The Solar Wind Termination Shock and the Outer Heliosphere

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Abstract

Beginning in mid-2002, Voyager 1 observed an extended period of field-aligned flows of low energy ions and electrons that was unlike previous observations, suggesting that the spacecraft was in the vicinity of the solar wind termination shock. However, the observations differed from expectations and have resulted in differing interpretations as to whether or not Voyager 1 crossed the termination shock and entered the subsonic flow in the heliosheath for a seven month period. The puzzling aspects of the observations suggest that the shock is more complex and dynamic than generally expected and that there could be more surprises as Voyager 1 will likely encounter the shock several times before durably entering the heliosheath sometime in the next few years.

1. Introduction

Two Voyager spacecraft were launched in 1977 on a journey of exploration of Jupiter, Saturn, Uranus, Neptune, and the outer heliosphere. We were fortunate that this alignment of the giant planets was such that the Voyager spacecraft are headed in the general direction of the nose of the heliosphere where the solar wind and the interstellar wind meet (see Figure 1). In July 2002 Voyager 1 was at 85 AU and Voyager 2 at 68 AU, with radial speeds of 3.6 and 3.1 AU per year.

The size of the heliosphere is determined by the pressure balance between the outward supersonic expansion of the solar wind and the pressure in the local interstellar cloud that surrounds the Sun. The distance to the termination shock will vary by $\geq$10 AU as the dynamic pressure of the solar wind varies over the solar cycle. Because of uncertainties in these pressures, the distances to the termination shock and heliopause are not precisely known. However, a summary of recent estimates [2] suggests that the termination shock may be at 90$\pm$10 AU, indicating that Voyager 1 may now be in the vicinity of the termination shock.

2. Energetic Particle Observations

In mid-2002, when Voyager 1 was at 85 AU, an unusual enhancement of low energy ions and electrons was observed [3,4]. Prior to mid-2002, the intensity

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of low energy protons at the two spacecraft exhibited similar variations with a quasi-periodicity of ∼140 days and an intensity at Voyager 1 that was typically 40% of that at Voyager 2 (Fig. 2). However, in mid-2002 the intensity at Voyager 1 increased by a factor of ∼100, with no corresponding increase at Voyager 2. The increase persisted for seven months, suggesting that Voyager 1 was in the vicinity of the termination shock.

