Magnetic Cloud and Sheath in the Ground-level Enhancement Event of 2000 July 14. II. Effects on the Forbush Decrease

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Abstract

Forbush decreases (Fds) in galactic cosmic ray intensity are related to interplanetary coronal mass ejections (ICMEs). The parallel diffusion of particles is reduced because the magnetic turbulence level in the sheath region bounded by the ICME’s leading edge and shock is high. In the sheath and magnetic cloud (MC) energetic particles would feel an enhanced magnetic focusing effect caused by the strong inhomogeneity of the background magnetic field. Therefore, particles would be partially blocked in the sheath–MC structure. Here, we study two-step Fds by considering the magnetic turbulence and background magnetic field in the sheath–MC structure with diffusion coefficients calculated using theoretical models, to reproduce the Fd associated with the ground-level enhancement event on 2000 July 14 by solving the focused transport equation. The sheath and MC are set to spherical caps that are portions of spherical shells with enhanced background magnetic field. The magnetic turbulence levels in the sheath and MC are set to higher and lower than those in ambient solar wind, respectively. In general, the simulation result conforms to the main characteristics of the Fd observation, such as the pre-increase precursor, amplitude, total recovery time, and two-step decrease of the flux at the arrival of the sheath and MC. It is suggested that the sheath plays an important role in the amplitude of the Fd while the MC contributes to the formation of the second-step decrease and prolonged recovery time. It is also inferred that both magnetic turbulence and background magnetic field in the sheath–MC structure are important for reproducing the observed two-step Fd.

Unified Astronomy Thesaurus concepts: Forbush effect (546); Galactic cosmic rays (567); Solar coronal mass ejections (310); Space weather (2037)

1. Introduction

Forbush decreases (Fds) are short-term variations of galactic cosmic ray (GCR) intensity first observed by Forbush (1937) using ionization chambers. Fds can be classified into two groups, i.e., sporadic Fds and recurrent Fds. A sporadic Fd with non-recurrent decrease includes two phases related to transient interplanetary coronal mass ejection (ICME), i.e., an impulsive initial phase in which GCR intensity decreases to its minimum within one day, and a gradual recovery phase in which the intensity recovers to the pre-event level for several days. The initial phase of a sporadic Fd sometimes shows a two-step decrease (e.g., Cane 2000; Jordan et al. 2011; Bhaskar et al. 2016; Shaikh et al. 2017). The other types of Fds with recurrent decrease, caused by high-speed streams from coronal holes, have gradual declines and recovery phases in which their intensity profiles are more symmetric (e.g., Cane 2000; Wawrzynczak & Gall 2008; Melkumyan et al. 2019). In this paper, the term Fd is used to denote the type with non-recurrent decrease.

Using neutron monitors, Simpson (1954) confirmed that the origin of Fds is in the interplanetary medium. Before the discovery of ICMEs, some research had already suggested interplanetary plasma clouds to explain Fds (Forbush 1937; Morrison 1956; Cocconi et al. 1958; Piddington 1958). Based on in situ observations by spacecraft, ICMEs were found behind interplanetary shocks in the 1970s, and consequently several research efforts explained Fds by considering shocks, turbulent sheath regions, and ICMEs or magnetic clouds (MCs) which are an important subset of ICMEs (Burlaga et al. 1981; Richardson & Cane 2010).

Badruddin et al. (1986) pointed out that MCs may contribute to Fds. Furthermore, Sanderson et al. (1990) reported that both MCs and turbulent sheath regions are able to act as a barrier to Fds. In contrast, Zhang & Burlaga (1988) inferred that MCs have a little influence on Fds, and the main cause is the scattering effect by turbulent sheath regions. In addition, Lockwood et al. (1991) argued that MCs do not have a significant effect on GCRs while the reduced diffusion in the turbulent sheath region makes a large contribution to Fds. Using the isotropic intensity of GCRs provided by the IMP 8, Cane (1993) confirmed that MCs can cause a decrease in GCR intensity. Cane et al. (1997) and Richardson et al. (1999) found that even small ICMEs can produce a signal of GCR decrease at 1 au. Richardson & Cane (2011) carried out a statistical study of over 300 ICMEs and showed that 80% of them were associated with Fds; they also concluded that the maximum depths of Fds caused by MCs are much deeper than by non-MC ICMEs. Jordan et al. (2011) found that the small-scale magnetic structures in sheath regions can modulate GCR intensities significantly. Yu et al. (2010) and Arunbabu et al. (2015) showed that the enhanced magnetic turbulence level and background magnetic field in the sheath region contribute to the formation of Fds. Note that the total magnetic field is a superposition of the background magnetic field and the turbulent magnetic field.

