Forbush decrease spectrum in a magnetic cloud in the 2004 July 27 event

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Abstract. Magnetic clouds affect the intensity of galactic cosmic rays. The diffusion mechanism is usually used as the formation mechanism for Forbush decrease (FD) in a magnetic cloud (MC). An FD is an observed decrease in the cosmic ray intensity. There is a new theory of FD formation, in which the mechanism is the loss of particle energy in the electromagnetic field of a magnetic cloud. The shape of the FD spectrum is calculated for a wide range of particle energies in the 2004 July 27 event. According to the measurements of ground-based neutron monitors and muon telescopes, synchronous changes in the FD amplitude in time indicate that the FD is formed in a magnetic cloud for all energies. However, the calculated FD spectrum differs from the obtained one from measurements. The reasons for the difference can be: 1) the mechanism of formation is not the electromagnetic one; 2) the method for determining the FD spectrum, using the notion of mean or median energies, needs additional studies.

Introduction

Interplanetary coronal mass ejections (ICME) coming from the Sun can affect the intensity of galactic cosmic rays. A CME with the super-Alfven speed creates the shock front in front of itself. The region between the shock front and CME is the sheath region. The CME may contain an MC. Thus, the whole parts of the ICME participate in the FD formation. FD is a decrease of cosmic rays (CRs), usually detected by neutron monitors, muon telescopes, and spacecraft.

There are three stages in FD [1]. The first one starts with the shock front and ends after the sheath region coinciding with the first step of the FD amplitude. To determine the amplitude of this stage, one can use the "propagative diffusive barrier" model [2]. The second stage containing an MC is usually described by diffusion [3, 4, 5, 6] or drift [7, 8]. The third stage (slow recovery of the CR intensity to unperturbed level) begins after the exit from the MC, and the "casting shadow" model describes it [9, 10].

Early we developed the theory of FD formation in the electromagnetic field of an MC having the form of a moving loop with a helical magnetic field connected to the Sun [11]. The mechanism of the FD formation is energy losses of CRs in the inductive electric field and their quasi-capture in the helical magnetic field of an MC (Flux rope (FR)). The calculated characteristics generally correspond to the observed FD characteristics. The goal of this work is to calculate the FD amplitudes for different CR energies and compare them to the measurements during the 2004 July 27 event.

Forbush decrease spectrum in a magnetic cloud

According to our model, the MC having the torus form at the initial time moves with spherically symmetric plasma flow. Miller and Turner's model [12] is used for the initial magnetic field. The frozen-in condition describes its subsequent propagation. The CR distribution function is determined by the electromagnetic field. We used the backtracing method [13] to solve the Boltzmann equation. We do not take into account particle scattering. The system of particle motion equations is solved numerically with the Runge-Kutta fourth-order method to determine the trajectories.

The calculations show that the FD is a multifactorial phenomenon. The FD characteristics depend on the MC properties [11]: i) the magnitude of the magnetic field strength, the state of the helical field in the entire volume, the velocity, and velocity gradient, and MC type; ii) geometric dimensions (cross-sectional size and angular size of the MC); iii) orientation (relative position of the intersection trajectory and the MC).

Figure 1 shows the measured and model MC parameters and calculated FD amplitude in time. The measurements of the plasma velocity and magnetic field components during the event are from the OMNI database (https://omniweb.gsfc.nasa.gov/form/dx1.html). The FD amplitude of neutron monitors was obtained by the global survey method (GSM) [14].

The initial model parameters are $r_{ta} = 0.22 * 10^{-2}$ AU, $r_{tc} = 0.85 * 10^{-2}$ AU, $r_{ts} = 2.2 * 10^{-2}$ AU, $\varphi_{max} = 29°$, $B_{max} = 20$ nT, $w_1 = 1100$ kms^{-1}, $w_2 = 830$ kms^{-1}. Here, r_{tc} is the cross-section radius of the torus; r_{ta} is the distance from the torus center to its axis; r_{ts} is the distance between the Sun and torus centers; φ_{max} is the angular half-width in longitude; B_{max} is the magnetic field strength at the torus axis; w_1, w_2 are the maximum and minimum velocities of the MC boundaries. The MC type is NES according to the nomenclature by Bothmer and Shwenn [15]. Figure 1a shows the magnetic field components; 1b is plasma velocity; 1c is FD amplitude for 10 GeV CRs. As we can see from the figure, the calculated and measured parameters agree quite well.

