Study cosmic ray modulation near the heliopause: A numerical approach

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Study Cosmic Ray Modulation Near the Heliopause: A Numerical Approach

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Abstract.
By incorporating the MagnetoHydroDynamic (MHD) global heliospheric data into the Parker's cosmic-rays (CRs) transport equation, we constructed a hybrid galactic cosmic ray transport model to study the galactic cosmic-rays (GCR) behaviour near the heliopause(HP). Based on this hybrid model, we found that: (1)By increasing the ratio of the parallel diffusion coefficient to the perpendicular diffusion coefficient in the outer heliosheath (the region near HP and beyond), the simulated radial flux gradient near the HP increases as well. As this ratio multiplying factor reaches 10^{10}, the flux experiences a sudden jump near the HP, similar to what Voyager 1 had observed in 2012. (2)After increasing the ratio of the diffusion coefficients beyond the HP, more pseudo-particles in our numerical approach which have been traced from the upwind nose region exit in the downwind tail region. It is thus possible that they diffuse more directly from the tail region to the nose region.

INTRODUCTION

After nearly four decades since it was lunched, Voyager 1 is now more than 130 AU from the Earth. Recent observations indicate that Voyager 1 have already entered into the local InterStellar Medium (ISM). It was found that the above 70 MeV GCR intensity increased about 30% on 25 August,2012 as the spacecraft was at 121.7 AU [9]. The CRs observational data from Voyager 1 has stimulated several theoretical investigations of GCR transport near the HP (mainly about the issue whether there is modulation happened beyond the HP). Scherer et. al. [3] and Strauss et. al. [4] argued that the HP is not the modulation boundary for GCR so that there should be some level of modulation happened beyond the HP (in the outer heliosheath). On the other hand, Kota et. al. [6] arrived at the opinion that GCR modulation is very small beyond the HP if the diffusion coefficients in this region are set to be large enough. Later, Guo et. al. [7] shared the same opinion that GCR modulation beyond the HP is negligible. Thus, we are motivated to perform an independent study and strive to contribute some understanding for the community.

Numerical Models

The Parker's transport equation is changed to Stochastic Differential Equations (SDEs), and by incorporating modelled MHD global heliospheric data, this set of differential equations are integrated to solve the local value of distribution function [8].

Cosmic-Ray Transport Model

Parker's transport equaiton [1]:

$$\frac{\partial f}{\partial t} = -(\vec{V} + \left\langle \vec{V_D} \right\rangle) \cdot \nabla f + \nabla \cdot (K^{(s)} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \vec{V}) \frac{\partial f}{\partial \ln p} \quad . \tag{1}$$

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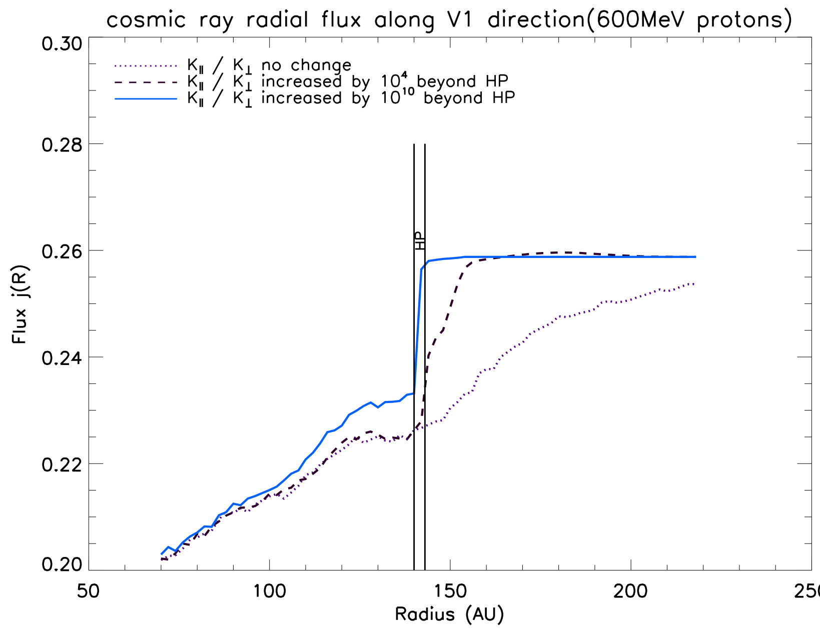

