Remote Sensing: a new feature caused by the GMIR on cosmic ray transport in the heliosheath

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Abstract: Using a combined GMIR and cosmic ray modulation model, we investigate the effect of the GMIR on cosmic ray transport in the heliosheath. In our simulation, the GMIR is approximated by a partial shell of particle diffusion barrier with enhanced magnetic field and plasma speed. It can propagate inside the heliosphere. Our simulation has reproduced previous scenario of the GMIR effect. However, as we move our simulation location outside of the termination shock (2006 Voyager 1 location), it shows a new feature. Cosmic ray intensity will begin to decrease as GMIR arrives at Termination Shock (TS). Spacecraft inside heliosheath, such as Voyager 1, can remote sense when GMIR arrives at TS. This remote sensing feature provides us a way to estimate the radial distance of the TS and GMIR propagation speed.

Keywords: Cosmic Ray, GMIR, Termination Shock, Voyager

1 Introduction

Global Merged Interaction Region (GMIR) is a solar wind structure formed in the outer heliosphere. It is a build-up of multiple large coronal mass ejections with enhanced magnetic field and solar wind speed. Using Voyagers’ CRS data, it was found that cosmic ray intensity decreases when a GMIR passes by [11].

Modern cosmic ray transport theory treats GMIR as a diffusion barrier to explain the CR intensity decrease inside GMIR. Adapting this concept, the step decrease of the cosmic ray intensity during the ascending phase of the solar maximum can be well simulated [12, 14]. It is argued that the interplay of GMIR and current sheet as separate dominating factors is essential to explain the complete 11-year solar cycle of cosmic ray modulation [13].

However, previous understandings about GMIR are mainly confined inside the termination shock. As Voyagers crossed the Termination Shock [7], entering into the vast region called heliosheath, it is worthwhile to move our attention there, and study the cosmic ray transport, such as GMIR effects inside heliosheath.

2 Simulation model

2.1 Cosmic Ray Modulation Model

Our cosmic ray modulation model is based on Parker’s transport equation [1].

\[
\frac{\partial f}{\partial t} = - (\vec{V} + \langle v_D \rangle) \cdot \nabla f + \nabla \cdot (K^\parallel \nabla f) + \frac{1}{3} (\nabla \cdot \vec{V}) \frac{\partial f}{\partial \ln P} .
\]

The equivalent Stochastic Differential Equation forms are [2]:

\[
d\vec{X} = \sqrt{2\kappa} \cdot d\vec{W}(s) + (\nabla \cdot K - \vec{V}_sw - \vec{V}_d)ds \\
dp = \frac{1}{3} \nabla \cdot \vec{V}_sw pds
\]

\[
K = \begin{pmatrix}
\kappa_\perp & 0 & 0 \\
0 & \kappa_\perp & 0 \\
0 & 0 & \kappa_\parallel
\end{pmatrix}.
\]

Here, \(\beta\) is the ratio of the particle speed with respect to the light speed and \(B_{eq}\) is the magnetic field magnitude near earth.

As for the solar wind, we use a modified symmetric model. Inside the termination shock, the solar wind speed change

\[
\kappa_\parallel = \kappa_{0,\parallel}(\frac{P}{P_0})^{0.5}(\frac{B_{eq}}{B}) \\
\kappa_\perp = \kappa_{0,\perp}(\frac{P}{P_0})^{0.5}(\frac{B_{eq}}{B})
\]

A coordinate transform needed to convert this diffusion tensor into the simulation coordinate system. In our simulation we use the following form for \(K\),

\[
\kappa_\parallel = \kappa_{0,\parallel}(\frac{P}{P_0})^{0.5}(\frac{B_{eq}}{B}) \\
\kappa_\perp = \kappa_{0,\perp}(\frac{P}{P_0})^{0.5}(\frac{B_{eq}}{B})
\]
with the latitude. Outside the termination shock, speed decrease with respect to a modified factor. Similarly, a modified Parker’s magnetic field:

$$\vec{B} = \frac{A}{r^2}(e_r + 0.05r\hat{e}_\theta - \frac{r\sin\theta}{V_{sw}}\hat{e}_\phi)(1 - 2S[\theta - \theta_{cs}]) \quad (5)$$

is introduced in our simulation model.