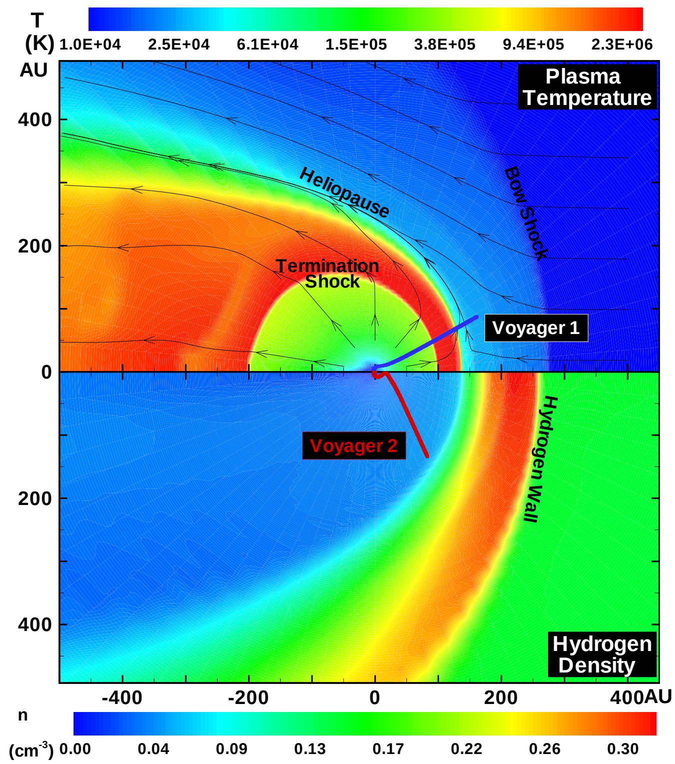

Fig. 1. An MHD model of the heliosphere [1] showing the range of plasma temperatures (top) and hydrogen densities (bottom) in a plane through the nose of the heliosphere and perpendicular to the ecliptic. The ions in the interstellar wind approaching from the right are deflected around the heliosphere as indicated by the flow lines. Interstellar neutral atoms such as hydrogen flow deep into the heliosphere, although some of the H atoms charge exchange with the interstellar H^+ ions to form a hydrogen wall between the bowshock and the heliopause. The heliospheric bubble is created by the radial outflow of the supersonic solar wind. As the solar wind approaches the heliopause, a termination shock forms as the wind abruptly slows, forming a heliosheath of hot (10^6 K), subsonic plasma that is deflected toward the heliospheric tail as indicated by the flow lines. The trajectories of Voyager 1 and 2 are projected onto the plane, illustrating that one is headed upward and the other downward out of the ecliptic.

There were highly anisotropic flows of energetic particles in the azimuthal direction during this period of enhanced intensities (Fig. 3). This is consistent

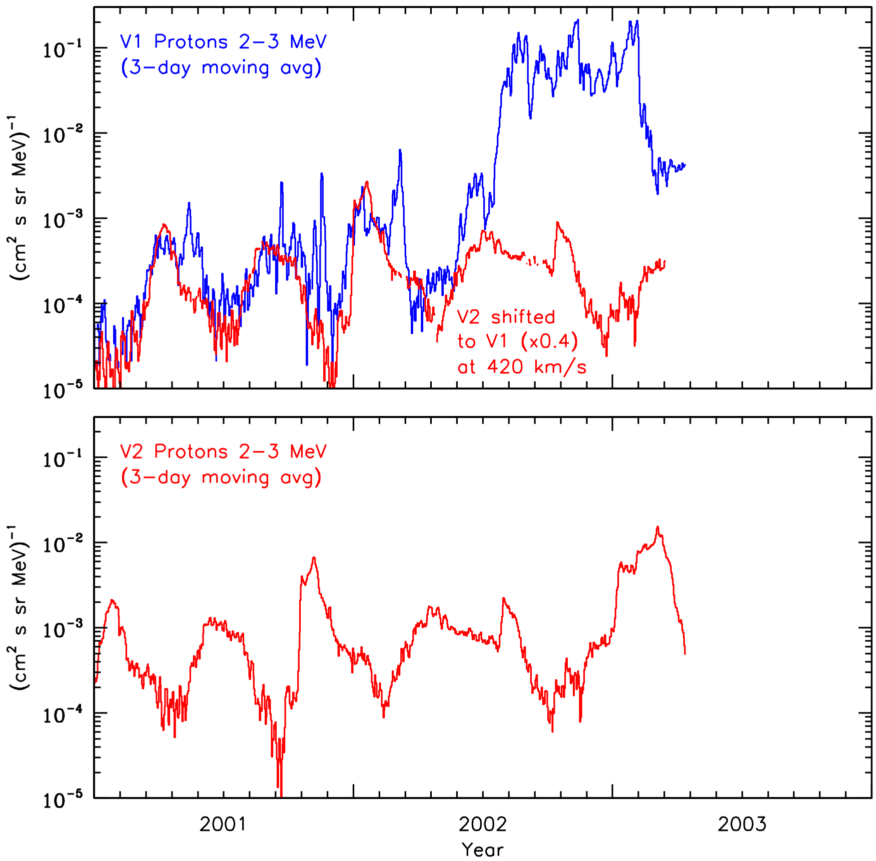

Fig. 2. The intensity of protons with 2-3 MeV observed by the Cosmic Ray Subsystem on Voyager 1 and 2 [4]. The intensity at Voyager 2 is shown as observed in the lower panel and is also shown in the top panel with a delay corresponding to a convection speed of 420 km s^{-1} from Voyager 2 to Voyager 1. The Voyager 2 intensities have also been multiplied be 0.4 to match those at Voyager 1, corresponding to a radial gradient of -5.5% per AU.

with a strong flow of particles along the interplanetary magnetic field which is essentially azimuthal at this radial distance [5]. Similar azimuthal flows are observed for ions over broad range of energies as shown in Figure 4. The direction of the flow is outward along the magnetic field, indicating that the source is radially inward of Voyager 1. However, the symmetry axis of the average flow in is sector 7, offset by 22° from the direction of the magnetic field that is expected to be azimuthal on the average.

