Galactic Cosmic Ray Modulation near the Heliopause

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**Galactic Comic Rays:**
High-energy particles (mainly protons, typically $>100$ MeV) originating from outside the heliosphere but generally from within our galaxy. Most GCR are thought to be accelerated by shocks associated with supernova explosions that occur approximately every 50 years in our galaxy [Ackermann et al., 2013].
Voyager 1 has crossed heliopause

On September 12, 2013, it was officially confirmed by NASA that Voyager 1 have left solar system at a radial distance of 121.7AU from the Sun, and become the first spacecraft to enter interstellar space.

August 25, 2012

Sharp drop of Anomalous Comic Rays (ACR), but sharp increase for GCR (not shown here)
Outline

1. Model Introduction
   Global MHD-neutral simulation + Stochastic simulation of GCR transport

2. Possibility of GCR modulation in outer heliosheath
   Heliopause is believed to be the modulation boundary for GCR, not modulation occurs beyond heliopause. But recently some researchers questioned it.

3. Simulation of GCR intensity near heliopause
   We attempt to reproduce the variation of GCR near heliopause through simulations, and make comparison with observations.
1. Model Introduction

Global MHD-neutral Model of the Heliosphere

Basic equations: \((B = 0\) for neutral)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = Q_\rho
\]

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot \left( \rho uu + p^* I - \frac{BB}{4\pi} \right) = Q_u
\]

\[
\frac{\partial e}{\partial t} + \nabla \cdot \left[ (e + p^*) u - \frac{B(u \cdot B)}{4\pi} \right] = Q_e
\]

\[
\frac{\partial B}{\partial t} + \nabla \cdot (uB - Bu) = 0,
\]

where

\[
p^* = p + \frac{B^2}{2}, \quad e = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2},
\]

\(Q_\rho, Q_u, \) and \(Q_e\) are the charge exchange terms [Pauls, et al. 1995]. They are numerically solved on a spherical 3D geodesic mesh [Florinski, et al. 2013]. A level 6 geodesic grid with 40,962 hexagonal cells on the sphere surface, 512 layers in radial direction.
Geometry and Boundary Conditions

Inner boundary (10 AU):
Solar wind condition at 1 AU adopted for the 23/24 solar cycle minimum (A<0) [Jian et al, 2011; Ebert et al. 2009]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solar wind (fast)</th>
<th>Solar wind (slow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n, \text{ cm}^{-3} )</td>
<td>1.61</td>
<td>5.5</td>
</tr>
<tr>
<td>(</td>
<td>u</td>
<td>, \text{ km s}^{-1} )</td>
</tr>
<tr>
<td>( T, \text{ K} )</td>
<td>219,000</td>
<td>64,100</td>
</tr>
<tr>
<td>( B_r, \text{ nT} )</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Outer boundary (900 AU):
Unperturbed Local Inter Stellar Medium condition:
proton number density \( n_{\text{LISM,P}} = 0.05 \text{ cm}^{-3} \)
neutral hydrogen density \( n_{\text{LISM,H}} = 0.195 \text{ cm}^{-3} \)
temperature \( T_{\text{LISM}} = 6200 \text{ K} \)
magnetic field \( |B_{\text{LISM}}| = 0.3 \text{ nT} \)
velocity \( v_{\text{LISM}} = 23.2 \text{ km/s} \) [McComas, et al, 2012]

The heliographic coordinate system. B is inclined by 30 degree with respect to \( v_{\text{LISM}} (v_{\text{He}}) \).
Heliosphere Background (from a plasma + 4 neutrals simulation)
The Stochastic Transport Model

Parker's equation [Parker, 1965]

\[
\frac{\partial f}{\partial t} + (u_i + v_{d,i}) \frac{\partial f}{\partial x_i} - \frac{\partial}{\partial x_i} \left( \kappa_{ij} \frac{\partial f}{\partial x_j} \right) - \frac{1}{3} \frac{\partial u_i}{\partial x_i} \frac{\partial f}{\partial \ln p} = 0.
\]

\( f(r, p) \): the pitch-angle-averaged phase-space density; \( p \): particle momentum; \( u \): the convection from the plasma background.

Gradient and curvature drifts:

\[
v_d = \frac{pcw}{3e} \nabla \times \left( \frac{B}{B^2} \right)
\]

Diffusion tensor:

\[
\kappa_{ij} = \kappa_{\perp} \delta_{ij} + (\kappa_{\parallel} - \kappa_{\perp}) b_i b_j
\]

\[
\kappa_{\parallel} = \lambda_0 \frac{w B_0}{3 |B|} \left( \frac{p}{1 \text{ GeV} \text{ c}^{-1}} \right)^\delta \quad \text{and} \quad \kappa_{\perp} = \eta \kappa_{\parallel}
\]

\( \delta = 1 \) for \( p > 1 \) GeV/c and \( \delta = 1/3 \) otherwise. \( B = B_0 \) outside heliosphere.