FIGURE 1. Simulated 600 MeV proton CRs flux as a function of radial distance along Voyager 1's direction. Three different scenarios are shown in this figure. Case A (the solid blue line): $\kappa_{\parallel}/\kappa_{\perp}$ is magnified by 10^{10} in the outter heliosheath; Case B (the brown dashed line): $\kappa_{\parallel}/\kappa_{\perp}$ is magnified by 10^4; Case C (the purple dotted line): no modification is made for $\kappa_{\parallel}/\kappa_{\perp}$. The flux unit is arbitrary.

is the basis of our GCR transport model. In the equation above, $\vec{V}$ is the solar wind velocity, $\langle \vec{V_D} \rangle$ is the averaged drift velocity, $\nabla \cdot (K^{(s)} \cdot \nabla f)$ is the diffusion term and $\frac{1}{3}(\nabla \cdot \vec{V})\partial f/\partial \ln p$ is the adiabatic energy change term, with p the momentum and f the CRs distribution function. Following Zhang [10], the transport equation is changed to the following set of SDEs:

$$d\vec{X} = (\nabla \cdot K^{(s)} - \vec{V} - \langle \vec{V_D} \rangle)ds + \sum_{\sigma} \vec{\alpha_\sigma} dW_\sigma(s) \quad , \tag{2}$$

$$dp = \frac{1}{3} p(\nabla \cdot V)ds \quad . \tag{3}$$

$dW_\sigma(s)$ is the Wiener process, and it can be generated in each step using a Gaussian distribution random number. In order to get the value of $f(\vec{X}, p)$, the above equations are integrated in the whole simulation domain.

Heliospheric MHD Plasma/Multi-Fluid Neutral Atom Model

We formulate the interaction between the solar wind and interstellar medium (ISM) by a set of MHD equations. The ISM is treated as ionized plasma and its multi-component neutral atoms interact with the solar wind plasma through charge-exchange and photo-ionization [2]. Although our MHD-neutral model overestimates the HP location along Voyager 1, this does not cause much differences on our qualitative study.

Simulation Results

Cosmic-RaysFlux Near HP

Figure 1 shows the simulated 600 MeV proton flux along Voyager 1's direction (polar angle $\theta = 56°$, azimuthal angle $\phi = 4°$ in our MHD coordinate system) and Figure 2 illustrates the value of diffusion coefficients for the simulation. We first set the $\kappa_{\parallel}/\kappa_{\perp} = 10$ in the whole simulation domain, and the purple dotted line of case C in Figure 1 shows the simulated results. For this scenario, the radial gradient does not vary much from the inner heliosphere to the interstellar

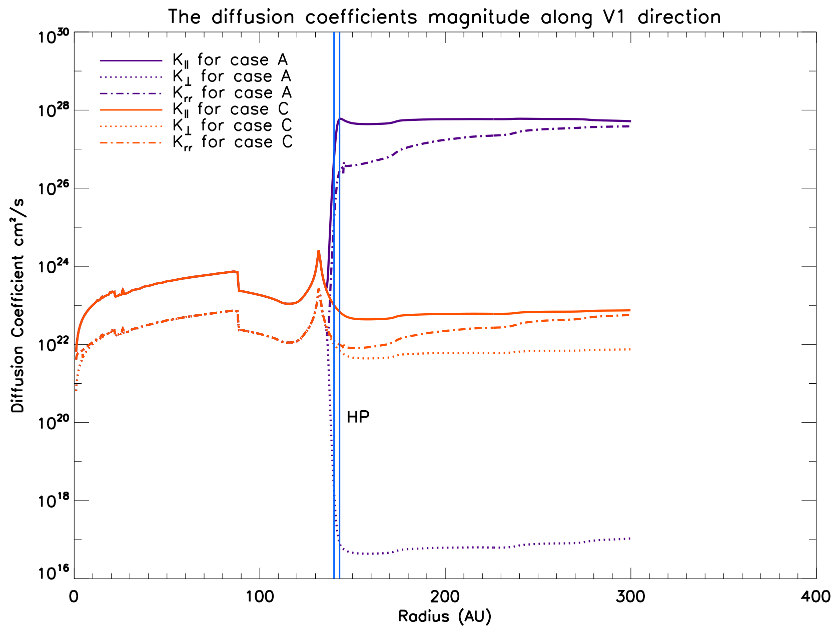

FIGURE 2. The magnitude of the diffusion coefficients in the simulation domain for cases A and C, as described in Figure 1.

boundary. When we magnify $\kappa_{\parallel}/\kappa_{\perp}$ by 10^4 in the outer heliosheath (the region near HP and beyond), the flux begins to jump from where we magnify $\kappa_{\parallel}/\kappa_{\perp}$, reaching the interstellar value within tens of AU. After we magnify $\kappa_{\parallel}/\kappa_{\perp}$ by 10^{10}, CRs radial gradient becomes much larger. Previously, Kota et. al. [6] and Guo et. al. [7] also reported that a small $\kappa_{\perp}/\kappa_{\parallel}$ value would cause a sharp increase of GCR flux at the HP. The picture is similar to what Voyager 1's CRS observed in Aug. 2012 [9]. In addition, $\kappa_{\parallel}$ reaches an order of 10^{28} cm^2/s and $\kappa_{\perp}$ decreases to about 10^{17} cm^2/s in this scenario. According to [5], the diffusion coefficient in the interstellar medium is about 10^{28} cm^2/s. Scenario A may reflect a realistic situation near the HP.

