Cosmic Ray Transport in the Distant Heliosheath

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Abstract: The character of energetic particle transport in the distant heliosheath and especially in the vicinity of the heliopause could be quite distinct from the other regions of the heliosphere. The magnetic field structure is dominated by a tightly wrapped oscillating heliospheric current sheet which is transported to higher latitudes by the nonradial heliosheath flows. Both Voyagers have, or are expected to enter a region dominated by the sectored field formed during the preceding solar maximum. As the plasma flow slows down on approach to the heliopause, the distance between the folds of the current sheet decreases to the point where it becomes comparable to the cyclotron radius of an energetic ion, such as a galactic cosmic ray. Then, a charged particle can effectively drift across a stack of magnetic sectors with a speed comparable with the particle's velocity. Cosmic rays should also be able to efficiently diffuse across the mean magnetic field if the distance between sector boundaries varies. The region of the heliopause could thus be much more permeable to cosmic rays than was previously thought. This new transport proposed mechanism could explain the very high intensities (approaching the model interstellar values) of galactic cosmic rays measured by Voyager 1 during 2010-2011.

Keywords:

1 Introduction

The years 2009–2011 marked the solar minimum in the outer heliosphere. During this period intensities of galactic cosmic-ray protons and alpha particles measured by Voyager 1 rose to record high levels. At the time of this writing Voyager 1 is at 117 AU heliocentric distance, which is at least 23 AU beyond the termination shock. There is evidence from plasma flow velocity decrease [5] that the spacecraft may be close to the heliopause and is observing a nearly pristine interstellar flux of galactic ions. This interpretation, however, is not consistent with models of the global heliosphere that predict a heliosheath thickness of $\sim$45 AU in the nose direction [9].

Galactic cosmic ray intensity was expected to be attenuated by a wall of enhanced magnetic field near the heliopause [8, 7]. Magnetic field magnitudes measured by Voyager 1 up to 2010 [2] are not consistent with the values predicted for the magnetic wall [1], which could indicate that the spacecraft is still far away from the heliopause. Below we show that the magnetic wall is actually quite permeable to cosmic rays in the region dominated by the tightly folded neutral sheet. The new transport process, first discussed in [6] provides a natural solution to the problem of cosmic ray intensity enhancement in the distant heliosheath.

2 Magnetic field structure in the heliosheath

Because the radial flow velocity vanishes on approach to the heliopause, plasma has a long (several decades) residence time in the heliosheath. The heliosheath is characterized by nonradial flows as the plasma is deflected away from the radial direction by the obstacle (the heliopause). The heliospheric current sheet is stretched in the latitudinal direction. The process is illustrated in Figure 1, which shows the shape of the current sheet projected onto the meridional plane. This result was obtained using tracers embedded in a 3D flow structure produced from an MHD-neutral model of the global heliosphere [6]. The initial tilt angle at the Sun was 20° in this simulation. One can clearly see an increase in the latitudinal extent of the current sheet in the heliosheath and a compression of the magnetic sectors. Similar results have been previously obtained by [4, 1].

In 2010, Voyager 1 was above the northward extent of the current sheet in the supersonic solar wind, but most likely well inside the extended sheet structure shown in Figure 1 [2]. It was shown [6] that energetic charged particles acquire a degree of mobility across the stack of magnetic sectors once the width of the sector d becomes less than $2r_g$, where r_g is the gyroradius. For a 160 MeV proton, this condition means a sector width of less than 0.25 AU assuming a background field intensity of $|\mathbf{B}| = 0.1$ nT. In

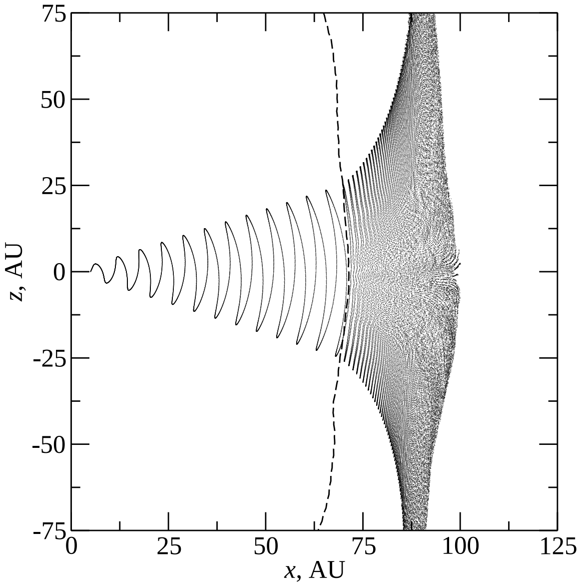

Figure 1: A projection of the heliospheric current sheet onto the meridional plane. The termination shock is shown with a dashed line (from [6]).

