

# Investigation of the transient cosmic ray decreases observed by voyagers in 2007: A numerical approach

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[1] In 2006 and 2007, Voyager 1 and 2 recorded a series of cosmic ray transient decrease events. It is believed that these transient decrease events are caused by the Local Merged Interaction Region (LMIR). Incorporating a LMIR model with our cosmic ray transport code, we investigate the causes for these cosmic ray transient decrease events. The simulation shows that the interaction between LMIR and termination shock (TS) affect the cosmic ray transport in the heliosheath, even if the observed location is beyond latitude extent of the LMIR. To further understand these transient decrease events observed by voyagers, we simulate a scenario of two LMIRs propagating into the heliosheath. One of the LMIRs arrived at Voyager 2 at 2007.43 and the other at 2007.55. They went further to interact with the TS at 2007.56 and 2007.76 separately, causing the cosmic ray intensity decreases observed by Voyager 1 which was about 10 AU beyond the TS.

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## 1. Introduction

[2] It has been known for a long time that some structures which originated from the Sun will affect the galactic cosmic ray transport in the heliosphere [McDonald *et al.*, 1981; Burlaga *et al.*, 1993]. One of these structures is the so-called Merged Interaction Region (MIR), which is the buildup of multiple interplanetary ejecta with enhanced solar wind speed, magnetic field, and plasma density.

[3] As galactic cosmic rays (CRs) traverse through the heliosphere, they have a chance to encounter the MIR. Since the properties of particle transport inside the MIR are different, the intensity of CRs is further modulated [Burlaga *et al.*, 1993]. Based on voyager observations, an empirical equation has been proposed by Burlaga *et al.* [1985] to relate the local magnetic field strength  $B$  inside MIR and the cosmic ray counting rate  $I_{CR}$ :

$$\frac{dI_{CR}}{dt} = -D \times \left( \frac{B}{\langle B \rangle} - 1 \right) \quad B > \langle B \rangle \quad (1)$$

$$\frac{dI_{CR}}{dt} = R \quad B < \langle B \rangle, \quad (2)$$

where  $\langle B \rangle$  is the yearly average of observed magnetic field strength which represents a large-scale average of interplanetary magnetic field near the observation point;  $D$  and  $R$  are both constants. The CR-B relation shows that if the local magnetic field is larger (less) than the average magnetic field, the cosmic ray intensity would decrease (increase).

[4] It is believed that there are four major mechanisms dominating the transport of the galactic cosmic ray particle in the interplanetary medium: diffusion, drift, convection, and adiabatic cooling [Parker, 1965; Jokipii and Davila, 1981; Ferreira *et al.*, 2008; Potgieter and Ferreira, 2001; Potgieter, 2011; Manuel *et al.*, 2011]. Because of the strong magnetic field inside MIR, the observed cosmic ray intensity decrease is usually attributed to the diffusion and drift effect [Perko and Fisk, 1983; Perko and Burlaga, 1987; Le Roux and Potgieter, 1991, 1995; Le Roux and Fichtner, 1999]. Following the classification of MIR [Burlaga *et al.*, 1993; Burlaga, 1995], Global Merged Interaction Region (GMIR) extends 360° in longitude and up to relatively high latitude. On the other hand, the Local Merged Interaction Region (LMIR) is localized in both longitude and latitude.

[5] By reducing the diffusion and drift coefficient, Le Roux and Potgieter [1995] constructed an outward propagating GMIR model. The cosmic ray modulation model, which contains both time-dependent drifts and GMIRs, can successfully simulate the complete 22 year modulation cycle. Later, Le Roux and Fichtner [1999] studied the effect of GMIR on cosmic ray modulation with a self-consistent model containing the interaction of solar wind with cosmic rays. It was found that the long-term global diffusion variation should be included to interpret the cosmic ray modulation; in addition, GMIR is not an effective diffusion barrier beyond TS since it decays a lot after the interaction with the TS.