In the absence of inward radial diffusive flow, outward convection of the energetic particles by the solar wind would produce an observed radial anisotropy (the Compton-Getting anisotropy) with an amplitude $\delta_{\rm CG} = 2(1-\gamma)V_{\rm SW}/v$, where $\rm V_{SW}$ is the speed of the solar wind, v the particle speed, and γ the power law index

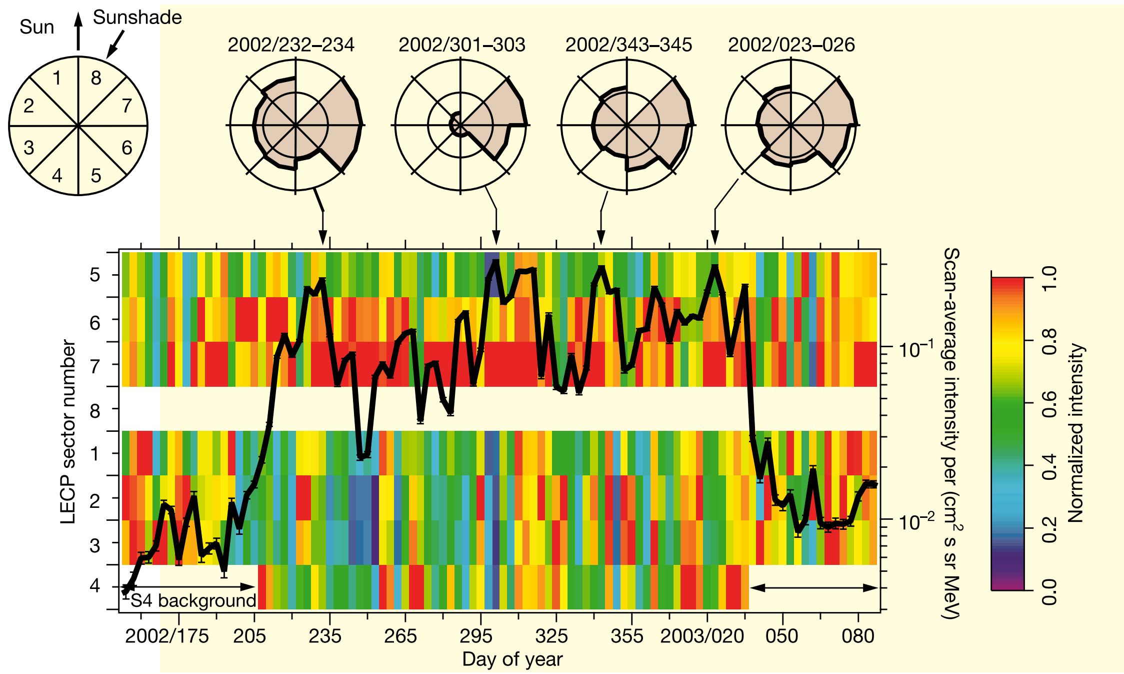

Fig. 3. The anisotropic flow of protons with 0.57-1.78 MeV observed by the Low Energy Charged Particle System on Voyager 1 [3]. A sensor telescope is stepped through eight sectors in a plane nearly parallel to the R-T plane in the [R,T,N] coordinate system with the R-axis radially outward, the T-axis azimuthal, and the N-axis meridional. The solid line in the lower panel shows the intensity (daily averages). It is superimposed on a gray scale panel that displays the relative intensities in each sector, normalized to the maximum sector on a daily basis. Also shown at the top are the sectored rates for four three-day periods selected for high intensities. Typically the highest intensities occurred in sector seven, corresponding to very strong beams that are nearly azimuthal.

of the energy spectrum. Kane et al. [6] have shown that the solar wind velocity can be derived from the observed radial anisotropy using this relationship in the absence of an inward diffusive flow.