the solar wind sectors are about 3 AU apart and their width decreases to under 1 AU downstream of the termination shock. The width continues to decrease into the heliosheath without a comparable increase in the magnitude of $\mathbf{B}$ (the excess plasma escapes between the current sheet to higher latitudes). It is likely that the condition $d < 2r_g$ is satisfied at the current position of Voyager 1. As we show in the following section, cosmic ray ions experience enhanced transport across a stack of closely spaced sectors. This is an essentially kinetic process that depends on a particle's gyrophase. It is not captured with a nearly isotropic (Parker) model of cosmic ray transport [10].

3 Cosmic ray drift and diffusion in a sectored field

When the condition $d < 2r_g$ is satisfied, a charged particle is unable to close its gyroorbit inside one sector and will cross into an adjacent sector of opposite magnetic polarity. The guiding center then undergoes drift motion both parallel to the current sheets and across the sectors. When the sectors all have the same width d, the drift velocity in the perpendicular direction is given by [6]

$$v_{dx} = \frac{vdeB}{pc(\pi - \phi_1 - \phi_2)}, \tag{1}$$

where e is the particle's charge, v velocity, p momentum, and ϕ_1, ϕ_2 are the gyrophases corresponding to the trajectory crossing points with two adjacent current sheets. The drift is bi-directional, i.e., particles can cross the stack of sectors both left-to-right and right-to-left, depending on their initial position and gyrophase.

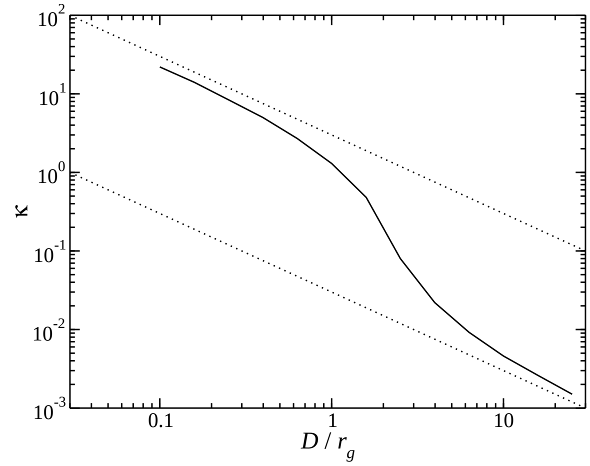

Figure 2: Cross-sector diffusion coefficient κ_{xx} as a function of sector width relative to the gyroradius. The normalization chosen is $r_g = 1$ and $v = 1$. Dotted lines correspond to $\kappa_{xx} \sim D^{-1}$.

Magnetic sectors observed by the Voyagers in the solar wind have variable widths with about a factor of 10 difference between the shortest and the longest sectors [3]. When the sector width varies in a random way, cosmic rays undergo random walk (diffusion) in the cross-sector direction. Particles reverse the direction of drift motion when the next sector encountered is wider than their gyroradius. Suppose the sectors are, on average, parallel to the yz plane with the magnetic field $\mathbf{B} = \pm B\hat{y}$. The trajectory of the particle's guiding center $\xi(t)$ in the direction perpendicular to the sectors (x) is described by the following relation:

$$\xi_{n+1} = \begin{cases} d_n - \xi_n, & d_n - \xi_n < r_g, \\ \xi_n, & d_n - \xi_n > r_g, \end{cases} \tag{2}$$

$$t_{n+1} = \begin{cases} t_n + \frac{r_g}{v}\left(\pi - \cos^{-1}\frac{\xi_n}{r_g} - \cos^{-1}\frac{d_n - \xi_n}{r_g}\right), \\ \qquad d_n - \xi_n < r_g, \\ t_n + \frac{2r_g}{v}\left(\pi - \cos^{-1}\frac{\xi_n}{r_g}\right), \\ \qquad d_n - \xi_n > r_g, \end{cases} \tag{3}$$

where the index n refers to nth sector. The turn-around condition is $d_n - \xi_n > r_g$.