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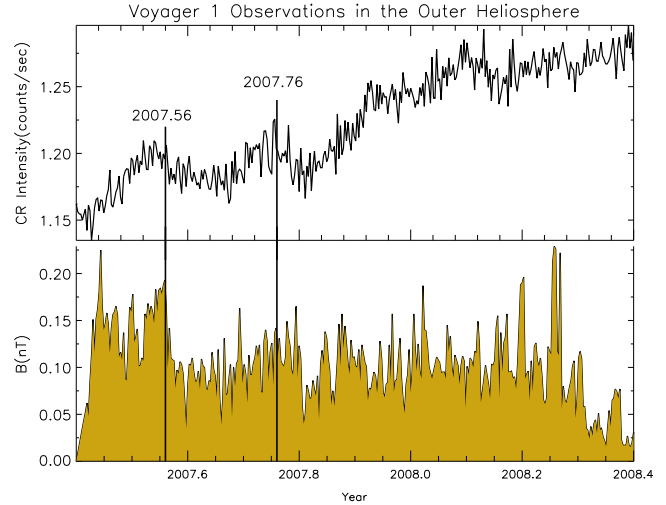
[6] Another important structure which affects the cosmic ray transport in the inner heliosphere is the Corotating Interaction Regions (CIRs), where fast solar wind overtakes slow solar wind. It has been known that CIRs can produce the transient cosmic ray decrease in the inner heliosphere [Burlaga *et al.*, 1984]. Kóta and Jokipii [1991] use a numerical model simulate the effect of CIRs on cosmic ray transport, and they argued that it is the reduction of the diffusion coefficient in CIRs causing the local decrease of cosmic ray intensity. The modulation of CRs intensity by CIRs may appear in the form of 26 day intensity variation. Cosmic ray observations by Ulysses found that this effect can propagate to high-latitude region where no CIRs have been observed [Zhang *et al.*, 1995; Simpson, 1998]. Using a numerical model, Kóta and Jokipii [1995] illustrated that this remote feature is due to the cross-field particle diffusion which transports the CIRs effect to high-latitude region.

[7] After voyagers crossed the TS, entering into the heliosheath region, it is very rare for any Sun origin structure to propagate that far to be observed by the spacecraft. However, in the year of 2006 and 2007, the spacecraft recorded a series of cosmic ray transient decrease events causing by these structures. It provides a very good opportunity for studying how these structures affect the cosmic ray transport in the heliosheath, since Voyager 1 has already crossed the TS. Therefore, studies have been carried out to investigate these events [Webber *et al.*, 2009; Burlaga *et al.*, 2011]. Using Voyager measurement of CRs and plasma, Luo *et al.* [2011] have found that Global Merged Interaction Region (GMIR) can have a remote effect on cosmic ray transport in the heliosheath. When a GMIR arrives at the TS, it can produce a decrease of cosmic ray intensity at Voyager 1 location deep in the heliosheath. Such a remote sensing feature of CRs modulation by GMIR has enabled them to figure out the distance of the TS in 2006 when Voyager 1 was quite far away from the TS.

[8] This paper focuses on the cosmic ray intensity variation observed by voyager spacecraft in 2007. Specifically, a numerical approach combining the cosmic ray transport code and MIR model is used to investigate the 2007 cosmic ray transient decrease events. The paper is structured as follows: First, we present Voyager cosmic ray and plasma observations in 2007 and the characteristics of the cosmic ray transient decrease events. Then we present the simulation model to reproduce the basic feature of LMIR modulation of CRs locally and remotely. Finally, we apply the simulation result to voyager observations by proposing a scenario of two LMIRs propagating into the heliosheath.

## 2. Voyager Observation in 2007

[9] In 2007, Voyager 1 spacecraft, which is about 104 AU far away from the Sun, observed a series of  $>70$  MeV/nucleon cosmic ray transient decrease events. (See Figure 1.) The first transient decrease event happened at 2007.56 and the second one happened at 2007.76. The signatures of local enhancement of the magnetic field and cosmic ray intensity decrease indicate the events are related to LMIR. But, as far as we know, there is still no consensus on the detailed scenario of these two transient decrease events.

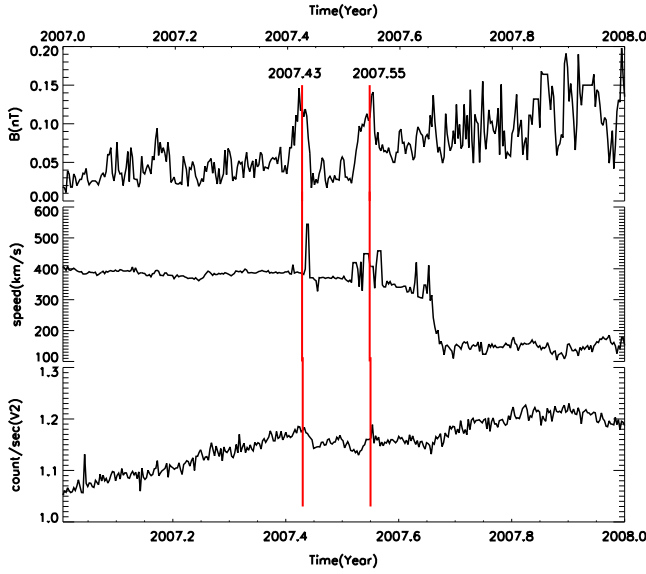


**Figure 1.** Voyager 1 observations of  $>70$  MeV/nucleon cosmic ray intensity and magnetic field strength in 2007. (top) The daily averages of the cosmic ray intensity observed by Voyager 1 in the heliosheath during 2007. (bottom) The daily averages of the magnetic field strength observed by Voyager 1 in the heliosheath from 2007.4 to 2008.4.