Observational studies were also devoted to exploring the effect of polarity states of the heliospheric magnetic field on Fds. The polarity A determines the direction of drift velocity, which is usually used to explain the polarity dependence of Fds in the literature. Most of this research statistically compared Fd characteristics under different polarity conditions. Lockwood et al. (1986) observed no significant difference in the characteristic recovery time, defined as the time for the decrease to decay up to $e^{-1}$ times its amplitude, with the reversal of the heliospheric magnetic field. In contrast, Rana
et al. (1996) and Singh & Badruddin (2006) found that the characteristic recovery time is longer during the $A < 0$ epoch than that during the $A > 0$ epoch. Rana et al. (1996) also observed no significant difference in the percentage of recovery up to the 10th day during the two polarity states, which indicates that the total recovery time may be less influenced by particle drift than the characteristic recovery time. Singh & Badruddin (2006) showed that the amplitude of Fds is not significantly different under $A > 0$ and $A < 0$ polarity conditions. Mulder & Moraal (1986) found that there is a small drift effect on Fd profiles, especially on small ones, i.e., the reset time, defined as the time at which Fds have reset to 75%, 50%, 37% ($e^{-1}$), and 25% of their amplitude, is longer for $A < 0$ than that for $A > 0$. They considered that the background heliospheric magnetic field configuration responsible for the drift is essentially wiped out because of the large blast wave so that the reset time is not dependent on polarity for large Fds.

Increasingly complex numerical simulations have been developed over several decades. By solving a 1D diffusion–convection transport equation, Nishida (1982) studied the precursory increase during an Fd event. Kadokura & Nishida (1986) developed a 2D GCR transport model to study Fds using a diffusion barrier. In addition, Thomas & Gall (1984) studied the dependence of the maximum intensity decrease and recovery time of Fds on diffusion coefficient, particle rigidity, and flare geometry using Monte Carlo simulations, reporting that the geometry of flare compression can significantly affect the maximum intensity decrease and recovery time of Fds. By considering the propagating diffusion barrier as the main cause of Fds and solving a 2D transport equation where adiabatic cooling and particle drift are included, le Roux & Potgieter (1991) demonstrated the effect (which can be weakened if the tilt angle of heliospheric current sheet (HCS) increases) that the recovery time of Fds is longer when the polarity of the solar magnetic field is negative than that when the polarity is positive. Their simulation indicated that the Fd amplitudes are almost equal under different polarity conditions, in contrast to the results of Kadokura & Nishida (1986). Recently, Luo et al. (2017, 2018) carried out a 3D simulation of proton and electron Fds based on a stochastic differential equation approach, also adopting the scenario that Fds are mainly caused by propagating diffusion barriers. Their results inferred that the characteristic recovery time of proton Fd is longer/shorter than that of electron Fd when the polarity of the heliospheric magnetic field is negative/positive, while there is little charge-sign dependence on the amplitude of the Fds.

From the above discussion it is suggested that there are contradictions between observations and simulations for Fds. On the one hand, observational studies showed that the sheath region and MC are sometimes able to cause Fds with a two-step decrease. On the other hand, simulation studies in the literature have concentrated on producing Fds using a diffusion barrier, in which the diffusion is reduced artificially, with only a one-step decrease generated. Furthermore, ground-level enhancement (GLE) events of solar energetic particles (SEPs), usually accompanied by large and fast ICMEs which drive strong ICME shocks, are of great interest to researchers (e.g., Gopalswamy et al. 2012; Mewaldt et al. 2012; Wu & Qin 2018, 2020; Firoz et al. 2019). In the GLE59 that occurred on 2000 July 14, there was a very fast and strong MC (Lepping et al. 2001), for which event Wu & Qin (2020, hereafter, WAQ-1) studied the effect of the sheath and MC on the SEPs accelerated by the ICME shock by numerically solving the focused transport equation, with background magnetic field and magnetic turbulence levels in the sheath and MC quite different from those in ambient solar wind, and diffusion coefficients calculated using diffusion theory. In this work, it is shown that a two-step Fd was observed when the ICME–shock structure associated with GLE59 arrived at the Earth. As a continuation of WAQ-1, using a similar model for the sheath–MC structure and diffusion coefficients, we numerically study the Fd to reproduce the two-step decrease. The simulation results of WAQ-1 showed that the sheath–MC structure reduced the proton intensities for about two days after shock passing through the Earth. It was further found that the sheath contributed most of the decrease while the MC facilitated the formation of the second-step decrease. The simulation also inferred that the combination of background magnetic field and magnetic turbulence in the sheath–MC structure can produce a stronger reduction of SEP intensities. The observations of the Fd associated with GLE59 are presented in Section 2. The simulation model is described in Section 3. We present the simulation results in Section 4 and conclusions and a discussion in Section 5.

