High-Rigidity Cosmic Ray Penetration Mechanism in Interplanetary Magnetic Flux Ropes

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***Abstract*. We discuss cosmic ray behavior in an interplanetary magnetic flux rope, especially cosmic ray penetration mechanism. We derive analytical solutions for cosmic ray behavior based on the equation of motion of a cosmic ray particle to investigate how to penetrate cosmic rays into the magnetic flux rope under an assumption of no scattering by small-scale magnetic field irregularities. The results show that behavior of the particle is determined by only one parameter; a ratio of Larmor radius at the flux rope axis to the flux rope radius. We calculate density and anisotropy distributions inside the magnetic flux rope from the solutions. A comparison between observed and calculated density and anisotropy distributions implies that only gyration process cannot account for observed anisotropy. We must consider diffusion process by small-scale magnetic field irregularities for cosmic ray penetration into the magnetic flux rope. This implies that a primary mechanism for high-rigidity cosmic rays to penetrate the magnetic flux ropes changes from diffusion dominant process near the Sun to gyration dominant process around the Earth as the magnetic flux rope expands and propagates through interplanetary space.**

***Keywords*: Cosmic Rays, Magnetic Flux Rope, Forbush decreases**

I. INTRODUCTION

Forbush decreases, which are sudden decreases in cosmic ray intensity during geomagnetic storms, were discovered in late 1930's (Forbush, 1937). Observations of cosmic rays by neutron monitors and muon detectors revealed that Forbush decreases are caused by the passage of interplanetary shock waves with downstream highly turbulent magnetic fields and by magnetic clouds that have well-ordered strong magnetic fields, which is often observed as a magnetic flux rope.

When interpreting and modeling the observations of Forbush decreases, it is very important to clearly separate the shock wave effect and the magnetic cloud effect because their characteristics are quite different (Wibberenz, *et al.* 1998). Although we have good understandings of interplanetary shock wave effect for Forbush decreases, our knowledge of magnetic cloud effects have limited because few theoretical and numerical models of the cosmic ray behavior in a magnetic flux rope have been studied, especially for high-rigidity cosmic rays.

In the case of high-rigidity cosmic rays inside an interplanetary magnetic flux rope, the Larmor radius of cosmic ray particle is comparable to the spatial scale of a magnetic flux rope near the Earth. Indeed, as the radius and magnetic field intensity on the axis of a typical magnetic flux rope near the Earth are 0.1 AU and 20 nT, respectively (Marubashi 1997), the ratio of the Larmor radius for 60 GV cosmic ray particle (e.g., Kuwabara *et al.* 2004) to the flux rope radius is about 0.669. This implies that high-rigidity cosmic ray particles are hardly scattered by a small-scale magnetic field irregularity inside the magnetic flux rope because, according to pitch-angle scattering theory, a charged particle is scattered most effectively by a magnetic field irregularity having a spatial scale comparable to the Larmor radius of the particle. Therefore, diffusion process may not be important for high-rigidity cosmic ray penetration into the interplanetary magnetic flux ropes.

The purpose of this paper is to discuss the penetration process for high-rigidity cosmic rays by considering the cosmic ray particle motions under an assumption of no scattering to understand cosmic ray behavior in an interplanetary magnetic flux rope. In this paper, we derive analytical solutions describing the behavior of cosmic ray particles inside a magnetic flux rope on the basis of the equation of motion of each cosmic ray particle.

II. THE MODEL OF COSMIC RAY BEHAVIOR IN THE MAGNETIC FLUX ROPES

Although an interplanetary magnetic flux rope expands as it propagates through interplanetary space, we consider a non-expanding cylindrical magnetic flux rope model with radius R_0 because expansion speed is by many orders of magnitude less than the speed of a cosmic ray particle. The model is defined in cylindrical coordinates (r,φ,z) as

$$\boldsymbol{B} = B_0[sJ_1(a\rho)\boldsymbol{e}_\varphi + J_0(a\rho)\boldsymbol{e}_z], \tag{1}$$

$$\rho = \frac{r}{R_0} \quad (0 \le \rho \le 1), \tag{2}$$

where B_0 is the magnetic field intensity along the flux rope axis, and J_0 and J_1 are zeroth-order and first-order Bessel functions of the first kind, respectively; further, $s = 1$ and $s = -1$ correspond to parallel and antiparallel types of flux rope, respectively. Parallel/antiparallel flux ropes are those with electric current flowing parallel/antiparallel to the magnetic field in the flux rope (Marubashi, 1997). The constant a is the smallest positive number of the zero point of the zeroth-order Bessel function of the first kind; that is, $J_0(a) = 0$.

The equation of motion for a cosmic ray particle inside a flux rope is written as

$$m\gamma \frac{d\boldsymbol{v}}{dt} = q\frac{\boldsymbol{v}}{c} \times \boldsymbol{B}, \tag{3}$$

where m, q, $\boldsymbol{v}$, γ, and c are the mass, electric charge, velocity, Lorentz factor of a cosmic ray particle, and the speed of light, respectively.