Information From Pseudo-particles

The SDEs enable us to trace the individual pseudo-particles' trajectory in the phase space $(\vec{X}, p)$. In addition, there is little modulation happened near the HP, the pseudo-particles have the same distribution as the entering CRs. Thus, these pseudo-particles can be treated as real CR particles approximately. By investigating the exiting characteristics of these pseudo-particles, we can obtain information of the real particles entering locations. The red points in Figure 3 illustrate the exit locations at a simulation boundary of 300 AU for 200 MeV pseudo-particles which start at 140 AU along the Voyager 1 direction. If we consider the pseudo-particles as real CR particles, these red points represent the entering locations for the CRs which are observed at the location (140AU, 56°, 4°) inside the heliosphere. Comparing these two figures, it can be seen that after we magnify the $\kappa_{\parallel}/\kappa_{\perp}$, more CR particles enter the heliosphere from the tail region instead of the nose region where they are observed. In our opinion, near the HP, some magnetic field lines in the nose region have their origin in the tail region, which follow the Parker spiral. As $\kappa_{\parallel}/\kappa_{\perp}$ is magnified, the parallel diffusion becomes more efficient, thus CRs diffuse more easily from the tail region to the upwind nose region without experiencing additional modulation. It should be noted that setting the simulation outer boundary at 300 AU may cut the heliotail region, and allow an excessive entrance for the unmodulated GCR. We will expand our simulation domain in our futher study to overcome this problem.

Summary

Based on a hybrid CR transport model, we investigate the behavior of GCR transport near the HP. It has been found that after the $\kappa_{\parallel}/\kappa_{\perp}$ is significantly magnified, the GCR flux jumps near the HP and the flux's radial gradient is similar to what Voyager 1 observed in Aug. 2012. Concerning the agreement between our parameter setup and the

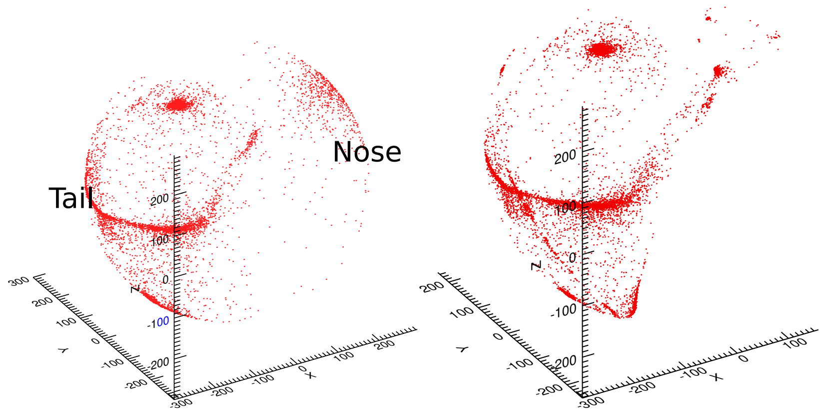

FIGURE 3. The red points exhibit the exit locations for 200 MeV pseudo-protons which start at 140 AU along Voyager 1s direction. The left plot is for the case where we do not vary the ratio of the parallel diffusion coefficient to the perpendicular diffusion coefficient in the outer heliosheath. The right plot illustrates the simulation results which $\kappa_{\|}/\kappa_{\perp}$ is increased by 10^{10} beyond HP. As the ratio is increased, more pseudo-protons exit the simulation domain from the tail region of the heliosphere.

observation of the value for interstellar diffusion coefficient, we argue that our scenario for the diffusion coefficient near the HP should be realistic. We also investigate the pseudo-particles' exit locations to gain information for the real GCR particles. The simulation demonstrates that after the diffusion coefficient is magnified significantly, more GCR particles, which are observed in the upwind nose region, enter the heliosphere from the tail region. This may relate to the heliospheric magnetic field line topology: in the nose there are some magnetic field lines that originated from the heliospheric tail.

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