As shown by the model calculations in Figure 4, if the wind were 400 km s^{-1} and there was no inward diffusive flow, the intensities in sector 1 should be higher than observed and that in sectors 3 through 6 should be much lower. Based on this analysis, Krimigis et al. [3] conclude that the wind speed must have been $<$50 km s^{-1} during this period, indicating that Voyager 1 crossed the termination shock on 2002/213 at 85 AU and remained in the subsonic heliosheath until the shock moved back past the spacecraft on 2003/38. The direction of the field-aligned anisotropy is consistent with the outward flow of particles from a shock that is radially inside Voyager 1.

An alternative interpretation [4,5] is that the radial component of the large

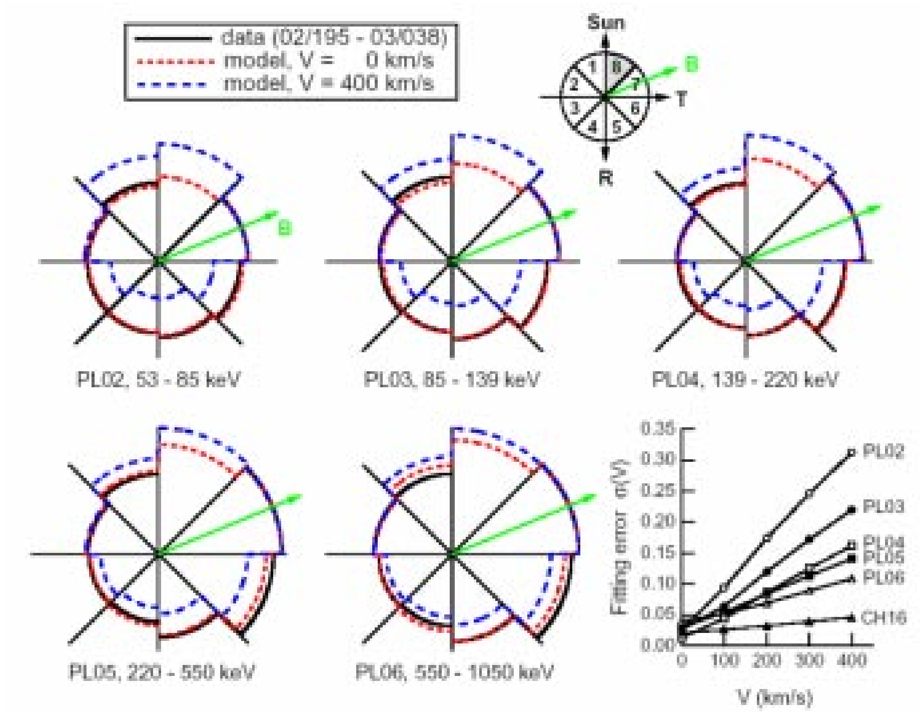

Fig. 4. Normalized sector counting rates averaged over the entire 209-day period of enhanced intensities [3]. The intensity is a maximum in sector seven at all energies. Also shown by the shorter and longer dashes are the predicted angular distributions assuming that the particle distribution is gyrotropic about an axis of symmetry (shown as the arrow in sector seven) in a solar wind frame having a speed of either 0 or 400 km s^{-1}.

field-aligned streaming also contributes to the radial anisotropy as the magnetic field varies about its average azimuthal direction. Although the field-aligned anisotropies (see, e.g., sectors 6 and 7 in Fig. 3) and the resulting radial components (e.g., sectors 1, 4, and 5) are highly variable on a daily basis, on the average they result in an inward radial flow that is determined by the requirement that intensity and the radial anisotropy due to convection and diffusion must be continuous across the shock [7]. Thus, on the average the observed radial anisotropy within ~10 AU upstream of the shock should be equal to that downstream in the subsonic heliosheath flow.