2. Observations

Figure 1 shows the observations of the Fd associated with GLE59. Panel (a) is the normalized count rate from the Oulu neutron monitor (NM). Panels (b)–(d) show the intensity, polar angle, and azimuthal angle of the interplanetary magnetic field (IMF) in GSE angular coordinates from the Wind spacecraft, respectively. In panel (a), there was an X5.7 class flare that began at 10:10 UT on 2000 July 14 indicated by the pink vertical dashed line, and the flare located at N22W07. There were also three interplanetary shocks that arrived at the Earth, denoted by the green vertical dashed lines, and the second shock corresponding to the solar eruption. An ICME behind the second shock was observed at the Earth with start and end times 19:00 UT on July 15 and 8:00 UT on July 17, indicated by the two red vertical lines. The ejecta is believed to be an MC (Richardson & Cane 2010) with boundaries at 21:00 UT July 15 and 10:00 UT July 16, denoted by the two blue vertical lines. After the flare onset, the cosmic ray intensity had an impulsive increase called GLE59, and then the cosmic ray intensity dropped rapidly to the pre-event intensity (normalized to a value of 1) for about half a day. When the shock corresponding to the flare arrived at the Earth, the GCR intensity dropped rapidly to about 0.97. In addition, the GCR intensity decreased to nearly 0.9 when the MC’s leading edge arrived at the Earth. After the two-step decrease, the GCR intensity recovered gradually for several days. Figure 1(b) exhibits that the sheath region between the ICME shock and ICME’s leading edge had an impulsive magnetic field enhancement right behind the ICME shock. The background magnetic field increased again when the ICME arrived at the Earth and the enhancement lasted until the MC left the Earth. The magnetic field observed at the Earth also indicates that the magnetic turbulence levels in the sheath and MC were higher and lower than in ambient solar wind, respectively.

From Figure 1 it can be seen that the occurrence of the two-step decrease of GCR intensity coincided with the arrivals of the sheath and MC, so we assume the two-step Fd associated with GLE59 was caused by the sheath–MC structure.
3. GCR Transport Model

3.1. Transport Equation

The Parker transport equation (Parker 1965) is widely used to study the modulation of GCRs:

$$\frac{df}{dt} = -(V_{sw} + \langle v_b \rangle) \cdot \nabla f + \nabla \cdot (K_s \cdot \nabla f)$$
$$+ \frac{1}{3} (\nabla \cdot V_{sw}) \frac{df}{d \ln p},$$

where $f(x, p, t)$ is the omnidirectional particle distribution function, with $x$ the particle position in a 3D non-rotating heliographic coordinates, $p$ the particle momentum, and $t$ the time. The first term on the right-hand side represents the solar wind flowing and particle drift in an inhomogeneous IMF, with $V_{sw} = V_{sw} e$, the solar wind velocity in the radial direction, and $\langle v_b \rangle$ the pitch-angle averaged drift velocity. The second term on the right-hand side refers to the diffusion effect, with $K_s$ the symmetric part of the diffusion tensor. The last term on the right-hand side is the adiabatic energy loss.

WAQ-I suggested that the rapidly changed magnetic fields in the sheath and MC act as magnetic mirrors due to the magnetic focusing effect, blocking the passage of SEPs, which depends on particle’s pitch-angle cosine $\mu$. However, the pitch-angle cosine has been eliminated in Equation (1) assuming GCRs to be isotropic. In this work, we therefore choose the focused transport equation rather than the Parker equation for modeling the transport of GCRs in the presence of the sheath and MC. The focused transport equation is given by (Skilling 1971; Schlickeiser 2002; Qin et al. 2006; Zhang et al. 2009, 2019)

$$\frac{df}{dt} + (\nu \hat{b} + V_{sw} + \langle v_b \rangle) \cdot \nabla f - \nabla \cdot (K_s \cdot \nabla f)$$
$$- \frac{\partial}{\partial \mu} \left( D_{\mu \nu} \frac{\partial f}{\partial \mu} \right)$$
$$- p \left[ \frac{1 - \mu^2}{2} (\nabla \cdot \hat{b} V_{sw} + \hat{b} \cdot \nabla V_{sw}) + \mu^2 \hat{b} \cdot \nabla V_{sw} \right] \frac{\partial f}{\partial p}$$
$$+ \frac{1 - \mu^2}{2} \left[ -\frac{\nu}{L} + \mu (\nabla \cdot V_{sw} - 3 \hat{b} \cdot \nabla V_{sw}) \right] \frac{\partial f}{\partial \mu} = 0,$$

