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Estimate of the location of the solar wind termination shock

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Abstract. Over the next three years the termination shock is expected to reach its minimum distance from the Sun before moving outward again in response to increased solar wind dynamic pressure during the new solar cycle. Five different methods of inferring the distance to the shock lead to estimates that cluster in the range of 90±10 AU. In August 2001 Voyager 1 will be at 82 AU and moving outward at 3.6 AU per year, suggesting the possibility of encountering the termination shock by 2005 before it starts moving outward again.

1 Introduction

The size of the heliosphere is determined by the balance of the dynamic pressure of the outward expansion of the solar wind and the pressure of the local interstellar medium. Because the relevant properties of the interstellar medium are uncertain, the distance to the heliopause is also uncertain. The distance also varies over the solar cycle because of changes in the dynamic pressure of the solar wind, with the maximum distance predicted to occur near solar minimum (see, e.g., Whang and Burlaga (2000)).

As the supersonic solar wind approaches the heliopause, the transition to subsonic flow likely occurs in a termination shock. The Voyager 1 encounter with the termination shock will provide both an indication of the size of the heliosphere and the opportunity to study the acceleration of anomalous cosmic rays by the termination shock and the modulation of galactic cosmic rays in the heliosheath beyond.

2 Recent Estimates

Although the distances to the termination shock and the heliopause are uncertain, there are five methods for estimating these distances: pressure balance, timing of episodes of low frequency radio emissions, backscattering of solar ultraviolet radiation from interstellar hydrogen, intensity gradients in anomalous cosmic ray fluxes, and the timing and duration of transients in galactic cosmic ray fluxes. Some of the most recent estimates are summarized in Table 1 and discussed below.

Based on the radial and temporal dependence of the solar wind dynamic pressure observed in the outer heliosphere by Voyager 2, Belcher et al. (1993) calculated that the average location of the termination shock was between 78 and 105 AU in the period between 1990 and 1993. This estimate assumes that the interstellar pressure was due to a 0.5 nT magnetic field. Since with this assumption the distance to the shock scales inversely with the magnetic field magnitude, which Belcher et al. point out is very uncertain, the estimate is correspondingly uncertain.

The ISSI Workshop on the Heliosphere in the Interstellar Medium (von Steiger et al., 1996) led to refined estimates of the local interstellar pressure (private communication, A. C. Cummings et al., ISSI Working Group 7). These estimates of the magnetic field ($0.15^{+0.2}_{-0.1}$ nT) and the H+ ($0.07^{+0.07}_{-0.03}$ cm^{-3}), H (0.14±0.04 cm^{-3}), and He+ ($0.015^{+0.015}_{-0.0075}$ cm^{-3}) densities result in an average shock distance of 88±22 AU.

Using Ulysses observations of interstellar pickup ions, Gloeckler et al. (1997) derived the thermal pressure of the local interstellar cloud. By imposing a lower limit from EUV radiation models of 0.17 for the ionized fraction of H, they place an upper limit to the shock distance of ∼85 AU. According to their Figure 3a, the limit would increase to 90 AU if the ionized fraction is only 0.13.

Ulysses observations of the latitude dependence of the solar wind dynamic pressure at solar minimum have also been incorporated into MHD and semi-analytical models. Using a three dimensional MHD model that includes a latitude dependent solar wind but not the effects of charge exchange with interstellar neutrals, Pauls and Zank (1996) found that in the upwind direction the shock was at 88 (subsonic VLISM) or 135 AU (supersonic VLISM). Including the effects of interstellar neutrals in the model with the supersonic VLISM moved the shock in to 95 AU (Pauls and Zank, 1997). Linde et al. (1998) also included the effects of interstellar neutrals

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Table 1. Estimates of the Termination Shock Location*

Dynamic Pressure Balance	R_S (AU)	Observation period
Belcher et al. (1993)	78-105	1990-93
ISSI Working Group 7 (1995)	88±22	1977-93 average
Gloeckler et al. (1997)	$\leq$85	1996
Pauls and Zank (1996, 1997)	88, 95	1992-94
Linde et al. (1998)	80±10	1992
Exarhos and Moussas (2000)	88, 103	1992-94
Radio Emissions		
Gurnett and Kurth (1996)	80-115	1983, 1992
Zank et al. (2001)	$\leq$90	1983, 1992
Hydrogen Ly-α Backscattering		
Hall et al. (1993)	70-105	1989-1992
Anomalous Cosmic Ray Gradients		
Stone and Cummings (1999)	84±5	1980-1990
Cosmic Ray Transients		
McDonald et al. (2000)	88.5±7	1992
Webber et al. (2001)	83±1	1999

* Note that the quoted uncertainties do not include those arising from model approximations

in a three dimensional model having a supersonic VLISM, finding 80±10 AU. Using a semianalytic approach Exarhos and Moussas (2000) find 88 and 103 AU depending on the assumed interstellar pressure.