Figure 2 presents the measured cosmic ray intensity obtained by the following detectors: Tixie Bay neutron monitor (71.6°N,128.9°E) (www.ysn.ru/ipm); Oulu neutron monitor (65.0°N,25.5°E) (http://cosmicrays.oulu.fi/); Nagoya muon telescope (35.2°N,137.0°E) (http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/); Misato underground muon multi-directional telescope (36.2°N,138.0°E, 30 m w.e.) (http://cosray.shinshu-u.ac.jp/crest/DB/Public/Archives/UGMD.php). According to Figure 2, the FD spectrum is formed in the MC.

Figure 3 shows the FD spectrum depending on rigidity during the 2004 July 27 event. The green circles are the calculations; the multi-colored circles are the FD amplitude for corresponding cosmic ray detectors. The FD amplitude is the difference between the amplitude at the MC leading edge and the maximum decrease. Median rigidities for Nagoya muon telescope and Misato underground muon multi-directional telescope are taken from [16]. Median rigidities for Tixie Bay neutron monitor and Oulu neutron monitor were calculated using the reception coefficients [17].

The figure presents the difference between the calculated FD spectrum and the measurements. The calculated FD spectrum has a cut off for high rigidities. The FD in the MC is formed under the geometric condition $r_L \ll d$, where r_L is Larmor radius; d is the MC cross-section radius. In the event, these parameters are $d \approx 0.2$ au, $B_{max} = 20$ nT, and the geometric condition is violated for 60 and 145 GV rigidities.

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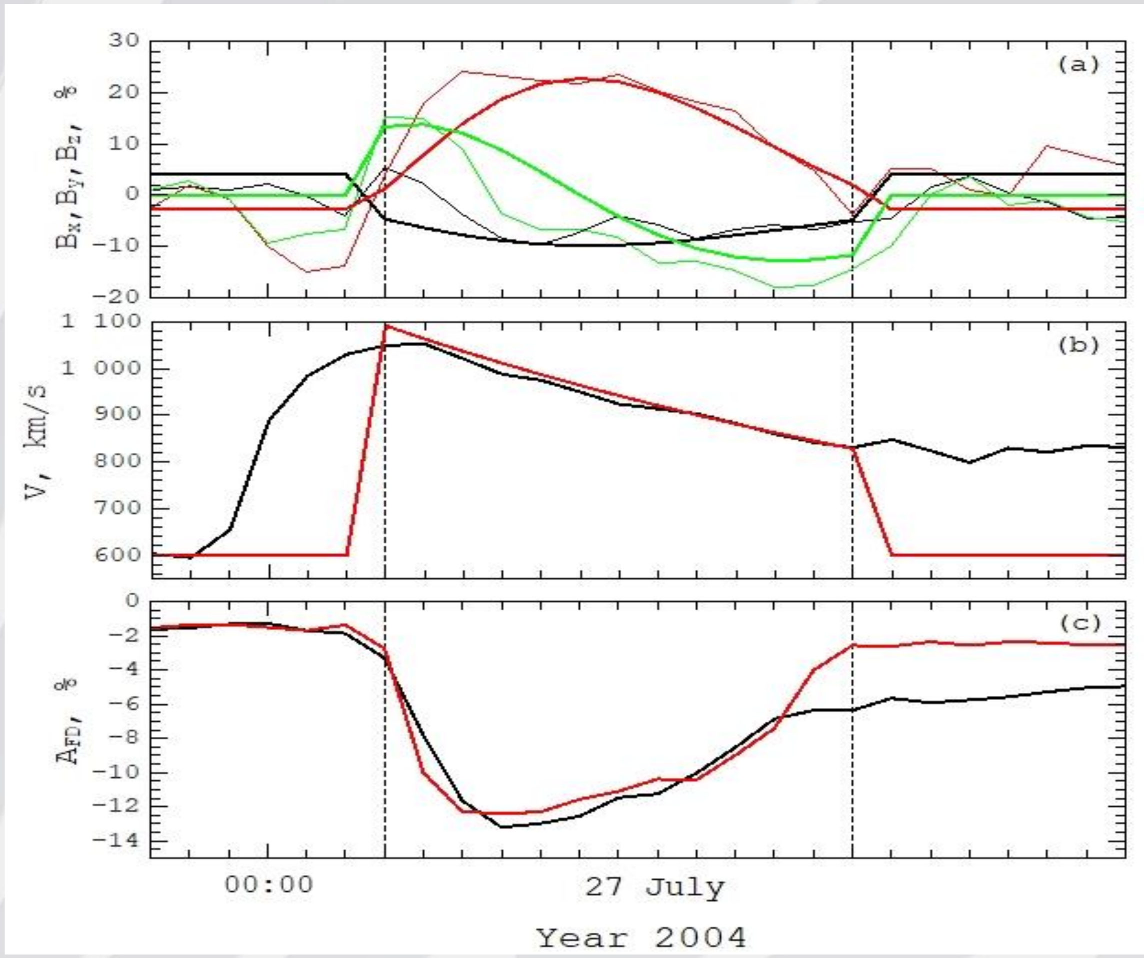