[10] Burlaga *et al.* [2011] suggested that the 2007.56 event is attributed to the local enhancement of the magnetic field, and the observed cosmic ray intensity fits the CR-B relationship proposed by Burlaga *et al.* [1985]. Since there is no observed magnetic field enhancement corresponding to the 2007.76 event, Burlaga *et al.* [2011] suggested that this may be due to the arrival of Local Merged Interaction Region (LMIR) with a limited latitude extent which is slightly below the latitude of the Voyager 1 spacecraft. Due to the particle diffusion, this MIR can remotely affect the cosmic ray transport beyond its extent of enhanced magnetic field. One weakness for this scenario is that there is still no theoretical work to affirm that the MIR can produce cosmic ray intensity decrease in the region beyond the MIR's latitude in the heliosheath. In addition, the local enhancement of the magnetic field at 2007.56 is not that apparent. Without further information from the plasma data, the evidence of the arrival of MIR at Voyager 1 at 2007.56 is a little weak.

[11] On the other hand, Webber *et al.* [2009] asserted that these transient decrease events are related to the December 2006 instigating event observed at the Earth. The MIR reaches the Voyager 2 spacecraft at 2007.43. It should be able to propagate further to the TS at 2007.56 and Voyager 1 spacecraft's heliosheath location at 2007.76 causing cosmic ray intensity decrease. As shown in Figure 2, a MIR has also been detected by Voyager 2 spacecraft at 2007.55 [Burlaga *et al.*, 2011]. However, this MIR event has not been mentioned in this scenario. Another drawback for this scenario is that at 2007.76, the magnetic field strength observed by Voyager 1 spacecraft did not show significant enhancement, which indicates no arrival of a MIR locally.

[12] In summary, both Webber *et al.* [2009] and Burlaga *et al.* [2011] agree it is an LMIR-associated event. To clarify the confusion about the LMIR arrival detailed scenario, we use numerical model to investigate these transient decrease



**Figure 2.** Daily averages of the magnetic field, plasma speed, and cosmic ray intensity observed by Voyager 2 during 2007. Two MIRs which are marked by vertical lines are detected in 2007.43 and 2007.55, respectively.

events observed by voyager spacecraft in 2007. Specifically, a limited-latitude LMIR model is constructed and incorporated into the galactic cosmic ray transport model. A series of simulations are carried out with this model.

### 3. Simulation Model

#### 3.1. Cosmic Ray Transport Model

[13] In order to simulate the cosmic ray transport in the heliosphere, we use the Parker equation of particle transport [Parker, 1965],

$$\frac{\partial f}{\partial t} = -(\vec{V} + \langle \vec{V}_d \rangle) \cdot \nabla f + \nabla \cdot (K^{(s)} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \vec{V}) \frac{\partial f}{\partial \ln P}, \quad (3)$$

where  $f$  is the distribution function,  $\vec{V}$  is the solar wind speed, and  $\vec{V}_d$  is the drift speed due to the large-scale variation of the interplanetary magnetic field (IMF). Because of the scattering from IMF's irregularities, a diffusion term is also included in this equation.  $K^{(s)}$  is the symmetric diffusion tensor and has the following form if expressed in the local magnetic field coordinate system:

$$K^{(s)} = \begin{pmatrix} \kappa_{\perp} & 0 & 0 \\ 0 & \kappa_{\perp} & 0 \\ 0 & 0 & \kappa_{\parallel} \end{pmatrix}. \quad (4)$$

[14] Following Markov stochastic method [Zhang, 1999], we rewrite the transport equation with the following time backward stochastic differential equations (SDE):

$$d\vec{X} = (\nabla \cdot K^{(s)} - \vec{V} - \langle \vec{V}_d \rangle) ds + \sum_{\sigma} \vec{\alpha}_{\sigma} dW_{\sigma}(s), \quad (5a)$$

$$dP = \frac{1}{3} P (\nabla \cdot \vec{V}) ds. \quad (5b)$$

In the equation above,  $dW_{\sigma}(s)$  is the Wiener process, and it can be generated in each step using a Gaussian distribution random number. The vector parameter  $\vec{\alpha}_{\sigma}$  is related to the diffusion coefficient by the following form:

$$\vec{\alpha}_1 = \begin{pmatrix} \sqrt{2\kappa_{\parallel}} \\ 0 \\ 0 \end{pmatrix}, \quad \vec{\alpha}_2 = \begin{pmatrix} 0 \\ \sqrt{2\kappa_{\perp}} \\ 0 \end{pmatrix}, \quad \text{and} \quad \vec{\alpha}_3 = \begin{pmatrix} 0 \\ 0 \\ \sqrt{2\kappa_{\perp}} \end{pmatrix}. \quad (6)$$

[15] The solution of this set of equations gives the position and momentum increments of pseudoparticles in the phase space  $(\vec{x}, p)$ . In order to calculate the distribution function  $f(\vec{x}, p)$ , we trace a large number ( $N$ ) of pseudoparticles, until they reach the boundary where an interstellar spectrum  $f_{\text{ISM}}$  is assumed. Then we record each pseudoparticle's value at the boundary  $f_{\text{ISM}}(p_i)$  and perform an ensemble average  $f(\vec{x}, p) = \sum_{i=1}^N f_{\text{ISM}}(p_i)/N$ .