Figure 1. Observations for the Forbush decrease associated with GLE59. (a) The normalized intensity of galactic cosmic ray measured by the Oulu neutron monitor is plotted with the black solid curve, and the pre-event level is presented as the black horizontal dashed line. The pink and green vertical dashed lines denote flare onset and the passages of interplanetary coronal mass ejection (ICME) shock, respectively. The boundaries of the ICME and magnetic cloud are presented as the red and blue vertical solid lines, respectively. (b)–(d) Intensity, polar angle, and azimuthal angle of interplanetary magnetic field provided by the Wind spacecraft in GSE angular coordinates, respectively.
where \( f(\mathbf{x}, \mu, p, t) \) is the gyrophase-averaged distribution function, \( v \) is the speed of particles, \( \kappa_2 \) and \( D_{\text{rel}} \) are the perpendicular and pitch-angle diffusion coefficients, respectively, \( L = (\hat{\mathbf{b}} \cdot \nabla \ln B_0)^{-1} \) is the magnetic focusing length, \( \hat{\mathbf{b}} \) is the unit vector along the local magnetic field, and \( B_0 \) is the strength of the local magnetic field.

The numerical solution of Equation (2) needs more computing resources than that of Equation (1) because there is one more independent variable, \( \mu \). On the other hand, \( F_d \) is a short-term process caused mainly by local structures to last several days, during which we focus on the relative variation of GCRs, so that the outer boundary is set to a symmetric spherical boundary at 10 au (e.g., Zhang 1999) instead of 85 au (e.g., Qin & Shen 2017) or beyond (e.g., Potgieter et al. 2014) to save computing resources, where the source of GCRs can be written as (Zhang 1999; Shen & Qin 2018; Shen et al. 2019)

\[
f_{\mu} = \frac{f_0 p_0^{2.6}}{p(m_0^2 c^2 + p^2)^{1.8}},
\]

where \( f_0 \) is a constant, \( m_0 \) is the proton mass, and \( p_0 = 1 \text{ GeV} \text{c}^{-1} \). In Figure 2(a) we plot the energy spectrum of the GCR source calculated from the model of Equation (3) in arbitrary units at 10 au as the black line.

As discussed in Section 1, from observations the characteristic recovery time is, on average, longer during the \( A < 0 \) epoch than during the \( A > 0 \) epoch. However, there is no clear polarity-dependent effect on the reset time for large \( F_d \). Besides, the total recovery time may be less influenced by particle drift than the characteristic recovery time. In simulations, the polarity-dependent effect on the characteristic recovery time could be weakened if the tilt angle of the HCS increases. Furthermore, particle drift may have no significant effect on the amplitude of \( F_d \) because there is little polarity dependence on the amplitude of \( F_d \) both in observations and simulations. In this work, both the \( F_d \) amplitude and the tilt angle of the HCS in the \( F_d \) event that occurred following the GLE59 on 2000 July 14 are large. Therefore, we assume that the diffusion and magnetic mirror effects in the sheath–MC structure are more important than the drift effect in forming the \( F_d \) associated with GLE59, so we neglect the drift term \( v_d \) in our simulation to focus on the formation of the two-step decrease, amplitude, and total recovery time of the \( F_d \), although particle drift might affect the characteristic recovery time slightly in this event.

In order to compare the GCR count rate provided by NMs with flux from simulation model, the effective energy of the NMs is used (Alanko et al. 2003; Zhao et al. 2014):

\[
E_{\text{eff}} = E_1 + \frac{E_2 \left( \frac{p}{P_1} \right)^{1.25}}{1 + 10 \exp\left(-0.45 \frac{p}{P_1}\right)},
\]

where \( P_c \) is the local geomagnetic cutoff rigidity of the NMs, and \( E_1, E_2, \) and \( P_1 \) are constants with \( E_1 = 6.4 \text{ GeV}, E_2 = 1.45 \text{ GeV}, \) and \( P_1 = 1 \text{ GV} \). The count rate, \( N \), is proportional to the integral GCR flux above the effective energy, i.e.,

\[
N \propto \int_{E_{\text{eff}}}^{\infty} \mathcal{J}(E) dE,
\]

where \( \mathcal{J}(E) = p^2 f \) is the differential flux and \( f \) is obtained from Equation (2). Following previous studies (Qin et al. 2006; Zhang et al. 2009), we use a time-backward Markov stochastic process method (Zhang 1999) to numerically solve Equation (2) in a 3D heliocentric coordinate system to obtain the anisotropic distribution function \( f(\mathbf{x}, \mu, p, t) \). In addition, to average \( f(\mathbf{x}, \mu, p, t) \) over \( \mu \) we can finally get the isotropic distribution function \( f(\mathbf{x}, p, t) \). Here, the position \( \mathbf{x} \) is set to Earth.