Figure 1. (a) Magnetic field components in UT. The black, red, and green curves correspond to B_x, B_y, B_z magnetic field components. Thin curves are measurements according to the OMNI database; thick ones of the corresponding color are model calculations. (b) Plasma velocity. (c) FD amplitude. GSE coordinate system. The interval between ticks is one hour; the long tick is the beginning of the day. The vertical dashed lines are the MC boundaries.

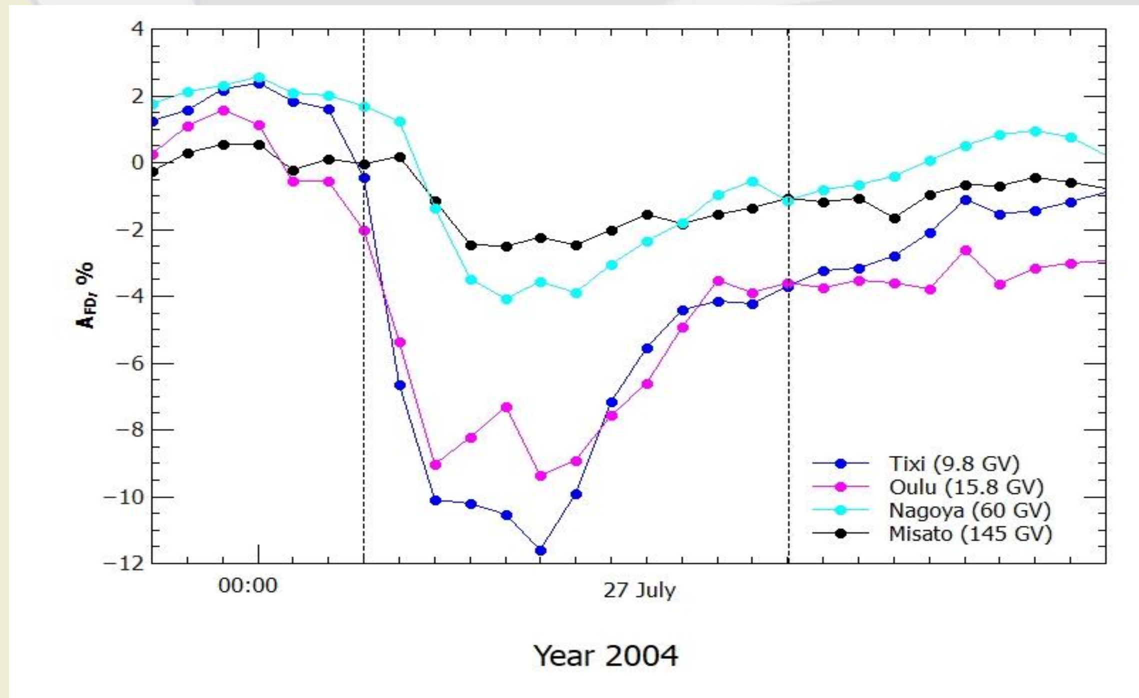

Figure 2. FD amplitudes in time. The vertical dashed lines are the MC boundaries. The number (GV) is median CR rigidities for vertical flux.