[16] For the diffusion coefficient, in this investigation, we use the following relations:

$$\kappa_{\parallel} = \kappa_{\parallel 0} \beta \left( \frac{P}{p_0} \right)^{0.5} \left( \frac{B_{\text{eq}}}{B} \right), \quad \kappa_{\perp} = \kappa_{\perp 0} \beta \left( \frac{P}{p_0} \right)^{0.5} \left( \frac{B_{\text{eq}}}{B} \right). \quad (7)$$

[17] Here,  $P$  and  $B$  are the particle momentum and magnetic field strength, respectively, and  $\beta$  is the ratio of particle speed to the speed of light. The parameter  $p_0$  is the reference momentum (in our case it is  $1 \text{ GeV c}^{-1}$ ), and  $B_{\text{eq}}$  is the magnetic field strength at the heliospheric equator at 1 AU. The constant  $\kappa_{\parallel 0}$  determines the magnitude of parallel diffusion coefficient. It is chosen to be  $50 \times 10^{20}$ , with the unit of  $\text{cm}^2 \text{ s}^{-1}$ . As for the perpendicular diffusion coefficient  $\kappa_{\perp 0}$ , according to Giacalone and Jokipii [1999], a ratio of  $\kappa_{\perp 0}/\kappa_{\parallel 0} = 0.04$  is adopted in our simulation. The choice of the above form is a little arbitrary but approximately consistent with the overall modulation level inferred by various observations.

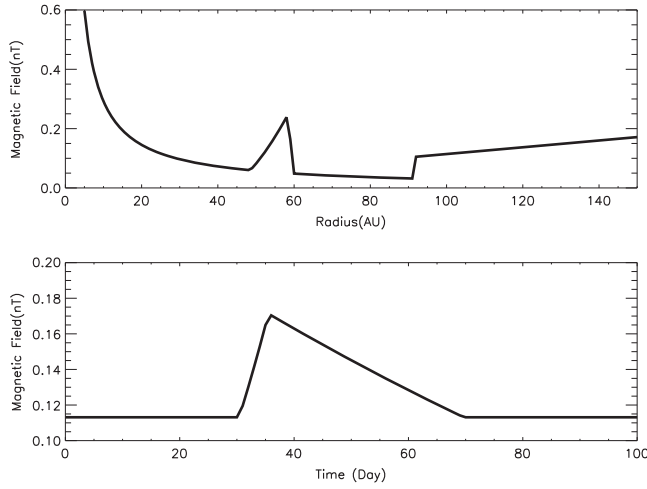
[18] For the solar wind, we use a modified symmetric model. Inside the TS, solar wind speed varies with latitude, the solar wind speed is high (low) near the polar (ecliptic) region. In the heliosheath region, the plasma is assumed to be incompressible (there may be a little heating or cooling, but it is not strong), thus  $\nabla \cdot \vec{V} = 0$  leading to  $\vec{V} \propto \frac{1}{r^2}$ . Actually, in the LMIR model, we still have heating in the leading edge and cooling in the trailing edge.

[19] The TS is treated as infinite thin. To overcome the singularity problem when calculating the momentum gain rate from TS acceleration, we use a skew Brown motion method developed by Zhang [2000].

[20] In order to avoid the large perpendicular diffusion in the polar region, we use a modified Parker's magnetic field model:

$$\vec{B} = \frac{A}{r^2} \left( \hat{e}_r + 0.05 r \hat{e}_{\theta} - \frac{\Omega r \sin \theta}{V} \hat{e}_{\phi} \right) (1 - 2S[\theta - \theta_{cs}]). \quad (8)$$

[21] The inclusion of  $B_{\theta}$  component in non-Parker field only affect the magnitude of diffusion tensor in the polar region significantly. We have used the modification of Jokipii and Kóta [1989] in our code so that the diffusion coefficient at the pole does not become too large. Burger et al. [2008] used the Fisk field to enhance latitudinal transport. We think latitudinal transport does not affect modulation by



**Figure 3.** The magnetic field magnitude profile used in our simulation. (top) The curve shows the variation of the magnetic field magnitude along the upwind direction in the whole simulation domain. (bottom) The corresponding time profile. As LMIR approaches the observation point (60 AU,  $35^\circ$ ,  $0^\circ$ ), magnetic field magnitude increases from 0.114 nT to about 0.171 nT and then gradually return to the original value.

