Entering the “magnetic highway”: energetic particle anisotropies at the heliospheric boundary

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Received ___________; accepted ___________
ABSTRACT

In August of 2012 the Voyager 1 space probe entered a distinctly new region of space characterized by a virtual absence of heliospheric energetic charged particles and magnetic fluctuations, dubbed a “magnetic highway”. Prior to their disappearance, the particle distributions strongly peaked at a 90° pitch angle implying a faster particle escape along the magnetic field lines. We investigate the process of particle crossing from the heliosheath region into the “magnetic highway” region using a kinetic approach resolving scales of the particle’s cyclotron radius and smaller. We show that a “loss-cone” type distribution naturally arises as the orbiting particles enter a region of space with an extremely low pitch-angle scattering rate.

Subject headings: cosmic rays — magnetic fields — turbulence — solar wind
1. Introduction

Since the end of 2004, the Voyager 1 space probe has been exploring the region of
space downstream of the solar wind termination shock, known as the heliosheath (e.g.,
Stone et al. 2005; Decker et al. 2005). Observations showed that the heliosheath plasma
is generally in a turbulent state (Burlaga & Ness 2010) with the mean magnetic field
magnitude increasing with heliocentric distance from some 1 \( \mu \)G just beyond the shock
(94 AU) to about 3 \( \mu \)G by mid-2012 when the spacecraft was at 122 AU from the Sun
(Burlaga & Ness 2012). The heliosheath is permeated by energetic ions with energies below
several MeV, produced inside the heliosphere from interstellar material (neutral atoms) and
accelerated at the termination shock (e.g., Decker et al. 2008; Florinski et al. 2009).

Starting in August of 2012, the HEP intensity experienced a series of rapid drops
and increases after which they disappeared altogether (Stone 2012; Decker et al. 2012b).
The last event was accompanied by a jump in the magnetic field strength from 3 \( \mu \)G to
4 \( \mu \)G without a change in direction (Burlaga & Ness 2012). Remarkably, the magnetic
field became very smooth after crossing the boundary with turbulent fluctuations virtually
absent. Such a change in the properties of the magnetic field was expected to happen across
the heliopause since it was generally thought that interstellar turbulence existed on vastly
greater scales (Armstrong et al. 1995). The absence of magnetic field rotation casts some
doubt on the interpretation that the boundary just crossed is indeed the heliopause. It is
clear, however, that particle escape along the field lines in the new region is very efficient,
which prompted the name “magnetic highway” (MH). It is not clear at this time whether
the new region is part of the heliosphere or the interstellar cloud around it, because of
the nonfunctional plasma instrument on Voyager 1. In the scenario discussed below this
difference is of no significance as long as the magnetic field remains turbulence free beyond
the boundary.
In this Letter we simulate the process of energetic particle crossing from a turbulent region (the heliosheath) into a laminar region (the MH or LISM). Specifically, we propose an explanation for the observational result that the intensity of particles streaming along the magnetic field decreased faster than those gyrating at nearly 90° angles resulting in a double loss cone pitch-angle distribution (Cummings et al. 2012). Because the HEP intensity changes occurred on short time scales (i.e., comparable to $V_{V1}/r_g$, where $V_{V1}$ is Voyager 1 speed and $r_g$ is the cyclotron radius of a typical HEP ion), a model must be capable of resolving scales of $r_g$ and smaller. A diffusive approach is obviously invalid here because the particle populations were highly anisotropic immediately beyond the boundary. Using a fully kinetic approach in a simple numerical model we show that a flattened pitch-angle distribution is a natural consequence of gyrating particles traveling farther from the boundary before escaping under scatter-free conditions.

2. The kinetic transport model

The large-scale geometry of our model is illustrated schematically in Figure 1. We consider a narrow region immediately adjacent to the boundary on either side. The $x$-axis is normal to the boundary and the $z$-axis is in the direction of the mean magnetic field. It is assumed that the magnetic field lines in the MH region are pressed against the boundary for a distance $z_{max}$ (the “connection region” in Fig. 1) after which they separate from the boundary. A particle reaching the end of the connection region is assumed to escape the region and is removed from the system.

The background plasma velocity indirectly measured by Voyager 1 was very small during 2010–2012 (Krimigis et al. 2011; Decher et al. 2012). For simplicity we assume here that the plasma velocity is zero on both sides of the boundary (this assumption is not critical as long as the plasma speed is much less than the particle velocity $v$, which is
Fig. 1.— An illustration of the particle transport model geometry. We consider a narrow “connection region” where the magnetic field presses against the boundary.
usually satisfied everywhere in the heliosheath). We take the mean field to be \( B_{\text{HS}} = 3 \mu G \) and \( B_{\text{MH}} = 4 \mu G \) on the heliosheath side, and the MH side of the boundary, respectively.