3.2. IMF, MC, and Sheath

In this work, we adopt the similar model of the IMF, MC, and sheath as in WAQ-I. The Parker field is adopted as the
background solar wind magnetic field

\[ B_p = A B_{Po} \left( \frac{r_{au}}{r} \right)^2 \left( \mathbf{e}_r - \frac{\omega r \sin \theta}{v_{sw}} \mathbf{e}_\phi \right), \]  

(6)

where \( B_{Po} \) is a constant and equal to the radial strength of the background magnetic field at 1 au without a local structure, \( r_{au} \) is equal to 1 au, \( \omega \) is the angular speed of solar rotation, and \( r, \theta, \phi \) are the solar distance, colatitude, and longitude of any point, respectively. Note that the HCS latitudinal extent is not included in Equation (6) because we neglect the drift effect.

In this work, the ICME shock, assumed not to affect the transport of GCRs, is used as a reference to determine some parameters of the sheath and MC. The shock is modeled as a spherical cap that is a portion of a spherical shell with a uniform speed that is obtained by dividing the Sun–Earth distance by the shock transit time, and the direction of nose in the flare location. The MC and sheath are taken to be thick spherical caps that are parallel to the ICME shock with thicknesses to be fixed at the observed ones at 1 au, and speeds and angular widths are the same as those of the shock. Due to the fact that the background magnetic field is presented in Figure 2(b) of WAQ-I, except the GCR source boundary which is added for the Fd study here.

The magnetic turbulence is based on a two-component 2D slab model with turbulence level given by

\[ \sigma = \frac{\delta b}{B_0} = \sqrt{\frac{\delta b^{2D}_{slab} + \delta b^{2D}_{2D}}{B_0}}, \]

(12)

where \( \delta b^{2D}_{slab} \) and \( \delta b^{2D}_{2D} \) are the slab and 2D components of magnetic turbulence, respectively. The ratio of 2D energy to slab energy is found to be 80%-20% (Matthaeus et al. 1990; Biebel et al. 1994), so that the turbulence levels of slab and 2D components in solar wind, sheath, and MC can be written as

\[ \left( \frac{\delta b^{2D}_{slab}}{B_0} \right)_i = \frac{\sqrt{5}}{5} \sigma_i \] (\( i = P, S, M \)),

(13)

\[ \left( \frac{\delta b^{2D}_{2D}}{B_0} \right)_i = \frac{2 \sqrt{5}}{5} \sigma_i \] (\( i = P, S, M \)),

(14)

where \( i = P, S, M \) is used to denote solar wind, sheath, and MC. The values of \( \sigma_S \) and \( \sigma_M \) should be set to higher and lower than that of \( \sigma_p \) due to the fact that the magnetic turbulence levels in the sheath and MC are higher than those in solar wind. We can also collectively refer to \( \sigma_S \) and \( \sigma_M \) as the ejecta model \( \sigma_{ejecta} \).

3.3. Diffusion Coefficients

As in WAQ-I, the diffusion coefficients are obtained with the models as follows. The pitch-angle diffusion coefficient \( D_{\mu\nu} \) in Equation (2) is given by (Beek & Wibberenz 1986; Teufel & Schlickeiser 2003)

\[ D_{\mu\nu}(\mu) = \left( \frac{\delta b_{slab}}{B_0} \right)^2 \frac{\pi (s - 1) v}{4s} \frac{R_L}{l_{slab}} \left( \frac{R_L}{l_{slab}} \right)^{s-2} \times (\mu \sqrt{s+1} + h(1 - \mu^2)), \]

(15)

where \( s = 5/3 \) is the Kolmogorov spectral index of the IMF turbulence in the inertial range, \( l_{slab} \) is the correlation length of the slab component of turbulence, \( R_L = pc/(|q|B_0) \) is the Larmor radius, \( \mu \) is the pitch-angle cosine, and \( h = 0.01 \) is introduced to model the nonlinear effect of pitch-angle diffusion at \( \mu = 0 \).