LMIR very much, since the LMIR is thin in the radial direction and thick in the latitudinal direction. For the heliosheath region, we assume the average magnetic field magnitude increases slowly, which is illustrated in Figure 3 (top).

[22] A wavy current sheet is also included in our simulation. Assuming the IMF is frozen in the solar wind which is flowing outward radially, current sheet can be derived as follows:

$$\tan(\theta_{cs}) = -\frac{\cos(\alpha)}{\sin(\alpha) \cos(\phi - \Omega(t - \frac{r}{V}) - \phi_m)}. \quad (9)$$

[23] In the above equation,  $\alpha$  is the tilt angle between the Sun's rotation axis and magnetic dipole axis,  $\theta$  is the colatitude of the current sheet at location  $r$ ,  $\phi$ , and time  $t$ . The offset longitude of the dipole axis is  $\phi_m$ , while the solar wind speed is  $V$ . In this study, we set the tilt angle  $\alpha = 10^\circ$  to represent the solar minimum condition in 2007.

[24] As for the drift speed  $\vec{V}_d$ , the classical form  $\langle \vec{V}_d \rangle = (pv)/(3q) \nabla \times \frac{\vec{B}}{B^2}$  is adopted in our simulation model. Along the current sheet, the drift velocity  $\langle \vec{V}_d \rangle = (pv)/(3q) \nabla \times \frac{\vec{B}}{B^2}$  becomes infinite. In reality, the cosmic ray particle drift along the current sheet is finite but large within a width of two gyroradii  $2R_g$  [Burger et al., 1985, 1989; Strauss et al., 2012]. We model the current sheet as a sheet with a width of two gyroradii, and delta function is denoted by  $1/(2 \times R_g)$  ( $\int \delta(\theta) d\theta = \int_{-R_g}^{R_g} \frac{1}{2 \times R_g} dr = 1$ ). It is found that the numerical representation of the  $\delta$  function will not affect the calculation. The direction of current sheet drift  $\vec{V}_{cs}$  is parallel to the current sheet and perpendicular to the interplanetary magnetic field. Using a similar method of Strauss et al. [2012], three components along  $\hat{r}$ ,  $\hat{\theta}$ , and  $\hat{\phi}$  can also be obtained.

[25] Beyond the TS, it is known that the solar wind speed decrease and the current sheet become compressed.

The distance between the nearby current sheet sector may even be smaller than the gyroradius of the cosmic ray particles. In this situation, some new drift theory is demanded in the simulation model [Florinski et al., 2011; Florinski, 2011; Drake et al., 2010]. Since this is still an ongoing research and the drift is primarily in the latitudinal direction affecting the radial transport a little, we turned off the drift in the sheath region in this study.

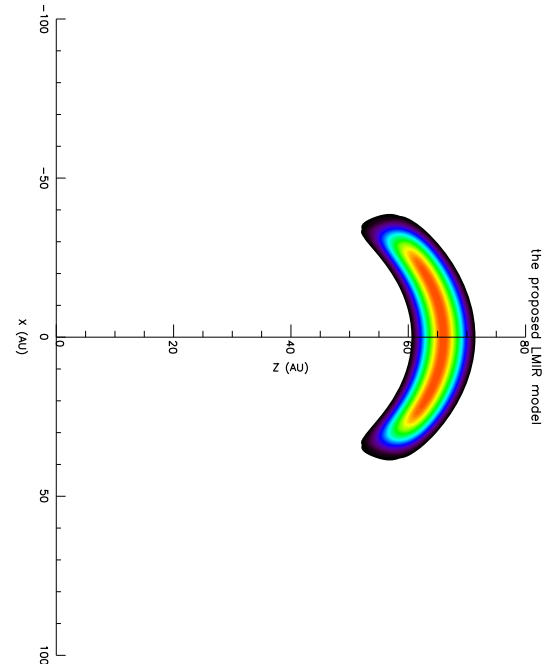
### 3.2. Local Merged Interaction Region Model

[26] It is suggested that the MIR that heads toward Voyager 1 in 2007 is below the spacecraft's latitude [Burlaga et al., 2011]. We should classify it to be a Local Merged Interaction Region (LMIR) with limited latitude extent. Figure 3 shows the magnetic field profile constructed in our simulation. Without LMIR, the magnetic field magnitude obeys the Parker model and its magnitude decreases up to the TS location (92 AU). A LMIR is a region of increased magnetic field superposed on the ambient Parker field. We assume the magnetic field in the LMIR obeys the following relationship:

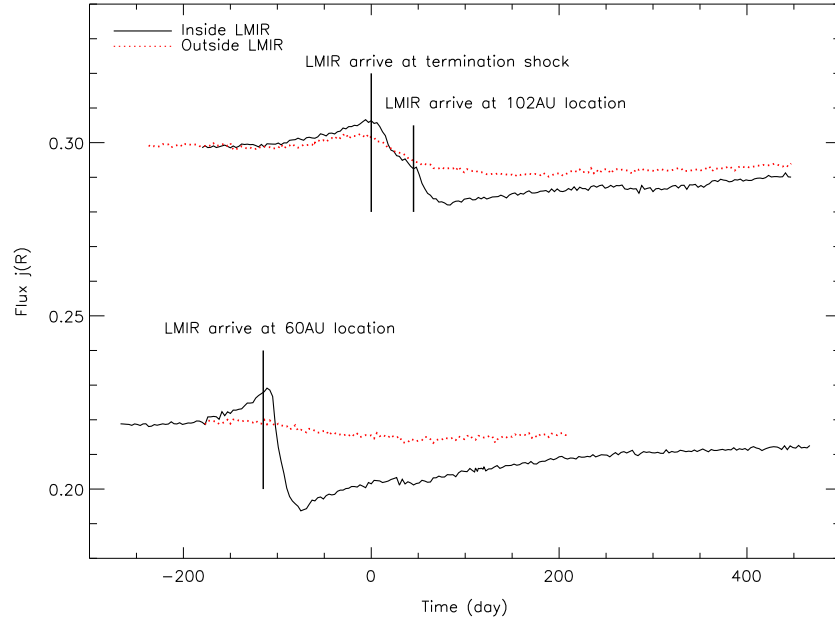
$$B_{LMIR} = \frac{B_0}{D(r, \theta)} \quad D(r, \theta) = g(r) \times e^{-\left(\frac{\theta - \pi/2}{\theta_{LMIR}}\right)^{10}}. \quad (10)$$

[27] Here,  $B_{LMIR}$  is the magnetic field inside the LMIR and  $B_0$  is the ambient plasma magnetic field, which is related to  $B_{LMIR}$  by the function  $D(r, \theta)$ . Similar to the magnetic field, plasma speed is also enhanced as LMIR passes by, as it is shown in Figure 6 (upper curve).

[28] Figure 4 illustrates the profile of function  $D(r, \theta)$  in the meridional plane. In our simulation, the LMIR model has a wedge shape with a width of  $L_{LMIR} = 12$  AU and extend to the latitude by  $\theta_{LMIR} = 30^\circ$ . Since the direction of Voyager 1



**Figure 4.** The function  $D(r, \theta)$  profile of LMIR model in the meridional plane. The  $x$  axis is along the solar rotation axis, and  $z$  axis points toward the node of the heliosphere.



**Figure 5.** Simulation result for the LMIR effect on cosmic ray transport. Time  $t = 0$  is set when the LMIR front arrives at the TS at  $R_{TS} = 92$  AU. The lower plot shows the cosmic ray flux profile at the location (60 AU,  $35^\circ$ ,  $0^\circ$ ). The upper plot shows the cosmic ray flux profile at the location (102 AU,  $35^\circ$ ,  $0^\circ$ ). The solid curves illustrate the effect caused by a LMIR of  $\pm 45^\circ$  wide in latitude, which covers the location of the observer. On the other hand, the red curves show the effect caused by LMIR with latitude extend to  $30^\circ$ , which is below the observation point.

is along  $35^\circ$ N latitude, our LMIR model is a little below the latitude of Voyager 1.

[29] As stated in the previous section, a time-dependent SDE approach (equation (5)) is adopted to solve the transport equation. The “particle” trajectory is stepped backward in time, and so is the entire heliospheric magnetic field structure. To incorporate the LMIR model into the cosmic ray transport code, we need to locate the LMIR and calculate the local magnetic field and plasma speed as the background condition for the cosmic ray transport. Therefore, a time-location relationship for LMIR needs to be established. In the simulation, by setting the time when LMIR arrives at TS ( $R_{ts}$ ) as  $t = 0$ , we can obtain the location of the LMIR ( $R_{LMIR}$ ) for any given time  $t$  as  $R_{LMIR} = R_{ts} - \bar{V}_{LMIR} \times t$ . Note the time  $t$  here is backward, since we trace the pseudoparticle time backward.

[30] As shown in equation (7), the magnitude of the diffusion coefficient is inversely proportional to the magnitude of the magnetic field. Therefore, in our simulation, as cosmic ray particles penetrate into the LMIR region with strong magnetic field, they tend to be trapped in this region due to the reduced diffusion.

#### 4. Simulation Results

[31] Based on the model described above, a series of simulations have been conducted. In the following, we will discuss the results.

