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ACR's and Magnetic Field at the Heliospheric Termination shock

J. R. Jokipii and J. Kóta
Departments of Planetary Sciences and Astronomy, University of Arizona, Tucson, AZ 85721
Presenter: J. R. Jokipii (jokipii@lpl.arizona.edu) usa-jokipii-JR-abs2-sh31-oral

Voyager 1 observations in the outer heliosphere and heliosheath impose important constraints on anomalous cosmic ray (ACR) acceleration at the heliospheric termination shock. The three-dimensional, vector anisotropies (radial, azimuthal and latitudinal) depend in an important way the large-scale structure of termination shock. In particular, the observations can be understood if the shape of the termination shock is not spherical, both globally and on a small scale. We have shown previously that all three components of the anisotropy may be understood if the global shape of the termination shock is as expected from simulation and analogy. Similarly, radial motion of the termination shock can change the intensity and energy spectra both upstream of the shock and in the heliosheat. Recent observations of the magnetic field from the Voyager 1 spacecraft, where, in the heliosheath, the magnetic field has remained directed outward from the Sun for several months. We show that this is a result rapid inward motion of the termination shock. The implications for the energy spectrum are also discussed.

1. Introduction

One of the most important goals of heliospheric exploration has been to observe the solar-wind termination shock, where the supersonic solar wind undergoes a sudden transition to subsonic flow, in response to the inward pressure of the local interstellar medium. Beyond the shock is the heliosheath, a region of subsonic solar outflow, where the solar plasma is deflected by the incoming interstellar plasma to flow backward toward the tail of the heliosphere. Anomalous cosmic rays (hereinafter ACR) are currently thought to be freshly-ionized interstellar neutrals accelerated at the termination shock probably by the mechanism of diffusive shock acceleration and have long been regarded as a remote probe of the termination shock Jokipii [1].

Recently, compelling observational evidence the first crossing of the heliospheric termination shock by Voyager 1 on December 5, 2004, was reported in a group of papers presented at the Spring, 2005 AGU meeting ([2, 3, 4, 5]. In these papers, a variety of observations of the heliosheath (post-shock solar wind) were reported. In particular, Burlaga [3], et al, reported the puzzling fact that the magnetic field in the heliosheath did not show any evidence of the change in sign associated with the sector structure, beginning at the time of crossing to in December, 2004 until mid-May, 2005. The sector structure had been observed to be normal in the period prior to the crossing of the termination shock. Moreover, the sense of the field was outward during this entire time. In addition, Decker [4] reported that the radial anisotropy of the low-energy anomalous-cosmic-ray particles was very small, indicating a very low plasma flow speed of less than 50 km/sec relative to Voyager 1. In addition, the energy spectrum showed *both* a power law at low energies and a modulation-related turnover of the spectrum at higher energies.

The location of the termination shock is expected to vary over a variety of temporal and spatial scales [6]. The first encounter of Voyager 1 with the termination shock occurred at such an incursion, because the incursion can move much faster than the spacecraft. The ACR spectrum, being accelerated at the shock, will fluctuate in time at any given location as the termination shock moves in and out, even if it does not cross the spacecraft.

2. Motion of the Termination Shock and the Magnetic Sector Structure

The general spiral nature of the interplanetary magnetic-field was predicted nearly 50 years ago by Parker [7] in a paper which also predicted the solar wind. The sector structure, in which the magnetic field is along the Parker spiral, but changes sign abruptly 2 or 4 times in a solar rotation, was recognized first some four decades ago from IMP-1 observations [8]. Subsequently, in the mid 1970's, observations from the Ulysses spacecraft [9] showed that the sector structure was the result of a general heliospheric current sheet which oscillated up and down in latitude about the heliographic equator and rotated with the Sun, as suggested by Schulz [10].

Hence, an observer moving slowly (as a spacecraft or planet) or at rest, in the supersonic solar wind will see this co-rotating sector structure if located closer to the equator than the maximum extent of the interplanetary current sheet at that time. If above the maximum extent of the current sheet the observer will see the appropriate polar magnetic field field with no changes in direction corresponding to sector structure.

This magnetic structure will be be convected into the heliosheath. At the termination shock we may regard the current sheet as being mainly normal to the heliographic radius vector and the solar wind vector. We assume that the local deviation of the shock normal from the radial direction is small. For simplicity, assume that the solar wind speed, V_w is a constant upstream of the termination shock. Hence, if the current sheet crosses a stationary observer in a time τ_1 , it extends a radial distance $S_1 = V_w\tau_1$, where V_w is the solar wind velocity. If we observe from a spacecraft moving radially at V_{obs}, $S = (V_w + V_{obs})\tau_1$.