Guiding center motion is strictly diffusive if d_n is a random variable. In [6] sector widths were uniformly distributed between 0 and D. A trajectory calculated according to (2)–(3) has no memory of sectors encountered previously (before a trajectory reversal). A particle's guiding center drifts along the sector boundaries (the z direction), which implies that the sector width must also vary randomly in the z direction (i.e., with latitude).

Here we extend the analysis of [6] with a series of guiding center trajectory simulations to reveal the dependence of the current-sheet diffusion coefficient on sector width and particle's gyroradius. Figure 2 plots the dimensionless diffusion coefficient κ_{xx}, calculated by fitting the mean square

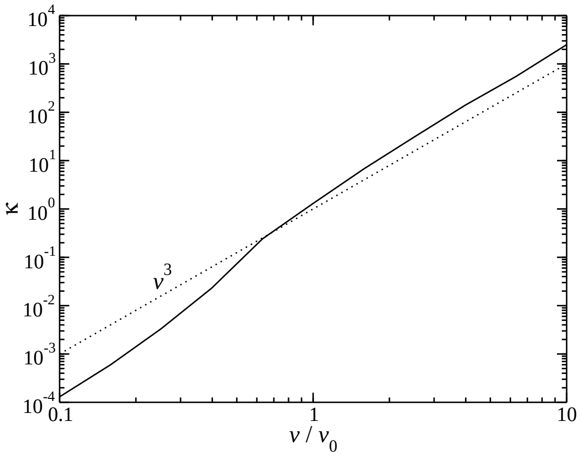

Figure 3: Cross-sector diffusion coefficient κ_{xx} as a function particle's speed. Here v_0 corresponds to $r_g = D$. Dotted line is $\kappa_{xx} \sim v^3$.

displacement $\langle(x - \langle x\rangle)^2\rangle$ with a power law with index 1 in time, as a function of d/r_g (for a fixed r_g). The dependence is asymptotically $\kappa_{xx} \sim D^{-1}$ at large and small D/r_g with a rapid transition near $D/r_g = 1$. Evidently, when the sector width is large, particles tend to drift along a single current sheet and their cross-sector transport is suppressed.

The second set of simulations reveals the dependence of diffusion on particle's velocity. The result for $\kappa_{xx}(v)$is shown in Figure 3. Here v_0 corresponds to a gyroradius $r_g = D$. Velocity dependence is well approximated with a cubic fit at large and small v with a more rapid transition in between. Using $B = 0.1$ nT and $D = 0.2$ AU yields a perpendicular diffusion coefficient $\kappa_{xx} = 1.5 \times 10^{22}$ cm^2/s for a 160 MeV proton. This value is well in excess of the perpendicular diffusion coefficient predicted by the NLGC theory [13]. We conclude that cross-field diffusion in the tightly compressed sector field in the heliosheath is very efficient which could explain the evident lack of cosmic-ray attenuation in the distant heliosheath.

4 The effect of solar cycle in the distant heliosheath

Owing to long plasma residence times in the heliosheath, a record of the entire previous solar cycle is preserved in a compressed form [11, 12]. Using the tracer method, we performed a simulation of the current sheet with a variable tilt angle α given by following expression

$$\alpha = 7 + 36.5 \left(1 + \sin \frac{2\pi t}{T}\right), \tag{4}$$

where $T = 11$ yrs and the angles are in degrees. Figure 4 shows the minimum (southward) and maximum (northward) extent of the heliospheric current sheet during a time near a negative solar minimum in the inner heliosphere.