Since the behavior of cosmic ray particles at position r is important in our model, it is better to rewrite the equation for time t as an equation for position r. Thus, Equation (3) is rewritten as an ordinary differential equation of r or ρ as

$$u_r \frac{d\boldsymbol{u}}{d\rho} = \frac{\boldsymbol{u} \times \boldsymbol{b}}{f_0}, \tag{4}$$

where $\boldsymbol{u} = \boldsymbol{v}/\left|\boldsymbol{v}\right|$ and $\boldsymbol{b} = \boldsymbol{B}/B_0$, respectively. For the flux rope, Equation (4) together with a condition $|\boldsymbol{u}| = 1$ and Equation (3) define the same curved line on the spherical sueface in the velocity space. For more detailed discussion, see Kubo and Shimazu (2009). Equation (4) shows that the behavior of cosmic rays inside the flux rope is regulated by only the parameter f_0, which is defined as the ratio of the Larmor radius of a cosmic ray particle at the flux rope axis to the flux rope radius.

The solutions of Equation (4) in cylindrical coordinates with boundary condition $\boldsymbol{u} = \boldsymbol{u}_0$ at $\rho = 1$ are

$$u_\varphi = \frac{1}{\rho}\left(u_{0\varphi} + \frac{J_1(a) - \rho J_1(a\rho)}{a f_0}\right), \tag{5}$$

$$u_z = u_{0z} - \frac{sJ_0(a\rho)}{a f_0}, \tag{6}$$

and

$$u_r = \pm\sqrt{1 - (u_\varphi^2 + u_z^2)}. \tag{7}$$

It is needless to say that these solutions include gyration and gradient-curvature drift effects.

Hereafter, we consider a parallel-type magnetic flux rope model (i.e., $s = 1$). We use $R_0 = 0.1$ AU and $B_0 = 20$ nT as typical values near the Earth (Marubashi 1997).

We can calculate the cosmic ray density and anisotropy distributions inside the flux rope using Equations (5) to (7). To calculate density and anisotropy, we assume a steady state where the cosmic ray flux from the outside is constant and penetrating cosmic rays always escape from the flux rope. This means that cosmic rays are not accumulating in the flux rope. Another assumption is the angular distribution of cosmic ray particles at the edge of the flux rope, $p_0(\cos\theta_0, \phi_0)$, does not depend on φ and z; that is, all angular distribution functions of cosmic ray particles at the edge of the flux rope are the same. Here, θ_0 is polar angle measured from the z axis, while ϕ_0 is azimuth angle measured from the r axis. This assumption allows us to calculate density and anisotropy distributions as functions of ρ only.

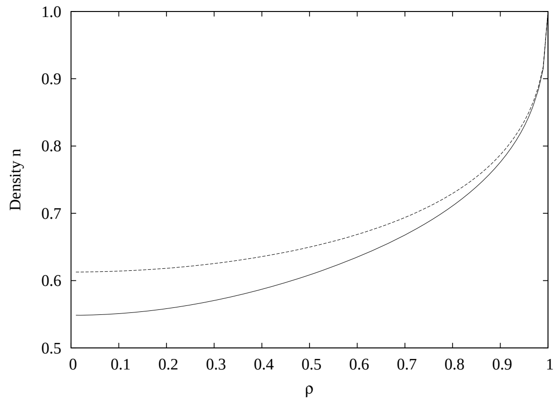

Fig. 1: Cosmic ray density distribution in an interplanetary magnetic flux rope. The abscissa and ordinate are, respectively, the cosmic ray density and the distance from the flux rope axis normalized by the flux rope radius. The solid and dashed lines show density distributions for $f_0 \approx 0.669$ and 1.338, respectively.

Here, we assume that the angular distribution of cosmic ray particles at the edge of the flux rope is isotropic; that is, $p_0(\cos\theta_0, \phi_0) = 1/(4\pi)$. Figure 1 shows the cosmic ray density distribution in a magnetic flux rope. The abscissa and ordinate in the figure are, respectively, the cosmic ray density normalized to unity at the edge of the flux rope and the distance from the axis of the flux rope normalized by the flux rope radius. The solid and dashed lines show density distributions for $f_0 \approx 0.669$ and 1.338, respectively. These parameter values correspond to values of cosmic ray rigidity of 60 and 120 GV, respectively. From the figure, we find that cosmic ray density obviously decreases toward the axis

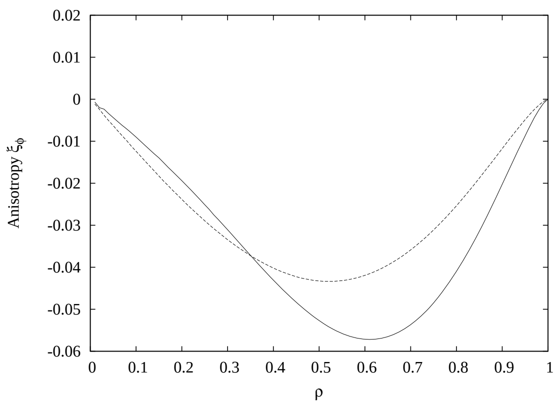

Fig. 2: Distribution of the φ component of the cosmic ray anisotropy vector in an interplanetary magnetic flux rope. The abscissa and ordinate are, respectively, the φ component of the cosmic ray anisotropy vector and the distance from the flux rope axis normalized by the flux rope radius. The solid and dashed lines are the same as those in Figure 1.