The other diffusion coefficient, the perpendicular diffusion coefficient \( \kappa_p \), in Equation (2) is from nonlinear guiding center theory (Matthaeus et al. 2003) with analytical approximations (Shalchi et al. 2004, 2010)

\[ \kappa_p = \frac{v}{3} \left[ \left( \frac{\delta b^{2D}_{2D}}{B_0} \right)^2 \frac{\pi (s - 1) \Gamma \left( \frac{s}{2} + 1 \right) \Gamma \left( \frac{s}{2} + rac{3}{2} \right)}{2s \Gamma \left( \frac{s}{2} + \frac{5}{2} \right) l_{2D}} \right]^{2/3} l_{2D}^{1/3} (I - \hat{b} \hat{b}), \]

(16)

where \( l_{2D} \) is the correlation length of the 2D component of turbulence, \( I \) is a unit tensor, and \( \lambda_p \) is the parallel mean free path (Jokippi 1966; Hasselmann & Wibberenz 1968; Earl 1974)

\[ \lambda_p = \frac{3v}{8} \int_{-1}^{+1} \frac{(1 - \mu^2)^2}{D_{\mu\nu}} d\mu. \]

(17)

We can also collectively refer to \( l_{slab} \) and \( l_{2D} \) as \( l_{turb} \).
Table 1
Parameter Settings for the Simulation

| Type         | Parameter | Meaning                           | Value          |
|--------------|-----------|-----------------------------------|----------------|
| Shock        | $v_s$     | speed                             | 1406 km s$^{-1}$|
|              | $\Omega_\infty$ | half-angular width               | $45^\circ$     |
| Solar wind   | $v_{sw}$  | speed                             | 450 km s$^{-1}$|
|              | $B_{PB}$  | radial strength of IMF at 1 au    | 3.62 nT        |
|              | $B_{PB1\ au}$ | total strength of IMF at 1 au   | 5 nT           |
| MC           | $L_M$     | half-thickness                     | 0.22 au        |
|              | $d_M$     | distance between MC center and shock | 0.45 au      |
| Sheath       | $L_s$     | half-thickness                     | 0.08 au        |
| Others       | $\omega$  | angular speed of solar rotation   | $2\pi/25.4$ rad day$^{-1}$ |
|              | $R_{in}$  | inner boundary                     | 0.05 au        |
|              | $R_{out}$ | outer boundary                     | 10 au          |
|              | $E_{eff}$ | effective energy of Oulu NM        | 6.54 GeV       |

Table 2
Turbulence Parameter Settings for the Simulation

| Parameter | Meaning                           | Value |
|-----------|-----------------------------------|-------|
| $\sigma_P$ | turbulence level in solar wind | 0.3   |
| $\sigma_{specta}$ | turbulence level in sheath | 1.6   |
| $\sigma_M$ | turbulence level in MC | 0.1   |
| $l_{hub}$  | slab correlation length           | 0.025 au |
| $l_{2D}$   | 2D correlation length            | 0.0096 au |
| $s$        | Kolmogorov spectral index         | 5/3   |
| $h$        | nonlinear effect index            | 0.01  |

4. Simulations and Comparisons with Observations

4.1. Parameter Settings

The main parameters of the simulations are listed in Table 1. According to the observed times of flare onset and shock passage at 1 au, the shock speed is set to 1406 km s$^{-1}$. The half-angular width of the shock, $\Omega_\infty$, is set to $45^\circ$. The solar wind speed is set to 450 km s$^{-1}$, and the radial strength of IMF at 1 au, $B_{PB}$, is set to 3.62 nT, making the total strength of IMF, $B_{PB1\ au}$, equal to 5 nT at 1 au. According to the observed start and end times of the MC and sheath, the half-thickness of the sheath and MC are set to 0.08 au and 0.22 au, respectively, and the distance from the ICME shock to the center of MC, $d_M$, is set to 0.45 au. The parameters of magnetic turbulence are listed in Table 2. We set $l_{slab} = 0.025$ au, so that $l_{2D}$ is equal to $l_{slab}/2.6 = 0.0096$ au according to multi-spacecraft measurements (Weygand et al. 2009, 2011). The magnetic turbulence levels in the solar wind, sheath, and MC are set to 0.3, 1.6, and 0.1, respectively. Note that, since it is not easy to measure turbulence levels in the transient region of the solar wind, sheath, and MC accurately, we set their values with the assumption of producing good results. The angular speed of solar rotation is set to $\omega = 2\pi/25.4$ rad day$^{-1}$, the inner and outer boundaries of the simulations are set to $R_{in} = 0.05$ au and $R_{out} = 10$ au, respectively, and the effective energy of the Oulu NM obtained from Equation (4) is equal to 6.54 GeV. Note that all the parameters in Tables 1 and 2 except the last two parameters in Table 1, which are specific for GCRs, are the same as in Tables 1 and 2 of WAQ-I. On the other hand, here we do not include the parameters for the source of SEPs moving with the shock that are in Table 1 of WAQ-I.