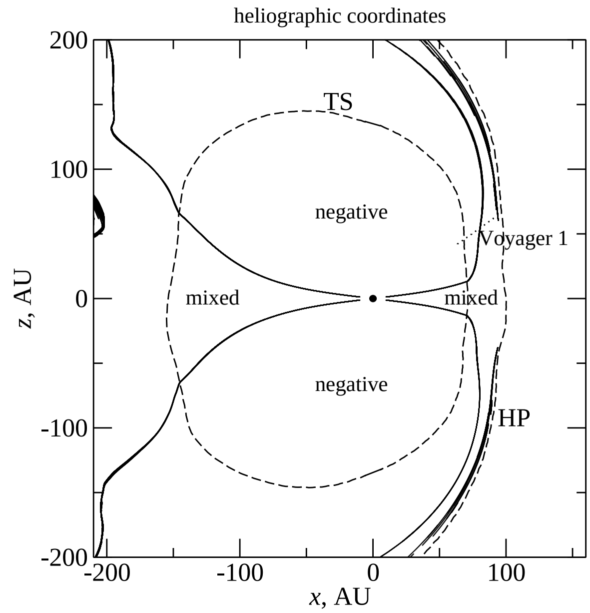

Figure 4: Regions of different magnetic polarities at the time of a negative solar minimum in the inner heliosphere. The projections of the termination shock and heliopause on the meridional plane are shown with dashed lines. The dotted line is Voyager 1 trajectory.

The two lobes in the north and south are regions of uniform polarity (toward the Sun in the north and away in the south). The near-equatorial region in between is filled with a warped current sheet and has mixed magnetic polarity. This regions extends to high latitudes in the heliosheath (a) because of the increase in the tilt angle toward the previous solar maximum and (b) because the warped current sheet is carried to higher latitudes by latitudinal flows in the heliosheath.

The current sheet tilt was low during the previous positive solar minimum around 1996. Solar wind plasma ejected by the Sun during that minimum is still traversing the heliosheath. This region is represented by two thin slices descending toward the ecliptic from high latitudes in the north and in the south in Figure 4. Voyager 1 trajectory passes above the lowest latitude of the 1996 solar minimum region. Given that the plasma velocity is near zero at Voyager 1 [5], the spacecraft may well be sampling parcels of solar wind emitted at increasingly earlier times. It is even conceivable that Voyager 1 will revisit the previous solar minimum in the heliosheath before its encounter with the heliopause.

5 Discussion

Conditions in the heliosheath vary on slower time scales than in the supersonic solar wind. One cannot easily characterize these conditions as specific to the solar minimum or solar maximum because both are present at the same time. Voyager 1 may now be sampling solar wind emitted by the Sun during the descending phase of solar cycle 23. In the framework of this model, one can even interpret the long positive sector observed by Voyager 1 at the end of 2009 [2] as an encounter with the positive unipolar region shown in Figure 4.

The tightly folded heliospheric current sheet is expected to dominate cosmic-ray transport near the heliopause, at least at low and mid latitudes. As the magnetic sectors become thinner, particles acquire mobility in the perpendicular direction allowing them to cross the modulation wall with relative ease. This process could be responsible for the record high galactic cosmic ray intensities measured by the Voyager probes during the past two years.

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References

[1] Borovikov, S. N., et al., Astrophys. J., 2011, **728**: L21

[2] Burlaga, L. F., Ness, N. F., Astrophys. J., 2010, **725**: 1306-1316

[3] Burlaga, L. F., Ness, Richardson, J. D., 2003, J. Geophys. Res., **108**: 8028

[4] Czechowski, A., et al., Astron. Astrophys., 2010, **516**: A17

[5] Decker, R. B., et al.: 2010, Pickup Ions Throughout the Heliosphere and Beyond, ed. le Roux et al., AIP

[6] Florinski, V., Adv. Space Res., 2011, **28**: 308-313

[7] Florinski, V., Pogorelov, N. V., Astrophys. J., 2009, **701**: 642-651

[8] Florinski, V., Zank, G. P., Pogorelov, N. V., J. Geophys. Res., 2003, **108**: 1228

[9] Heerikhuisen, J., et al., Astrophys. J., 2008, **682**: 679-689

[10] Kota, J., Jokipii, J. R., Astrophys. J., 1994, **429**: 385-390

[11] Nerney, S., Suess, S. T., Schmahl, E. J., J. Geophys. Res., 1995, **100**: 3463-3471

[12] Pogorelov, N. V., et al., Astrophys. J., **696**: 1478–1490

[13] Zank, G. P., et al., J. Geophys. Res., 2004, **109**: A04107