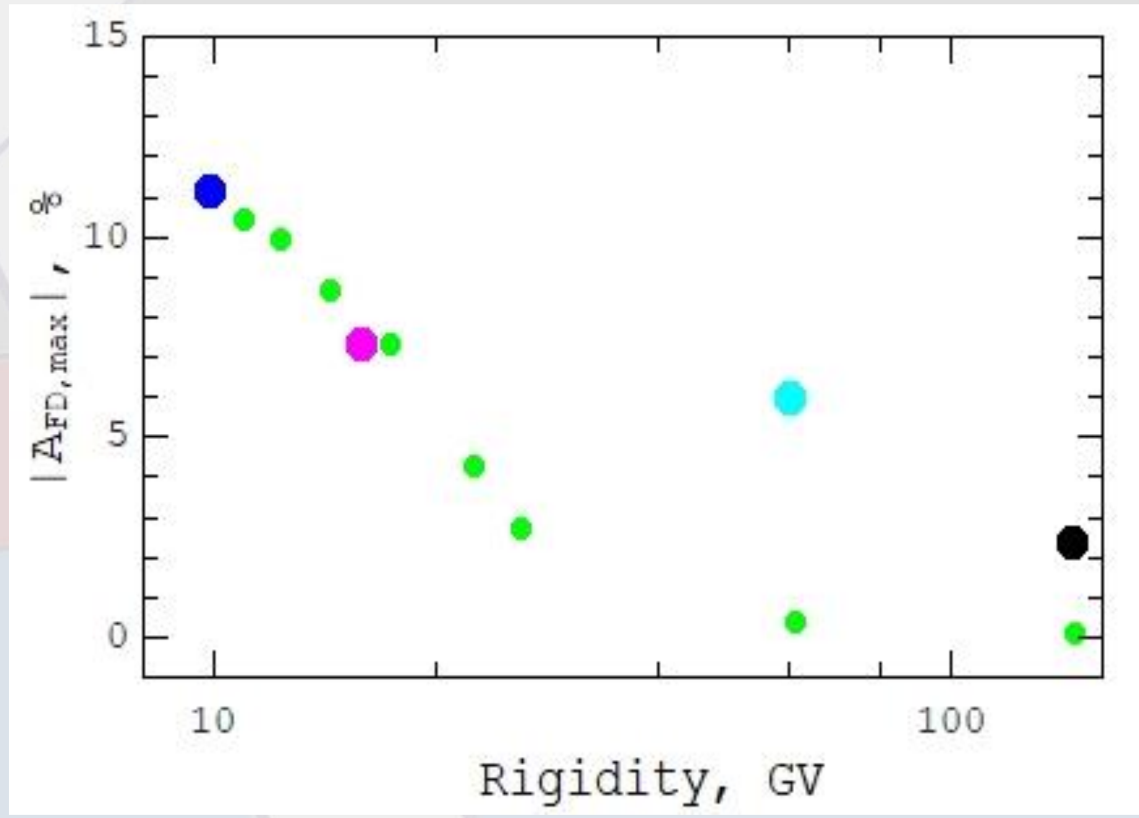

Figure 3. The FD spectrum depending on rigidity for the 2004 July 27 event. The green circles are the calculation; the multi-colored circles are the maximum FD amplitude for corresponding cosmic ray detectors.

Conclusion

The FD spectrum shows that the FD formation mechanism is effective in a wide range of rigidities. The calculated FD spectrum differs from the obtained one from measurements for high rigidities. The reasons for the difference can be:

1) the mechanism of formation is not the electromagnetic one;
2) the method for determining the spectrum, using the notion of mean or median rigidities, needs additional studies.

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