The general Boltzmann equation describing energetic particle transport in a magnetized plasma with turbulent fluctuations may be written as

\[
\frac{\partial f}{\partial t} + \boldsymbol{v} \sqrt{1 - \mu^2} \cos \varphi \frac{\partial f}{\partial x} + v\mu \frac{\partial f}{\partial z} - \Omega \frac{\partial f}{\partial \varphi} = Sf, \tag{1}
\]

where \( f(x, z, \mu, \varphi) \) is the phase space density, \( \mu \) is the pitch-angle cosine, \( \varphi \) is the gyrophase, and \( \Omega \) is the cyclotron frequency. The operator \( S \), describing particle scattering in solid angle, could be obtained from the theory of wave-particle interaction (e.g., Jokipii 1972).

The transport across the magnetic field is produced entirely by scattering of the particles in gyrophase. Because the plasma is stationary, there is no electric field and the energy of the particles is assumed to be conserved.

For simplicity we adopt a model with an isotropic scattering operator,

\[
Sf = D \frac{\partial}{\partial \mu} \left[ (1 - \mu^2) \frac{\partial f}{\partial \mu} \right] + D \frac{\partial^2 f}{1 - \mu^2 \partial \varphi^2}, \tag{2}
\]

where \( D \) is the scattering coefficient. The parallel mean free path corresponding to (2) is \( \lambda_\parallel = v\tau \), where \( \tau = (2D)^{-1} \) is the scattering rate. For large \( \Omega \tau \) used here the transport is predominantly along the magnetic field (e.g., Forman et al. 1974). Equation (1) is solved numerically along the characteristics using a stochastic integration method (e.g., MacKinnon & Craig 1991; Florinski & Pogorelov 2009). Instead of using Eq. (2) directly, we use the random walk on a sphere technique of Ellison et al. (1990) that avoids the singularity at \( \mu = \pm 1 \). For small scattering angles the process is identical to a two-dimensional random walk on a plane.
3. Intensity and pitch-angle distributions

We performed a series of simulations varying the scattering rates, $D_{\text{HS}}$ and $D_{\text{MH}}$, and the length of the connection regions $z_{\text{max}}$, within a sufficiently wide range. Figure 2 shows a typical result for 1 MeV protons obtained with $D_{\text{HS}} = 10^{-3}$ s$^{-1}$, $D_{\text{MH}} = 2 \times 10^{-6}$ s$^{-1}$, and $z_{\text{max}} = 32$ AU. Such a large difference in scattering rates is required to produce a noticeable difference between particles traveling at different pitch angles. The MH region is essentially scatter-free ($\lambda_{\parallel} = 23$ AU) and particles are only able to penetrate a distance comparable to $r_g = 0.0024$ AU before escaping into the LISM. Intensity profiles of $\mu = 1$ and $\mu = 0$ ions are shown with a solid and dashed lines, respectively.

The particle distribution is assumed to be isotropic at the left (heliosheath) boundary of the simulation and the two curves are almost identical up to $x = 0$. Afterwards, ions streaming along the magnetic field diminish earlier than ions near 90° pitch angle. The right (MH) boundary plays no role in the simulation because all particles exit the simulation box before reaching it. The difference in penetration depth is of the order of a cyclotron radius in the MH. We note that the result remains essentially unchanged if the ratio $D_{\text{MH}}/z_{\text{max}}$ is kept a constant. This means that the model applies for larger or smaller scattering rates as long as the unknown escape distance is adjusted accordingly.

Figure 3 plots the HEP pitch-angle distributions on the heliosheath side at $x = -0.005$ AU (solid line) and on the MH side at $x = 0.005$ AU (dashed line). The initially isotropic ion population becomes highly anisotropic past the boundary as it becomes depleted in $\mu = \pm 1$ particles. Some $\mu = 0$ particles have also scattered and escaped from the system, so that the total intensity is significantly reduced. This result is consistent with Voyager 1 observations showing a flattened (pancake like) pitch-angle ion distribution beyond the boundary (Cummings et al. 2012; Decker et al. 2012b).
Fig. 2.— Intensity profiles of $\mu = 1$ (solid line) and $\mu = 0$ (dashed line) particles as a function of distance from the boundary (the dotted line).
Fig. 3.— Pitch-angle distributions of HEPs in the heliosheath ($x = -0.005$ AU, solid line) and in the MH region ($x = 0.005$ AU, dashed line) The intensity is normalized to one at the left boundary of the simulation.
4. Discussion