The wavy current sheet is also included in our simulation. Using Parker’s magnetic field, assuming the Interplanetary Magnetic Field is frozen in the solar wind and solar wind is propagating outward radially, current sheet can be derived as:

$$\tan(\theta_{cs}) = -\frac{\cos(\alpha)}{\sin(\alpha)\cos(\phi - \Omega(t - \frac{R}{V_{sw}}) - \phi_m)} \quad (6)$$

In the above equation, $\phi$ is the tilt angle which is the angle between the rotation axis and sun’s dipole axis, $\theta$ is the latitude of the current sheet at location $R$, $\phi$ and time $t$.

Because of the existence of a step function in the magnetic field, there appears a delta function in the drift velocity $< V_d > = \frac{m}{e} \nabla \times \frac{\vec{B}}{r^2}$. Physically, this means that along the current sheet, the drift term is the dominant factor affecting the modulation, since its magnitude is much larger than other terms. In our simulation, we use the square wave method to deal with this delta function. Namely, the current sheet is modeled as a sheet with a width of two gyro radii of the cosmic ray, and delta function is denoted by $\frac{1}{2\pi R_{g}}$. Since $\int \delta(\theta) d\theta = \int_{-R_g}^{R_g} \frac{1}{2\pi R_{g}} \, dr = 1$.

2.2 GMIR model

Following the concept proposed by Burlaga [3, 4], the GMIR is a quasi-spherical propagating shell with intense magnetic field. We constructed a GMIR model: it has a trail region width of 1.5 AU and a 12 AU wide tail region, spanning up to the 40° above and below the equatorial plane. The GMIR is also propagating. Whang proposed the method of Characteristics to treat the GMIR propagation in the heliosphere [5]. Here we adapted Whang’s model, the shock strength and propagation speed can be solved. In order to quantify the magnetic field and plasma speed change inside GMIR, a proportional factor $R_k$, which relates the magnetic field and plasma speed to the background value, is introduced. On the equatorial plane (Latitude $0^\circ$), this factor has the maximum. It gradually reduces as latitude increase, according to:

$$R_k = R_{k0} \times e^{-\left(\frac{\theta - \pi/2}{\Theta_{gmir}}\right)^2}$$

Here $\theta - \pi/2$ is the latitude and $\Theta_{gmir}$ is the maximum span of the GMIR along the $\hat{\theta}$ direction. Apart from the latitude change, it also reduces as it approaches the GMIR boundary following:

![Figure 1: The Magnetic field profile of GMIR model. The upper panel shows the Magnetic field along Voyager 1 direction in the whole simulation region; the lower panel simulates the change of magnetic field at 2006 Voyager 1 location as GMIR passes by.](image)

$$R_k = R_{k0} \times \frac{r - R_{peak}}{d}$$

Figure 1 shows the magnetic field profile of our GMIR model. The upper panel is the radial profile which shows how the magnetic field changes in the whole simulation region along Voyager 1 direction.

Based on equation (4), the diffusion tensor will be inversely proportional to the local magnetic field magnitude. Thus, intensified magnetic field results in a reduced diffusion causing cosmic ray intensity decrease. This has been clearly illustrated by our results (See details in the next chapter).

Figure 2 shows the plasma speed profile in our simulation.

3 Results

3.1 Simulated result

In our simulation, first we place an “artificial spacecraft” at (60 AU, 55°, 0), which is roughly along Voyager 1’s direction. GMIR is propagating inside the heliosphere, and we set it arrive at termination shock at $t = 0$. The simulation result (Figure 3) records how the cosmic ray intensity and local magnetic field responses as GMIR passes by.

The upper panel of Figure 3 demonstrates the cosmic ray intensity profile at 60 AU location. As GMIR with intensified magnetic field arrives locally, cosmic ray intensity decrease. This scenario is consistent with previous understanding of the GMIR effect [9, 8]. However, as we...
move the “artificial spacecraft” outward the termination shock, e.g., (99AU, 55°, 0), some interesting features appear. Cosmic ray intensity decreases ahead of GMIR’s arrival locally. The beginning time of the intensity decrease is \( t = 0 \), as GMIR arrives at Termination shock. In other words, the event of GMIR arrival at TS has remote effect on the observation point inside the heliosheath. In the following section, we will the CRS instrument of Voyager 1 find similar feature in 2006.