The distance to the heliopause (and by scaling to the termination shock) has been estimated from the timing of low frequency radio emissions thought to be excited by the interaction of Global Merged Interaction Regions (GMIRs) with the local interstellar medium. By combining the observed 420-day delayed onset of the radio emissions with MHD models for the propagation of the GMIRs, Gurnett and Kurth (1996) estimated a heliopause distance of 110-160 AU, corresponding to a termination shock distance of 80-115 AU. In a recent MHD model of the propagation of GMIRs that includes the presence of interstellar neutrals and pickup ions in the heliosphere, Zank et al. (2001) estimate that the 420-day onset indicates a distance to the termination shock of less than 85-90 AU.

Comparisons of models of the flow of neutral interstellar H into the heliosphere with the observed intensities of backscattered solar H Ly-α radiation observed by Voyager (upwind) and Pioneer 10 (downwind) beyond $\sim$25 AU imply the existence of a termination shock between 70 and 105 AU (Hall et al., 1993).

The spectra and gradient of anomalous cosmic rays can be compared with models for their acceleration and propagation to estimate the distance from Voyager to the termination shock. This method depends on assumptions about the radial dependence of the diffusion mean free path and the role of drifts. Extrapolating the gradients observed during the 1980s inside 49 AU outward to the shock source led to a best fit shock location of 84±5 AU (Stone and Cummings, 1999).

The fifth method involves the timing of transient changes in the intensity of anomalous and galactic cosmic rays associated with Merged Interaction Regions (MIRs). Model calculations (le Roux and Fichtner, 1999) indicate that the duration of an MIR associated decrease reflects the transit time of the MIR to the shock. Although local temporal variations can perturb the observed recovery, Webber et al. (2001) identified one such event in 1999 that indicated the shock was only 10 AU beyond Voyager 1, corresponding to a shock at 83±1 AU. In a related approach, McDonald et al. (2000) used the duration of a transient inward flow of anomalous cosmic rays in 1992 to place the shock at 88.5±7 AU at that time.

Each of these estimates is shown in Figure 1 with uncertainties that arise from the model fits or from uncertainties in model parameters. Although the assumptions and simplifications in each of the models introduce further uncertainties that are more difficult to quantify, the models and the observations involved in the five methods of estimation are sufficiently different that these additional uncertainties are unlikely to be correlated among the methods. Thus, the clustering of the estimates between 80 and 100 AU lends additional weight to the individual estimates.

3 Furure Termination Shock Encounters

The location of the termination shock will vary as the solar wind dynamic pressure varies over the solar cycle. Whang and Burlaga (2000) have incorporated the temporal variations observed by Voyager 2 into an MHD model that includes interstellar pickup ions, finding that the location of the termination shock varies by about 20 AU over the solar cycle. The minimum distance is predicted to occur near solar