The energy spectra were another unexpected aspect of the observations. It is generally agreed that anomalous cosmic rays (ACRs) are accelerated at the termination shock, so it was expected that the ACR spectra at the shock would be a power law, with an exponential roll off at high energies as shown by the dotted lines for H and He in Figure 5. During the period of enhanced intensities at Voyager 1, the ACR He intensities at energies below ~20 MeV/nucleon are lower

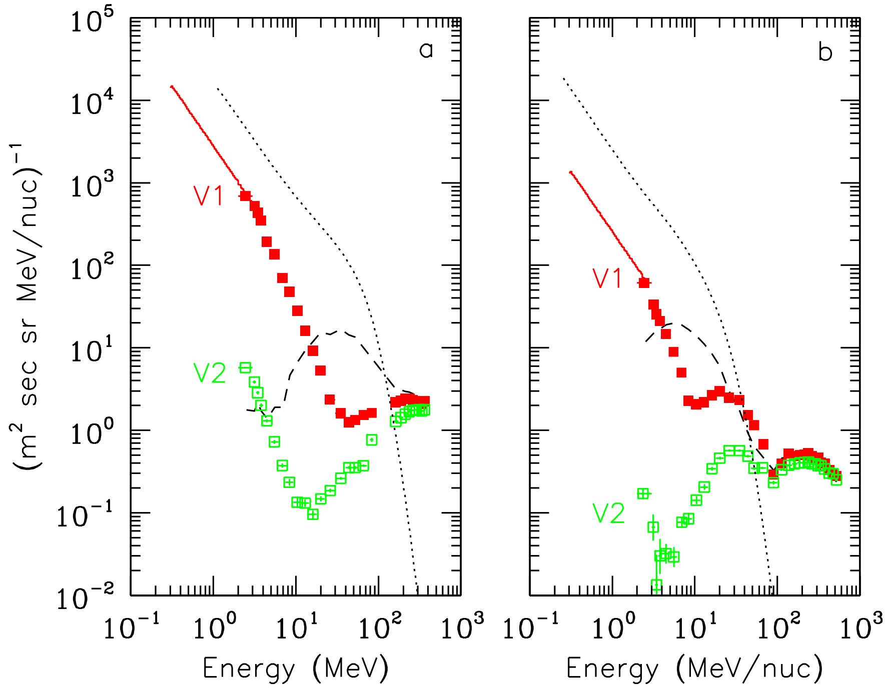

Fig. 5. Voyager 1 and 2 spectra [4] of hydrogen (a) and helium (b) for the period 2002/209 to 2002/364. Also shown are the predicted source spectra at the shock [8] for a weak shock (dotted lines) and the spectra observed by Voyager 1 between 69 and 74 AU during solar minimum in 1998/1 to 1999/182 (dashed lines). Galactic cosmic rays dominate the spectra above ∼100 MeV/nucleon, while ACR He dominates from ∼10 to ∼100 MeV/nucleon. The unusual enhancement at Voyager 1 is apparent below ∼40 MeV for H and below ∼10 MeV/nucleon for He.

than were observed at minimum solar modulation at a greater distance from the shock and less than 0.1 of the predicted intensity at the shock. Similarly, the intensity of H with 5 MeV is only 0.1 of what was observed at solar minimum and only ∼0.01 of the predicted intensity at the shock. Thus, there is evidence of strong residual modulation of intermediate-energy ACRs during the period when lower energy particles are enhanced at Voyager 1. This and other factors, such as the magnetic field discussed below, led McDonald et al. [4] to conclude that Voyager 1 did not cross the shock, but was in the foreshock region upstream.

In summary, the energetic particle observations are in general agreement, although the conclusions differ:

- There were highly variable beams of particles with flow predominantly outward along the magnetic field.
- There are large day to day variations in the radial flow, but when averaged over the 209-day period of enhanced intensities, the radial component is

much smaller than expected from the Compton-Getting anisotropy for a 400 km s^{-1} wind speed.

- The spectral shape is much different than the simple power law expected for shock accelerated anomalous cosmic rays, and the intensities at intermediate energies are much lower than observed at the previous solar minimum.
- Krimigis et al. [3] conclude that the absence of the expected Compton-Getting anisotropy is evidence that Voyager 1 was in the heliosheath subsonic flow for seven months.
- McDonald et al. [4] conclude that diffusive field aligned flows also contribute to the radial anisotropy, consistent with the requirement that the anisotropy be continuous across the shock.

