeV, by the fine thin solid curve; those with 30 GeV, by the bold dashed-and-dotted curve; those with 50 GeV, by the fine dashed curve; and those with 100 GeV, by the fine dotted curve.