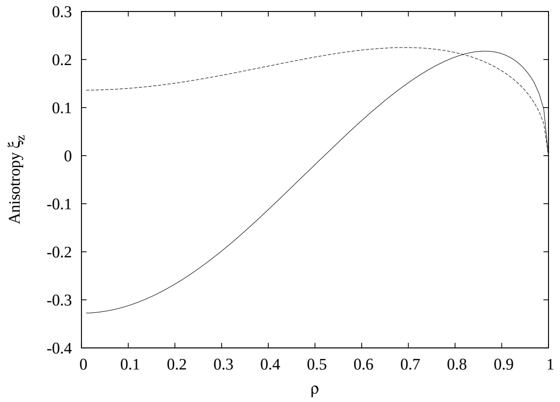

Fig. 3: Distribution of the z component of the cosmic ray anisotropy vector in an interplanetary magnetic flux rope. The abscissa and ordinate are, respectively, the z component of the cosmic ray anisotropy vector and the distance from the flux rope axis normalized by the flux rope radius. The solid and dashed lines are the same as those in Figure 1.

of the flux rope. The decrease is smaller with increasing particle rigidity.

We also calculate the anisotropy vector under the same assumptions. The r component of the cosmic ray anisotropy vector is zero because of the symmetry of the r component of the cosmic ray velocity. Figure 2 depicts the φ component of the anisotropy vector. We find weak cosmic ray anisotropy in the φ direction inside the magnetic flux rope. The amplitude of the anisotropy is several percent. Figure 3 depicts the z component of the anisotropy vector. It shows a strong cosmic ray anisotropy in the z direction inside the magnetic flux rope. The direction of the anisotropy is positive for all values of rigidity in the outer region of the flux rope. However, the direction depends on the cosmic ray rigidity in the inner region of the flux rope.

III. Discussion

Cosmic ray decrease events are observed for high-rigidity cosmic rays observed by muon detectors. As shown in Section II, we calculate the density and anisotropy distributions for such high-rigidity cosmic rays in an interplanetary magnetic flux rope. We compare the calculated density and anisotropy distributions with the observed distributions. The observed density decrease and anisotropy are of the order of several percent (e.g., Munakata *et al.* 2005). The calculated φ component of anisotropy is almost the same as the observed ones. However, the calculated cosmic ray density decrease is somewhat larger than the observed ones. The calculated z component of the anisotropy is large in comparison with the observed z component, especially in the inner region of a flux rope. The differences between observed and calculated density and anisotropy distributions show that cosmic ray behavior cannot be explained without diffusion process. For this reason, we must consider small-scale magnetic field irregularities.

A question is how small-scale magnetic field irregularities affect high-rigidity cosmic rays penetrating into flux rope. In this study, we only considered the case of a flux rope located around the Earth. However, since a magnetic flux rope is ejected from the Sun and propagates through interplanetary space toward the Earth while expanding, we must consider the flux rope near the Sun. According to the expanding cylindrical force-free magnetic flux rope model (Shimazu and Vandas 2002; Berdichevsky *et al.* 2003), the parameter f_0 is directly proportional to time t that has passed since the flux rope ejection at the Sun. This means that the parameter f_0 near the Sun is much less than that around the Earth; for example, $f_0 = 0.0669$ for a typical flux rope located 0.1 AU from the Sun and 60 GV cosmic ray particles. This small f_0 parameter value shows that the Larmor radius of high-rigidity cosmic ray particles is much smaller than the flux rope radius near the Sun. This implies that high-rigidity cosmic ray particles are scattered effectively by small-scale magnetic field irregularities and diffuse into the flux rope when it is located near the Sun. This shows that high-rigidity cosmic ray penetration may change from a diffusion-dominant process near the Sun to a gyration-dominant process near the Earth as the flux rope propagates through interplanetary space.

IV. Conclusion

We studied processes for the penetration of high-rigidity cosmic rays into a magnetic flux rope. We derived an analytical solution for cosmic ray behavior in a magnetic flux rope under the assumption that there is no scattering by small-scale magnetic field irregularities. The solution shows that cosmic ray behavior is determined by only one parameter f_0; that is, the ratio of the cosmic ray Larmor radius at the flux rope axis to the flux rope radius. By comparing calculation and observation, we suggest that there is a diffusion-dominant stage and a gyration-dominant stage during the flux rope expansion and propagation from the Sun to the Earth.

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