Numerical Implementation:
We use Monte-Carlo method to numerically solve the transport Equations[Zhang, 1999].
The Interstellar Spectrum

\[ J_{\text{LIS}} = \frac{18.9T^{-2.79}}{(1.0 + 6.75T^{-1.22} + 0.7T^{-2.6} + 0.1T^{-3.12})} \] (similar to [Webber & Higbie, 2010])

**Red:**
the interstellar spectrum used in the Simulations;

**Pink (triangles):**
Voyager 1 observations beyond the Heliopause;

**Pink (line segments):**
the widths of CRS energy bins;

**Green:**
the LIS of (Webber & Higbie 2010).

**Blue:**
the spectra observed by PAMELA near Earth at the beginning (solid) and the end (dashed) of the last solar minimum.
Eight Scenarios in the Simulation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\lambda_{\text{inner}}$(AU)</th>
<th>$\lambda_{\text{outer}}$(AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.075</td>
<td>$1.0 \times 10^5$</td>
</tr>
<tr>
<td>2</td>
<td>0.075</td>
<td>$1.0 \times 10^4$</td>
</tr>
<tr>
<td>3</td>
<td>0.0385</td>
<td>$1.0 \times 10^5$</td>
</tr>
<tr>
<td>4</td>
<td>0.0385</td>
<td>$1.0 \times 10^4$</td>
</tr>
<tr>
<td>5</td>
<td>0.075</td>
<td>$1.0 \times 10^1$</td>
</tr>
<tr>
<td>6</td>
<td>0.075</td>
<td>$1.0 \times 10^0$</td>
</tr>
<tr>
<td>7</td>
<td>0.0385</td>
<td>$1.0 \times 10^1$</td>
</tr>
<tr>
<td>8</td>
<td>0.0385</td>
<td>$1.0 \times 10^0$</td>
</tr>
</tbody>
</table>

**Scenarios 1 – 4:**
similar to those in [Strauss et al, 2013].

**Scenarios 5 – 8:**
the diffusion in inner and outer heliosheath are comparable.
See the right figure for parallel diffusion coefficients For a 100 MeV proton along Voyager 1 direction.
Arising Questions: Is GCR modulation possible in outer heliosheath?

Yes

No

[Scherer et al., 2011; Herbst et al., 2012; Strauss et al., 2013]

[Jokipii, 2001; Kota & Jokipii 2014]

2. Possibility of GCR modulation in outer heliosheath

Figure 4. Simulated variation of \( \approx 300 \) MeV (upper curves) and \( \approx 50 \) MeV (lower curves) GCR fluxes along the radial line directed to 30°N. Overlapping solid and dashed curves refer to \( \eta = 10^{-2} \) and \( \eta = 10^{-4} \), respectively. Dotted lines refer to \( \eta = 10^{-6} \). Note that extremely small perpendicular transport (\( \eta = 10^{-6} \)) results in a remarkably sharp increase at the HP.
Voyager 1 Observations near heliopause

[Burlaga & Ness, 2014]
Numerical Results

Intensities of 100 MeV protons in the Voyager 1 direction:
with drifts:
(A) scenarios 1–4, (B) 5–8.
without drifts:
(C) scenarios 1–4, (D) 5–8.

No modulation was found in OHS for Scenarios 1-4

Also, no apparent modulation for Scenarios 5, 7

Modulation occurs only if the diffusion in IHS and OHS are comparable for Scenarios 6, 8
Simulated GCR proton spectra at the heliopause (r = 122 AU) and in the IHS (r = 80 AU) along the Voyager 1 trajectory.

with drifts:
(A) scenarios 1–4, (B) 5–8.
without drifts:
(C) scenarios 1–4, (D) 5–8.

Scenarios 1-4, 5, 7: similarly, no modulation was found at HP; the diffusion beyond HP does not affect the modulation in the IHS.

Scenarios 6, 8: Modulation occurs
Back-in-time trajectories of 180 MeV/n GCR pseudo-particles terminating at 122 AU (red circles) along the Voyager 1 direction for Scenario 1, $\eta = 2 \times 10^{-6}$ in the OHS.

(A, B): with drift motion included, (C, D): with drifts turned off. Trajectory color shows travel time in years, with termination points corresponding to $t = 0$.

overwhelming majority

very few ($\sim 0.1\%$ with drift, $\sim 0.01\%$ without drift)
Conclusions

1. Our results clearly show that there is no change in GCR intensity beyond the heliopause for any physically reasonable value of the scattering mean free path in the outer heliosheath. This is fully consistent with the theoretical prediction of Jokipii (2001) and the simulation results of Kota & Jokipii (2014), but disagree with the picture of GCR modulation in OHS from [Scherer et al, 2011], [Herbst et al., 2012], and [Strauss et al. (2013)].
2. Simulation of GCR intensity near heliopause

Step-like Increase of GCR Intensity from Voyager 1

[Webber & McDonald, 2013]
Intensities of 180 MeV/n GCR protons observed near the heliopause by Voyager1 (diamonds) and the simulation results (solid and dashed lines) for diffusion Models 1–4 using two different perpendicular to parallel diffusion ratios beyond the heliopause, \( \eta = 0.02 \) and \( 2 \times 10^{-6} \).

(A) without drift
An extremely small perpendicular diffusion coefficient in the OHS is necessary to match the magnitude of the increase

(B) with drift.
Drifts along the HCS and the heliopause could restore the intensities to the levels comparable with Voyager 1 observations.
Differential intensity of 180 MeV GCR protons near the heliopause in the Voyagers 1 (blue) and Voyager 2 (red) directions. Solid and dotted lines represent simulation results with and without the drift terms, respectively. The two vertical dashed lines show the locations of the heliopause at about 112 AU and 122 AU in the two directions, respectively.
Conclusions

1. Our results clearly show that there is no change in GCR intensity beyond the heliopause for any physically reasonable value of the scattering mean free path in the outer heliosheath. This is fully consistent with the theoretical prediction of Jokipii (2001) and the simulation results of Kota & Jokipii (2014), but disagree with the picture of GCR modulation in OHS from [Scherer et al, 2011], [Herbst et al., 2012], and [Strauss et al. (2013)].

2. We also simulated the narrow step-like increases (treated in a simplified manner as a single large increase) of 180 MeV protons observed by Voyager 1 before its encounter with the heliopause. A small $K_\perp$ leads to abnormally low GCR intensities inside the heliosphere. We found that drifts along the heliospheric current sheet and the heliopause could restore the intensities to the levels comparable with Voyager 1 observations, and the resulted size of the intensity increase is in good agreement with the observations.