If the termination shock is stationary, the radial velocity downstream of the shock, in the heliosheath, is $U_2 = V_w/r_{sh}$, where r_{sh} (≤ 4 for an ideal shock) is the shock ratio. Also, the plasma is compressed radially by the ratio r_{sh}. Since the radial velocity is also reduced by the same factor, the observed time for the sector to cross the observer is unchanged. Hence, a stationary observer will continue to see the same time between current sheet crossings, with the same temporal scale in the heliosheath as in the solar wind. Radial motion of the shock or observer will change this result.

Suppose that the shock is moving radially at a constant speed $V_{sh}\hat{e}_r$. Denoting values in the shock frame with primes, with the upstream speed being U_1', we find immediately

$$\begin{aligned} U_1' &= V_w - V_{sh} \\ U_2' &= \frac{(V_w - V_{sh})}{r_{sh}} \end{aligned} \tag{1}$$

and in the frame at rest with respect to the Sun,

$$U_2 = U_2' + V_{sh} = \frac{V_w}{r_{sh}} + \left(1 - \frac{1}{r_{sh}}\right) V_{sh} \tag{2}$$

Note that U_2 becomes negative if

$$V_{sh} < -\frac{V_w}{(r_{sh} - 1)}. \tag{3}$$

From this, for an observer moving outward at a speed V_{obs}, τ_1 and τ_2 are related by:

$$\begin{aligned} \frac{\tau_2}{\tau_1} &= \frac{V_w - V_{obs}}{r_{sh}(U_2 - V_{obs})} \\ &= \frac{V_w - V_{obs}}{V_w + (r_{sh} - 1)V_{sh} - r_{sh}V_{obs}} \end{aligned} \tag{4}$$

Note that in this expression, *both* τ_1 and τ_2 are defined with respect to the observer, moving at velocity V_{obs}.

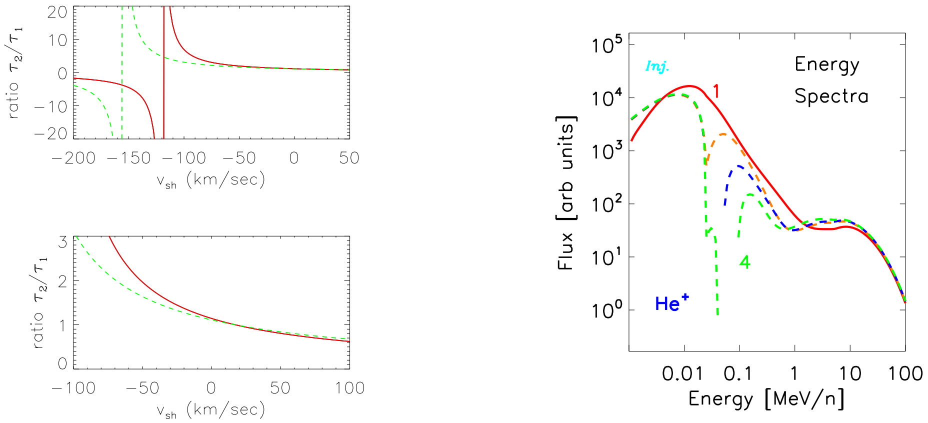

Figure 1. *Left panel*:The ratio of the sector-crossing time downstream of the termination shock (τ_2) to that upstream (τ_1), for an observer moving outward from the Sun at 17 km/sec and for a shock ratio $r_{sh} = 3.8$. The same curves is shown at different scales. The solid line is for an upstream solar wind speed of 350 km/sec, and the dashed line for 500 km/sec. *Right panel*: Sample spectrum computed for a time-dependent termination shock [12]

Figure (1,left) illustrates the ratios τ_2/τ_1 as a function of the shock speed, for an observer moving outward at 17 km/sec (approximately the speed of Voyager 1). Two different scales are shown in the two panels. Clearly, for strong shocks and inward shock speeds in the range 60-100 km/sec, the sector crossing times can become very large. The shock speed and the downstream flow are expected to change with time and distance behind the shock, so the above results are quantitatively correct only close to the shock. However, they are readily extended to any specified variation.