In this Letter we proposed a simple model to explain the double loss cone type
distributions of MeV heliosheath particles observed immediately beyond the boundary
crossed by Voyager 1 in 2012. The model is based on a concept that particle scattering
rates are much smaller in the MH region than in the heliosheath. Particles gyrating near
$\mu = 1$ are able to penetrate deeper into the new region because of their larger gyro-radius,
whereas particles streaming along the field rapidly escape into the LISM. The model does
not require magnetic mirrors on either side of the Voyager crossing point, but only that
there exist a boundary magnetic connection region of considerable extent (a few tens of
AU). Our model is unrelated to the concept proposed by McComas & Schwadron (2012),
where the drop in energetic particle flux is a consequence of Voyager 1 leaving the region
magnetically connected to the termination shock.

Our very simple model qualitatively reproduces the observed changes in particle
distribution across the boundary. The same model may be applied to ions with higher
and lower energies by adjusting the scattering rate accordingly. The contrast between
particles traveling at 0 and $90^\circ$ pitch angles in our model appears to be less than observed.
This is primarily due to a strictly perpendicular magnetic field geometry used here. The
model therefore lacks diffusive transport across the magnetic field from magnetic field
line meandering. A proper statistical treatment of this effect on kinetic scales requires a
prescription of the complete three-dimensional turbulent magnetic field, which is beyond
the scope of this paper. Magnetic field line diffusion would make particle intensity decrease
at a slower rate. Consequently, the HEPs may be still around several $r_g$ deep into the MH
region.

Another simplification is our use of a very thin boundary between the two regions.
The boundary could be diffuse and/or turbulent, which would also make the HEP intensity
decrease slower than predicted here. It should be pointed out that the true radial extent of
the particle decrease region is unknown because of a large uncertainty in the background
plasma speed measurement. If the flow was slightly anti-sunward, the region could be very
thin (perhaps of the order of $r_g$). Irrespective to this result, we think that the basic premise
of our model (particle escape into the LISM at different rates) adequately describes the
fundamental physics of the newly discovered boundary.

This work was supported, in part, by NASA grants NNX10AE46G, NNX12AH44G,
NSF grant AGS-0955700 and by a cooperative agreement with NASA Marshall Space Flight
Center.
REFERENCES

Armstrong, J. W., Rickett, B. J., & Spangler, S. R. 1995, ApJ, 443, 209

Burlaga, L. F., & Ness, N. F. 2010, ApJ, 725, 1306

Burlaga, L. F., & Ness, N. F. 2012, Abstract SH14B-01 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.

Cummings, A. C., Stone, E. C., McDonald, F. B., Heikkila, B., Lal, N., & Webber, W. R., 2012, Abstract SH14B-05 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.

Decker, R. B., Krimigis, S. M., Roelof, E. C., & Hill, M. E. 2012, Nature, 489, 124

Decker, R. B., Krimigis, S. M., Roelof, E. C., & Hill, M. E. 2012, Abstract SH11A-2194 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.

Decker, R. B., Krimigis, S. M., Roelof, E. C., Hill, M. E., Armstrong, T. P., Gloeckler, G., Hamilton, D. C., & Lanzerotti, L. J. 2005, Science, 309, 2020

Decker, R. B., Krimigis, S. M., Roelof, E. C., Hill, M. E., Armstrong, T. P., Gloeckler, G., Hamilton, D. C., & Lanzerotti, L. J. 2008, Nature, 454, 67

Ellison, D. C., Jones, F. C., & Reynolds, S. P. 1990, ApJ, 360, 702

Florinski, V., Decker, R. B., le Roux, J. A., & Zank, G. P. 2009, Geophys. Res. Lett., 36, L12101

Florinski, V., & Pogorelov, N. V. 2009, ApJ, 701, 642

Forman, M. A., Jokipii, J. R., & Owens, A. J. 1974, ApJ, 192, 535

Jokipii, J. R. 1972, ApJ, 172, 319
Krimigis, S. M., Roelof, E. C., Decker, R. B., & Hill, M. E. 2011, Nature, 474, 359

MacKinnon, A. L., & Craig, I. J. D. 1991, A&A, 251, 693

McComas, D. J., & Schwadron, N. A. 2012, ApJ, 758, 19

Stone, E. C. 2012, Abstract SH13D-01 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.

Stone, E. C., Cummings, A. C., McDonald, F. B., Heikkila, B. C., Lal, N., & Webber, W. R. 2005, Science, 309, 2017

This manuscript was prepared with the AAS \LaTeX macros v5.2.