3. Magnetic Field Observations

A key signature of crossing the termination shock is the slowing of the solar wind to subsonic speeds. Unfortunately, the plasma instrument on Voyager 1 failed during the Saturn flyby in 1980, so there is no direct measurement of the speed of the solar wind. However, the azimuthal magnetic field is frozen into the solar wind plasma and should increase in proportion to the increase in plasma density as the wind slows.

The intensity of the interplanetary field is determined by the strength of the magnetic field B_1 at 1 AU, the latitude θ, and the solar wind speed V_1 at 1 AU and V at r AU. The yearly average of the field $<B>$ observed through 2001 out to 81 AU agrees to within ±15% with the predicted Parker spiral field as given by [9]

$$B_P = 419.5(B_1/rV)(1 + (419.5/V_1)^2)^{-1/2} \cos\theta \text{ nT} \tag{1}$$

The observed magnetic field for 2001 and 2002 through 2003/61 is shown in Figure 6 [10]. There is no evidence for a substantial increase in the field strength in the latter half of 2002 as compared with 2001. More specifically, the predicted field for 2002/215 to 2003/33 for V=420 km s^{-1} is 0.047±0.003 nT, consistent with the observed average field of 0.044±0.007 nT for that period. For V<50 km s^{-1}, the predicted field is >0.39±0.02 nT and is inconsistent with the observations.

Burlaga et al. [10] also show that the usual correlation of decreases in the cosmic ray intensity associated with increases in the magnetic field persists throughout the time shown in Figure 6. In particular, the field nearly doubles around 2003/35 (2002/400 in the figure) at the same time as a decrease in galactic cosmic ray intensity occurs, as expected from the passage of an interplanetary

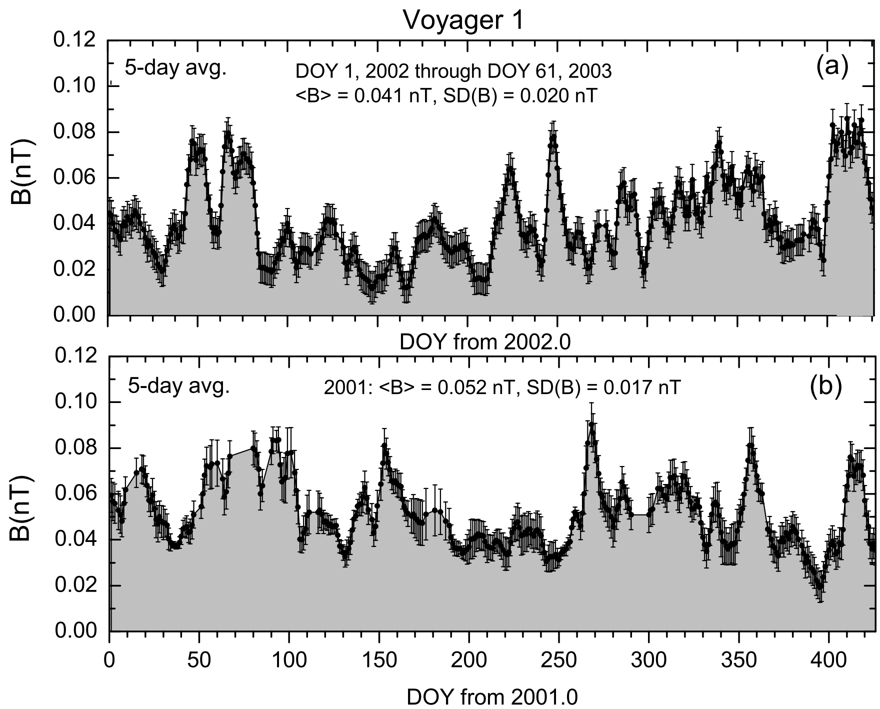

Fig. 6. Five-day moving averages of the magnetic field strength observed by Voyager 1 [10]. As indicated, the standard deviations of the running five-day averages about the indicated mean fields are 0.017 and 0.020 in 2001 and 2002 respectively. Although not shown, individual daily averages are determined with a one-sigma uncertainty of ± 0.015 nT.

disturbance [4]. As discussed above, the low energy particles also decrease significantly at this time. If this occurred because the spacecraft returned to the supersonic solar wind at that time, the field should have decreased rather than increased.