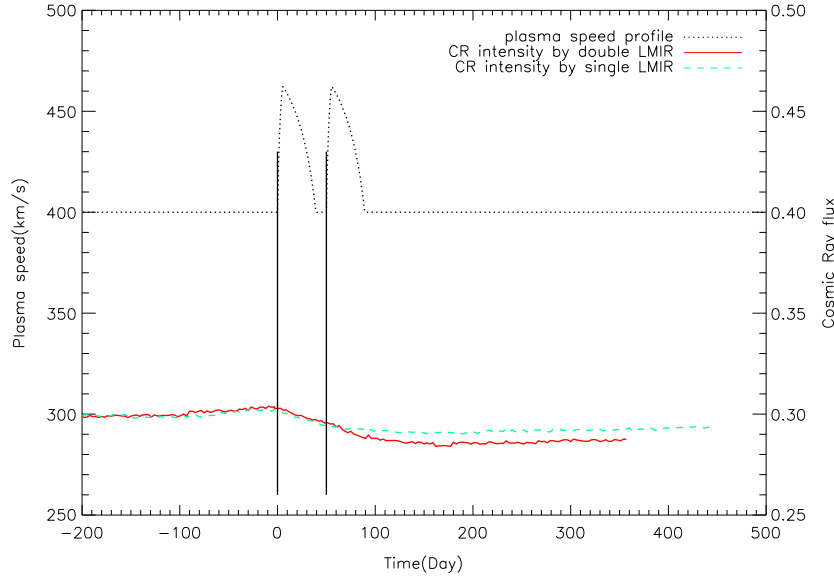
[32] As a test of our simulation model, we first simulate the cosmic ray intensity decrease caused by a LMIR in the supersonic solar wind region. Figure 5 (lower plot) shows how an observer at (60 AU,  $35^\circ$  latitude,  $0^\circ$  longitude) in the

supersonic solar wind region will see the variation of the cosmic ray intensity as the LMIR passes by.

[33] If observed inside the LMIR, the cosmic ray flux decreases as the LMIR passes by. This scenario is consistent with previous understanding of LMIR [Perko and Fisk, 1983; Potgieter *et al.*, 1993]. The LMIR acts like a propagating diffusion barrier. Encountered cosmic ray particles will be trapped in its strong magnetic field due to the reduced diffusion. As a result, less cosmic ray particles can penetrate. Those trapped cosmic ray particles inside the barrier have spent more time at smaller radial distance, causing them lose more energy. The red-dotted curve shows that even the observer is outside the LMIR, there is still a little decrease of intensity corresponding to the closest approach of the LMIR. Previous investigation of the Ulysses data also found similar feature which shows that CIRs modulation can propagate to higher-latitude region [Simpson, 1998; Kóta and Jokipii, 1995; Zhang, 1999].

[34] Figure 5 (upper plot) shows the situation for an observer in the heliosheath region. As stated by Luo *et al.* [2011], the interaction between MIR and TS has a remote effect on cosmic ray transport in the heliosheath; thus, the cosmic ray intensity will decrease as the MIR arrives at the TS. This feature is probably due to the fact that cosmic ray transport is a random walk process. The detected cosmic ray particles in the heliosheath may go through the TS multiple times and tour vast regions of the supersonic solar wind region. Thus, they are still affected by the shock acceleration caused by TS. As LMIR’s arrival at TS, this process may be disrupted and causing the cosmic ray intensity decrease observed in the heliosheath. The upper curves also demonstrate that even though an observer is outside





**Figure 6.** Simulation result for double LMIR effect on cosmic ray transport. Time  $t = 0$  is set when the heading LMIR front arrives at the TS. The upper dotted curve recorded the plasma speed profile at 92 AU location (the upstream of TS). The lower solid red curve recorded the simulated cosmic ray intensity profile at (102 AU,  $35^\circ, 0^\circ$ ) as these two LMIRs arrive at the TS. A notable feature for this red curve is the double decrease events, which correspond to the double LMIRs arriving at the TS. In comparison, the dashed green curve shows the cosmic ray intensity profile as a single LMIR passes by.

the LMIR, the detected cosmic ray flux will decrease as the LMIR arrives at TS. Inspired by this remote effect of LMIR, we propose a scenario to explain the cosmic ray transient decrease events seen by Voyager 1 in 2007.

## 5. Numerical Investigation of the 2007 Cosmic Ray Transient Decrease Events

[35] As shown in Figure 2 (upper plot), the magnetic field data observed by Voyager 2 shows a peak at 2007.43. Nearly at the same time, the plasma speed also peaks and the cosmic ray intensity begins to decrease. This evidence strongly supports that a MIR has arrived at Voyager 2 at 2007.43. At 2007.55, a similar event happens: The magnetic field and plasma speed both peak and cosmic ray intensity decreases as well. We believe the cause for this event is still a MIR, which is consistent with the opinion of *Burlaga et al.* [2011].