4.2. Results

The data from observations and simulations are presented as gray and red curves, respectively, in Figure 3 with the pre-event level of GCR intensity indicated by the black horizontal dashed line. The pink, green, and blue vertical dashed lines denote the flare onset, shock passages of the Earth, and MC boundaries, respectively. It is shown that the simulation result fits the observed decrease phase well to reproduce the two-step decrease. The pre-increase precursor of Fd, which can be found in some Fds, is also reproduced in the simulation result. From the observations and simulations we can see that the pre-increase started about 15 hr before the arrival of the shock, and the timescale is similar to the statistical result from observation, which is 10–14 hr on average (Lingri et al. 2019). Though the observation of the pre-event GCR intensity has been contaminated by GLE59, the pre-increase can be recognized roughly and is consistent with the simulation. The recovery phase of the simulation, however, deviates from that of the observation between July 16 and 18, after which the simulation is consistent with the observation again. At the end of the Fd, the observed GCR intensity was influenced by another ICME that was behind the third shock, so that the total recovery time is also affected. If the observed GCR intensity is not contaminated, it is suggested that the total recovery time may be about 4 days, which is in accord with the simulation.

To evaluate the influence of the sheath and MC, we run further simulations with only the sheath or MC, with the results shown as the green and blue curves in Figure 4(a), respectively. The other curves are the same as in Figure 3. It is seen that the simulation with only the sheath shows a sharp decrease right after the shock arrival, with an amplitude slightly larger than that of the simulation with the sheath–MC, i.e., the red curve. The green curve recovers more rapidly with a total recovery time about half that of the red curve. The simulation with only the MC shows a fairly rapid decrease when MC’s leading edge arrives at the Earth, followed by a slow decrease lasting for about 1 day, with the smallest amplitude. Afterwards, the blue curve recovers gradually with the recovery phase in line with the red curve in the last 2.5 days. So the amplitude of the Fd and first-step decrease are mainly determined by the sheath, while the MC contributes to the formation of the second-step decrease and the prolonged recovery time.

The magnetic turbulence and background magnetic field are the two distinguishing features of the sheath–MC structure, so their effect should be investigated. We run two simulations of the sheath–MC structure. In the first, the magnetic turbulence level is set according to Section 4.1 while the background magnetic field is the same as that of the ambient solar wind, with the result shown as the green curve in Figure 4(b). In the second, the background magnetic field is set according to Section 4.1 while the magnetic turbulence level is the same as that of the ambient solar wind, with the result shown as the blue curve in Figure 4(b). The other curves are the same as in Figure 3. It is seen that the green curve has a moderate decrease after the shock arrival, with a recovery time about half that of
the red curve. Though the blue curve shows a two-step decrease, the amplitude of the second step decrease is too small compared to the observation. The recovery phase of the blue curve is also in line with that of the red curve in the last 2.5 days. It is seen that neither magnetic turbulence nor background magnetic field can individually produce the observed two-step decrease. Instead, their combination in the sheath–MC structure produces the two-step Fd, and the enhanced background magnetic field in the sheath–MC structure extends the total recovery time.

5. Conclusions and Discussion

In our previous work, WAQ-I, we used the sheath–MC model to numerically reproduce the intensity–time profiles of relatively low-energy SEPs in the GLE event of 2000 July 14 successfully. It is suggested that both SEP events and Fds are important phenomena accompanied by ICMEs, so the results from compatible models should be consistent with both SEP and GCR observations. In this paper, as a continuation, we use the same sheath–MC model, same diffusion coefficients with magnetic turbulence as input, and similar numerical method as in WAQ-I to reproduce Fds associated with the same GLE. It is shown that there was a two-step decrease in the Oulu NM counting rates when the sheath–MC structure arrived at the Earth. We assume the two-step Fd was caused by the sheath and MC. Here, we solve the focused transport equation instead of the Parker equation since the focusing effect may be large in the sheath–MC structure. The simulation result is used to compare with the observed normalized intensity of GCRs measured by the Oulu NM with the effective energy as 6.54 GeV. Since Fd is a short-term process and we only focus on the relative variation of GCRs, the boundary for the GCR source is set to 10 au to reduce computing resource. Also, the drift effect is neglected since it may have no significant influence on the formation of the two-step decrease, amplitude, and total recovery time of the Fd.