In summary, for the seven month period with enhanced intensities of low energy particles:

- The magnetic field intensity was consistent with that predicted for a solar wind speed of 420 km s^{-1}, with no evidence of the expected increased in B due to compression of the frozen in field if the speed had slowed to <50 km s^{-1}.
- The correlation of the changes in B and cosmic ray intensities was similar to previous observations; in particular the field increased when the particle intensities abruptly decreased.
- Burlaga et al. [10] conclude that the magnetic field observations do not

support the interpretation that Voyager 1 was in region of subsonic flow during the period with enhanced intensities of low energy particles.

4. Overall Summary

Beginning in mid-2002, there was an extended period of highly anisotropic field-aligned flows that was unlike any previously observed, suggesting that Voyager 1 was in the vicinity of the termination shock. The observations differed in a number of ways from what had been expected, leading to different interpretations that pose the following questions that deserve further study. All indications are that Voyager 1 is now in the supersonic solar wind, so there will be one or more future shock crossings that should help resolve some of these questions.

If Voyager 1 remained in the solar wind throughout the period:

- Why is the beaming primarily outward along the magnetic field rather than inward if the shock is beyond Voyager 1?
- Why are the intermediate energy ACRs from the shock suppressed if the low energy ions are also from the shock?
- Given that the anisotropy must be continuous across the shock, how far upstream should the anisotropy match that in the heliosheath?

If Voyager 1 was in the heliosheath for seven months:

- Why is there no compression of the magnetic field as expected if the wind slowed to <50 km s^{-1}?
- Why does the axis of symmetry of the streaming on average differ by 22° from the average direction of the magnetic field?
- Why are the intermediate energy ACRs suppressed if the low energy ions are also from the shock?

It is likely that the shock is locally perturbed by variations in the solar wind dynamic pressure [11], resulting in a complex and dynamic shock region that differs significantly from a steady spherical shock. The next few years could brings more surprises as Voyager 1 surfs along a very dynamic shock and begins exploring the heliosheath beyond.

5. Acknowledgements

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6. References

1. Zank, G. P. 1999, Space Sci. Rev. 89, 413.
2. Stone, E. C. 2001, Science 293, 55.
3. Krimigis, S. M., Decker, R. B., Hill, M. E., Armstrong, T. P., Gloeckler, G., Hamilton, D. C., Lanzerotti, L. J., and Roelof, E. C. 2003, Nature 426, 45.
4. McDonald, F. B., Stone, E. C., Cummings, A. C., Heikkila, B., Lal, N., and Webber, W. R. 2003, Nature 426, 48.
5. Cummings, A. C., Stone, E. C., Burlaga, L. F., Ness, N. F., McDonald, F. B., and Webber, W. R. 2003, Proc. 28th ICRC (Tsukuba) 7, 3777.
6. Kane, M., Decker, R. B., Mauk, B. H., and Krimigis, S. M. 1998, J. Geophys. Res. 103, 267.
7. Jokipii, J. R., Kota, J., and Merenyi, E. 1993, ApJ 405, 782.
8. Cummings, A. C., Stone, E. C., and Steenberg, C. D. 2002, ApJ 578, 194.
9. Burlaga, L. F., Ness, N. F., Wang, Y.-M., and Sheeley, Jr., N. R. 2002, J. Geophys. Res. 107(A11), 1410.
10. Burlaga, L. F., Ness, N. F., Stone, E. C., McDonald, F. B., Acuña, M. H., Lepping, R. P., and Connerney, J. E. P. 2003, Geophys. Res. L. 30, SSC 9-1.
11. Suess, S. T. 1993, J. Geophys. Res. 98, 15,147.