3.2 comparison with Voyager Data

In 2006, a strong GMIR arrives at Voyagers. This GMIR is thought to originate from the high solar activities in 2005 September[6]. Based on Voyager 2’s plasma and Magnetometer Experiment Data, this GMIR can be clearly shown. Figure 4 demonstrates the observational data obtained from Voyager 2. During 2006.16 to 2006.24, plasma speed, density and magnetic field have a transient jump. Correspondingly, the > 70 Mev cosmic ray intensity decreases. This signifies GMIR arrival at Voyager 2 location.

The GMIR propagates outwards, crossing Termination Shock, then arrives at Voyager 1. What will happen for the CRS instrument of Voyager 1? The lower panel of Figure 5 demonstrates Voyagers’ > 70 Mev Cosmic ray intensity which responds to this GMIR event in 2006.

In contrast to V2’s CRS response, the CR intensity of V1 experiences a two-step decrease caused by the GIMR arrival event. At 2006, Voyager 1 already crossed the Termination shock, while Voyage 2 is still inside the termination shock[7]. Following our simulation result, the first decrease should come from the event of GMIR’s arrival at Termination Shock, while the CR intensity decrease of 2006.51 is caused by the GMIR’s arrival locally.

3.3 Estimate the TS radial distance and GMIR propagation speed inside heliosheath

If we treat the GMIR simply as a shock, using Voyager 2’s plasma data, we can get the GMIR propagation speed inside termination shock from the mass conservation equation.

\[
n_1(V_1 - V_{gmir}) = n_2(V_2 - V_{gmir})
\]
Figure 4: Voyager2 2006 observational data. The data shown from upper panel to lower panel are > 70 Mev energetic particle flux, plasma speed, plasma density, magnetic field.

Figure 5: Voyagers’ 2006 observational data. The upper panel shows the Voyager 2’s CRS data (> 70 Mev ions), Voyager 1’s data (> 70 Mev ions) is shown in the lower panel.

Here, \( n_1, V_1 \) are the plasma density, speed upstream, while \( n_2, V_2 \) for the downstream plasma density, speed downstream. Based on Voyager 2 data, 
\[
n_1 = 0.0011, \quad V_1 = 380 \text{ km/s}, \quad n_2 = 0.0032, \quad V_2 = 506.2 \text{ km/s}.
\]
These value gives the \( V_{gmir} = 573 \text{ km/s} \).

As stated above, GMIR arrives at TS at 2006.29. In addition, we know that Voyager 2 is about 79AU in 2006.19. Thus, the TS distance is just:

\[
R_{TS} = 79 \text{ AU} + V_{gmir} \times 0.1 \text{ year} = 91.04 \text{ AU}
\]

Since V1 crossed TS at 94.01 AU in 16 December 2004[7], we can calculate the inwards speed of TS as

\[
V_{TS} = \frac{94.01 \text{ AU} - 91.04 \text{ AU}}{2006.29 \text{ year} - 2004.96 \text{ year}} = 10.61 \text{ km/s}
\]

As we know the second decrease of Voyager 1 in 2006.51 corresponds to GMIR arrives locally, where Voyager 1 is about 99AU far from the sun. Thus the GMIR speed outside TS is:

\[
V_{gmir}(\text{sheath}) = \frac{99 \text{ AU} - 91.04 \text{ AU}}{2006.51 \text{ year} - 2006.29 \text{ year}} = 172.1 \text{ km/s}
\]

GMIR propagation speed decreased a lot as it crossed the termination shock.

4 Conclusion and Outlook

Using our combined model, we correctly simulate the transient decrease of CR intensity caused by GMIR in the heliosheath. Specifically, our simulation result explains the two-step decrease of Voyager 1 in 2006 caused by GMIR. There is a precursor event relates the GMIR’s arrival at TS. This precursor event enables us to estimate the TS radial distance and GMIR propagation speed.

In 2006, it is found that there is still another decrease of Voyager 1 CRS measurement corresponding with the GMIR shock arrival at the heliopause [10]. In future, we want to modify our model to explore this in more detail.

References