In the simulation model, the MC and sheath are set to spherical caps with fixed thickness moving with a uniform speed. The Parker field is adopted as the background magnetic field in the solar wind, on which magnetic enhancement in the radial direction expressed by Equations (7) is superposed as the background magnetic field in the sheath–MC structure. The magnetic turbulence levels in the sheath and MC are set to higher and lower values than that in the ambient solar wind, respectively. The simulation result for the sheath–MC structure reproduces well the Fd event except for the first half of the recovery phase, and the two-step decrease occurs at the arrival of the sheath and MC. The simulations with sheath or MC only infer that the former plays an important role in the amplitude of Fd while the latter contributes to the formation of the second-step decrease and prolongs the recovery time of Fd. To evaluate the respective effects of magnetic turbulence and background magnetic field in the sheath–MC structure on Fd, we carry out simulations with only one of these set with the ejecta model and the other set with the ambient solar wind model. The simulations show that neither the magnetic turbulence nor the background magnetic field in the sheath–MC alone is sufficient to produce the observed two-step decrease in terms of the shape and amplitude of Fd. Therefore, the sheath and MC and their distinguishing features, i.e., magnetic turbulence and background magnetic field, are important for the formation of the two-step Fd associated with GLE59.

In this work, the input parameters of the diffusion models, i.e., the turbulence level, correlation length, and magnetic field power spectrum index are simplified. In order to be consistent with WAQ-I, recent progress in turbulence theory (e.g., Zank et al. 2018; Zhao et al. 2018; Adhikari et al. 2020; Chen et al. 2020), especially the radial dependence of turbulence parameters, is not included in this work. It is supposed that the simplified turbulence parameters can be used to study the Fd, which is a local and short-timescale phenomenon.

Figure 3. Observation and simulation of the Forbush decrease plotted as gray and red curves, respectively. The black horizontal dashed line denotes the pre-event level of GCR intensity. The pink, green, and blue vertical dashed lines represent flare onset, shock passages, and MC boundaries, respectively.
In general, the simulation result with the sheath–MC structure captures the main features of the observation, such as the pre-increase precursor, two-step decrease, amplitude, total recovery time, etc. However, it is shown that the simulation deviates from observation in the first half of the recovery phase, which is reasonable due to the simplifications we make in this work. First, the shapes of sheath and MC are set to thick spherical caps, which is different from the real ones. Second, the background magnetic field enhancement in the sheath–MC structure is set in the radial direction, which is different from the real situation. In addition, the background magnetic field enhancement model we use is not divergence free. Third, the drift effect, which may influence the profile of the recovery phase of the Fd, is neglected. Further study can be carried out with the help of some new methods, e.g., the Grad–Shafranov reconstruction technique (Hu & Sonnerup 2002; Hu 2017) or magnetohydrodynamic (MHD) simulations (e.g., Luo et al. 2013; Pomoell & Poedts 2018; Wijser et al. 2019; Feng 2020), which can produce a more realistic sheath–MC structure. In addition, using an MHD simulation, which can produce a self-consistent HCS with the sheath–MC structure, we can investigate the drift effect. Finally, GCRs with high energy have large gyroradius relative to the length scale in which the background magnetic field varies significantly, so GCRs may evolve into a sheath–MC structure through gyromotions, and the focus transport equation based on the gyroaverage of particles becomes invalid. To deal with this kind of problem in the future, we can analyze a large number of trajectories of energetic particles by numerically solving the particle Newtonian equation of motion with Lorenz force in interplanetary space (e.g., Qin et al. 2002; Kong et al. 2017).

To evaluate the influence of the non-zero divergence, the relative divergence of the modeled background magnetic field in the Sun–Earth line is presented in Figure 5 as the blue dashed line at the time of MC arrival. In MHD simulations of solar wind, the relative divergence error of each cell in the discrete space can be defined as $\left| \nabla \cdot B \right| / R_c$, where $R_c$ is the characteristic size of the cell. The value of $R_c$ is about 0.01 au at 1 au, and is similar to that of the Larmor radius $R_L$ of 6.54 GeV protons at 1 au. The relative divergence error of less than $10^{-2}$ is supposed small enough to simulate solar wind stably and accurately (e.g., Shen et al. 2018). In this work, we therefore define the relative divergence as $\left| \nabla \cdot B \right| / R_c$. Figure 5 shows that the relative divergence of the modeled background magnetic field is less than or approximately equal to $10^{-2}$ except for the sheath region. The relative gradient, defined as $\left| \nabla B \right| / R_c$, is also shown in Figure 5 as the red solid line. It is seen that the relative divergence and gradient are of a similar order of magnitude. In the GCR model, a uniform

![Figure 4](image_url)
local background magnetic field is assumed, so the non-zero gradient introduces error. We assume the error in the GCR modeling from non-zero divergence of the magnetic field is at a similar level as that from the non-zero gradient of magnetic field in the sheath region.

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Figure 5. Relative values of gradient and divergence of the modeled background magnetic field in the Sun–Earth line vs. distance from the Sun at the time of MC arrival.

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