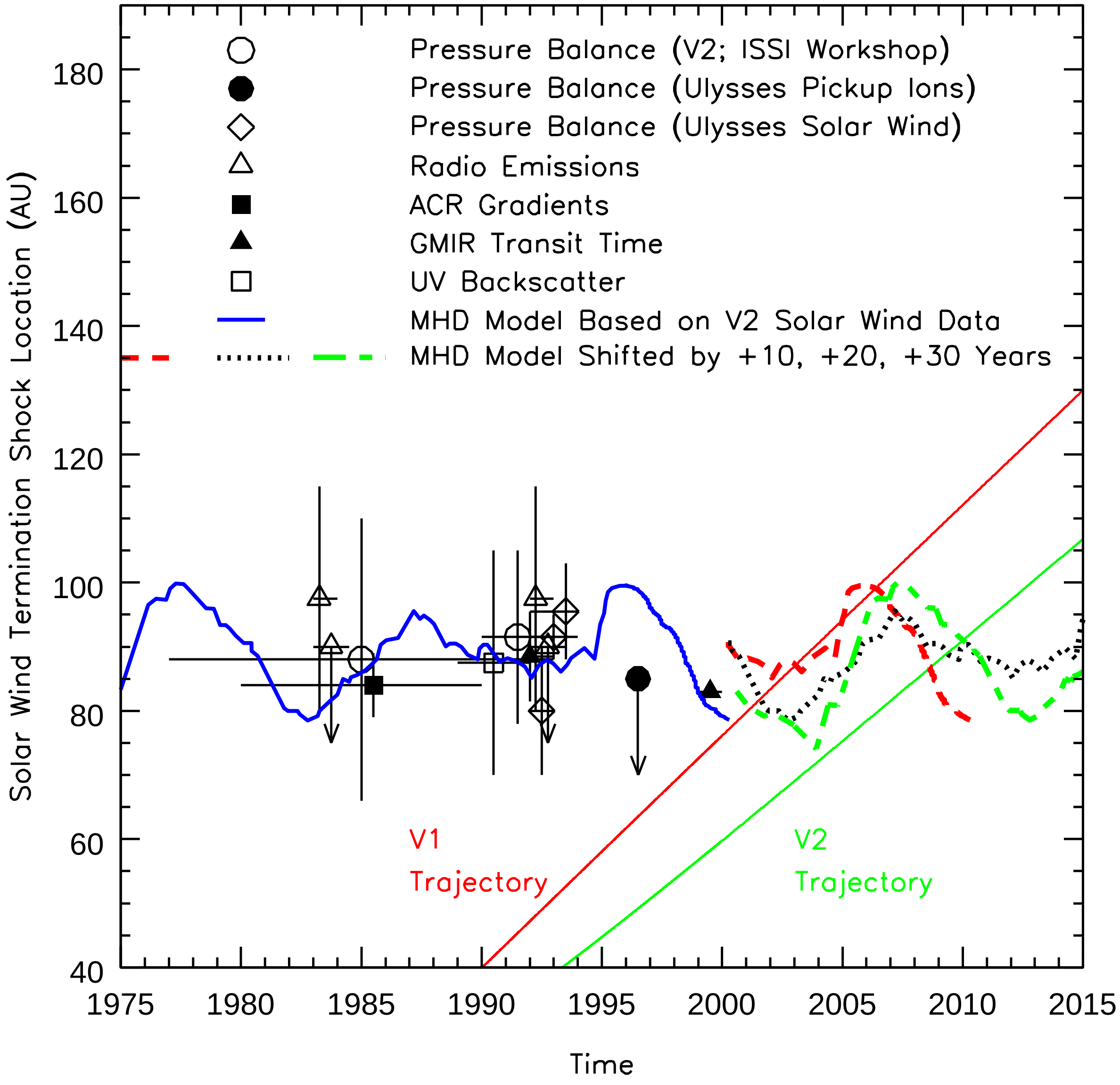

Fig. 1. Estimates of the location of the solar wind termination shock as described in the text. Also shown are the trajectories of V1 and V2.

maximum as shown in Figure 1. They used the distance derived from the anomalous cosmic rays to define the average location of the termination shock, and then adjusted for the effect of a non-spherical shock (curve b of their Figure 5).

As shown in Figure 1, the shock is presently moving inward. As Voyager 1 approaches the shock the low energy anomalous cosmic ray spectra should rapidly increase within a few AU of the shock. The spatial dependence shown in Figure 2 is an illustrative example based on extrapolating observed diffusion mean paths to the shock. Although the actual radial dependence may differ, this example suggests that the expected large gradients in the low energy ACR intensities near the shock should provide a means for estimating the remaining distance to the shock.

To illustrate the time period over which shock encounters may occur, Figure 1 shows the predictions from the previous solar cycles delayed by 10, 20, and 30 years. Comparison with the Voyager 1 trajectory suggests the possibility of one or more encounters with the termination shock by 2005. If there has been no encounter by then, the shock will likely again be moving outward with the arrival of increased pressure and it may be two to five years more before it moves back within Voyager's range.

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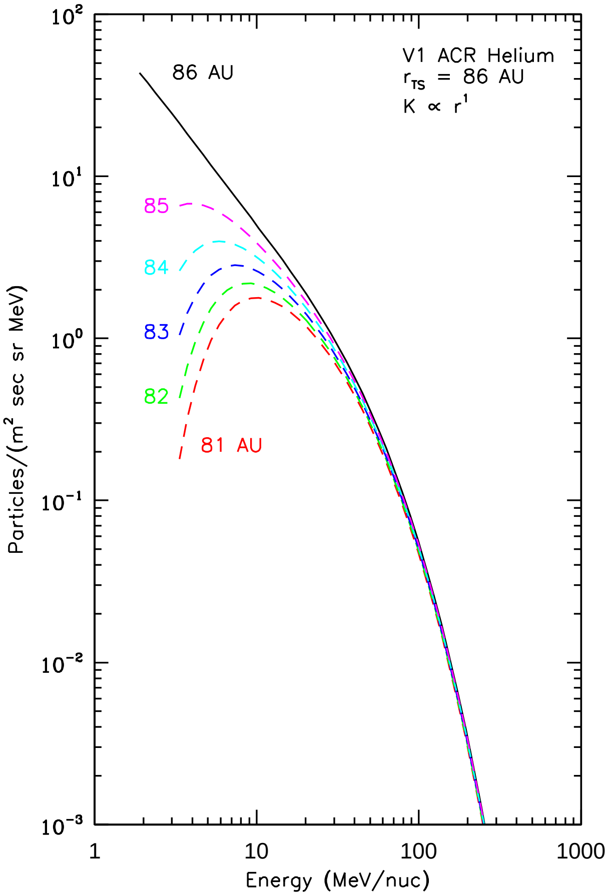

Fig. 2. Illustrative energy spectra of ACR He at different radial positions for a shock at 86 AU.

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