These considerations should be relevant to the first crossing of the termination shock by a spacecraft, when the shock is be moving inward toward the Sun and V_{sh} will be negative. Hence the sector crossing time will be larger than that in the solar wind, perhaps by a large factor. Various theoretical estimates of the shock propagation speed have been published. Most relevant here is the paper of Whang, etal., [11] who considered Voyager 1 explicitly and suggested a shock speed $V_{sh} = 67 \pm 41$ km/sec. The curves in figure (1) show that the sector structure observed from a spacecraft can be profoundly altered and perhaps even reversed for inward shock speeds which may be reasonably expected. Further analysis of the observations may be able to confirm or deny this possibility.

It is possible that the lack of magnetic sector crossings in the heliosheath and the magnetic field result from the effect discussed above – the shock was moving rapidly inward, so that the postshock flow at Voyager 1 was very and continues to be small. Hence, the current sheet structure takes a very long time to cross, resulting in the observed constant magnetic field sense. The outward direction of the field is simply a reflection of the fact that the sector which Voyager was in since the shock crossing contained outwardly directed magnetic field. If the field had happened to have the opposite sign at shock crossing, the observed field in the post-shock flow would have that sign. At a speed of several tens of km/sec, the shock will have moved several AU. At this distance from the shock, the subsonic postshock flow may already be deflected northward. This would deflect the outward magnetic field as well, and may account for the persistent northward component of the field which was observed [3].

Also, when, inevitably, the inward motion of the shock ceases, the sectors will be convected outward, past Voyager 1, and a *shorter* time between sectors will be observed.

The analysis here is for an ideal shock, where the energy in the fluid is conserved across the shock. It is expected, for example, that a fraction of the flow energy goes into the acceleration of anomalous cosmic rays, and this loss of energy may change the quantitative conclusions, although the general nature of the effect should remain unchanged.

3. The Energy Spectrum and Shock Motion

The above discussion suggests the likelihood of rapid motion of the spacecraft. Such motion will cause temporal changes in the energy spectrum of the accelerated ACR. This may help explain the anomalous spectra observed on Voyager 1 [2, 4, 6], where low-energy powerlaws coexist with modulation-related turnovers at higher energies. We have carried out preliminary modelling of such shocks [12]. A sample spectrum showing anomalies of the general nature as those observed is shown in figure (1,right). We are currently carrying out more such simulations. We conclude that temporal and spatial variations of the shock position may be able to explain the energy spectra observed both upstream of the termination shock and in the heliosheath.

4. Summary and Conclusions

The observations from Voyager 1, near the termination shock and now downstream in the heliosheath have shown unanticipated phenomena, particularly in the magnetic field structure and the energy spectra and streaming fluxes of the ACR. By extending previous models to include a nonspherical shock which is moving rapidely in the radial direction, we conclude that currently accepted paradigms of acceleration of the ACR at the termination shock show significant promise in accounting for the observations.

5. Acknowledgments

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References

[1] Jokipii, J. R., J. Geophys. Res., 300, 169 (1987).
[2] Stone, E.C., Paper SH22A-01, AGU Spring Meeting, EOS, 86, JA 443, 2005.
[3] Burlaga, L. F., et al, Paper SH22A-03 AGU Spring Meeting, EOS, 86, JA 443, 2005.
[4] Decker, R.B., Paper SH22A-03, AGU Spring Meeting, EOS, 86, JA 443, 2005.
[5] Gurnett, D., et al. et al, Paper SH22A-05 AGU Spring Meeting, EOS, 86, JA 443, 2005.
[6] Jokipii, J. R. and J. Giacalone, Proceedings of the 28th International Cosmic Ray Conference, Vol 7, 3753, Tsukuba, Japan, 2003
[7] Parker, E.N. Astrophys. J., 128, 664, 1958.
[8] Wilcox, J. M. and N. F. Ness, J. Geophys. Res., 70, 5793, 1965.
[9] Smith, E. J., B. T. Tsurutani, and R. L. Rosenberg, J. Geophys. Res., 83, 717, 1978.
[10] Schulz, M., Astrophys. Sp. Sci. 34, 371, 1973.
[11] Whang, Y. C., L. F. Burlaga, Y.-M. Wang and N. R. Sheeley Jr., Geophys. Res. Lett., 31, L0385, 2004.
[12] Kóta, Jozsef and J. R. Jokipii, ”Physics of the Outer Heliosphere”, AIP Conference Proceedings 719, page 272, Florinski, V., N. V. Pogorelov and G. Zank ed., American Institute of Physics, 2004.