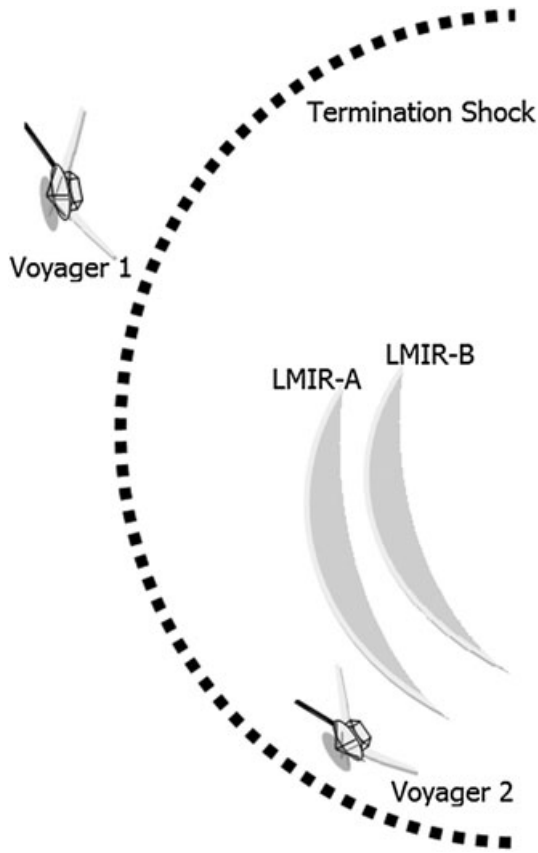
[36] In order to interpret the transient decrease events observed by Voyager 1 in 2007, a model with two LMIRs need to be constructed in our simulation. We extend the single LMIR model to a double LMIR one and let them propagate individually inside the heliosphere.

[37] The simulated results are shown in Figure 6. The upper dotted line shows the variation of the plasma speed with respect to time at a location before the TS, and the lower red line shows the simulated cosmic ray intensity profile at (102 AU,  $35^\circ, 0^\circ$ ) (roughly at Voyager 1 2007 location). At  $t = 0$  and  $t = 50$ , cosmic ray intensity curve indeed shows two transient decrease events, and they are both corresponding with the LMIR's arrival at TS (the plasma speed profile shows local enhancement). In order to show the remote effect caused by the second LMIR, the cosmic ray intensity variation curve (the dashed green one) for a single

LMIR case is also plotted, and there is no transient decrease at  $t = 50$ .

[38] Based on the simulation results, we believe that the causes for transient decrease events seen at Voyager 1 are the same twin LMIRs detected earlier by Voyager 2 at 2007.43 and 2007.55. They interact with the TS at 2007.56 and 2007.76, remotely affecting the cosmic ray intensity in the heliosheath at Voyager 1 location. Figure 7 is a diagram illustrating this scenario. In this figure, the relative locations of the double LMIRs (LMIR-A and LMIR-B), TS, and Voyager spacecraft in the meridional plane are shown. The main part of LMIRs are located in the southern heliosphere, below the latitude of Voyager 1.

[39] This scenario seems to agree well with the observation data. First, when LMIR arrives at Voyager 2, the local enhancement of the magnetic field and plasma speed are apparent. At 2007.43 (2007.55), the magnitude of the magnetic field increases up to 2 times of the ambient value, while the plasma speed increases about 30% (15%). Second, the decrease level ( $\frac{I_{\max} - I_{\min}}{(I_{\max} + I_{\min})/2}$ ) for the observed cosmic ray intensity by Voyager 1 is about 3% which is consistent with the simulated result. Third, there is no clear signature indicating the arrival of LMIR at Voyager 1, probably due to the fact that Voyager 1 is beyond the latitudinal extent of the LMIRs. Finally, as suggested by *Webber et al.* [2009], these transient decrease events originated from the Coronal Mass Ejections (CMEs) which occurred in December 2006. Using SOHO Large Angle and Spectrometric Coronagraph CME catalog, we found that in 2006 December, there are 55 CME events recorded and only four small CMEs cover the latitude of Voyager 1 direction. Most CMEs in 2006 December head toward south. As they propagated further, after coalescing, merging, these two LMIRs are formed and observed by Voyager 2 spacecraft.



**Figure 7.** An illustration showing our proposed scenario for the 2007 LMIR events. Two LMIRs approach voyager spacecraft in 2007. LMIR-A(B) arrives at Voyager 2 in 2007.43 (2007.55) and propagates further until it interacts with TS in 2007.56 (2007.76), causing the cosmic ray intensity decrease observed by Voyager 1.

## 6. Summary

[40] In this paper, using a numerical approach, we investigate the causes for the cosmic ray transient decrease events observed by voyager spacecraft in 2007. Our simulation shows that the LMIR's interaction with the TS will affect the cosmic ray modulation in the heliosheath even if the observation location is outside latitudinal extent of the LMIR.

[41] This unique feature enables us to propose a scenario for 2007 cosmic ray transient decrease events. Two LMIRs have arrived at Voyager 2 at 2007.43 and 2007.55, respectively. As they propagate further, they individually interact with the TS at 2007.56 and 2007.76, resulting in the observed cosmic ray intensity decrease events by Voyager 1.

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