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Advances in Space Research 41 (2008) 237–244
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Solar wind structure in the outer heliosphere

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Received 29 November 2006; received in revised form 8 February 2007; accepted 27 March 2007

Abstract

A solar wind parcel evolves as it moves outward, interacting with the solar wind plasma ahead of and behind it and with the interstellar neutrals. This structure varies over a solar cycle as the latitudinal speed profile and current sheet tilt change. We model the evolution of the solar wind with distance, using inner heliosphere data to predict plasma parameters at Voyager. The shocks which pass Voyager 2 often have different structure than expected; changes in the plasma and/or magnetic field do not always occur simultaneously. We use the recent latitudinal alignment of Ulysses and Voyager 2 to determine the solar wind slowdown due to interstellar neutrals at 80 AU and estimate the interstellar neutral density. We use Voyager data to predict the termination shock motion and location as a function of time.

Keywords: ICMEs; Solar wind; Heliosphere

1. Introduction

The Voyager spacecraft have been exploring the heliosphere since they were launched in 1977. After passing through the magnetospheres of the four giant planets, the Voyagers continued outward toward the boundaries of the heliosphere. Fig. 1 shows a schematic picture of the heliosphere and the locations of the two Voyager spacecraft. The solar wind flows outward at supersonic speeds until it passes through the termination shock. This shock slows and heats the solar wind and begins the diversion of the solar wind plasma down the tail of the heliosphere. This region of shocked solar wind plasma is the heliosheath. The heliopause is the dividing line between solar wind plasma and interstellar plasma and is thought to be 30–40% further out than the shock. Voyagers 1 and 2 are both headed roughly toward the nose of the heliosphere. Voyager 1 crossed the termination shock in December 2004 at 94 Astronomical Units (AU) and since then has been in the heliosheath. Voyager 2 was still in the solar wind in February 2007 but is seeing precursors of the shock.

The solar wind takes 6–12 months or longer to reach the Voyager spacecraft in the outer heliosphere and heliosheath. The solar wind evolves significantly over these large distances. Interplanetary coronal mass ejections (ICMEs) and fast streams overtake plasma ahead of them, producing compressed regions called merged interaction regions (MIRs). Rarefactions behind the MIRs form where the plasma has been cleared out. The solar wind also interacts with the interstellar medium; charge exchange of the solar wind ions with the neutrals from the Local Interstellar Cloud (LIC) causes the solar wind to slow down and be heated. This paper discusses the solar wind structures observed in the outer heliosphere and how they interact with the LIC and the energetic particles in the outer heliosphere.

Topics we discuss are the changes of solar wind structure over the solar cycle and with radial distance,

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doi:10.1016/j.asr.2007.03.069

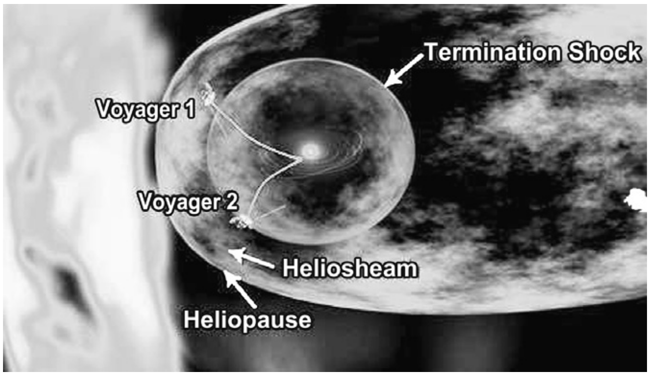

Fig. 1. Schematic picture of the heliosphere showing the termination shock, where the solar wind becomes subsonic, the heliosheath, consisting of the shock solar wind, the heliopause, and the locations of the Voyager spacecraft. (From the JPL Voyager web page.)

the influence of these changes on the heliospheric boundaries, the propagation of ICMEs through the heliosphere, and the effect of these structures on the energetic particle intensities.

2. Interplanetary shocks

The Voyager spacecraft were launched in 1977; in October 2006 Voyager 1 was at 100 AU and 30°N heliolatitude and Voyager 2 was at 82 AU and 27°S heliolatitude. The plasma instrument on Voyager 1 stopped working properly in 1980; thus we will discuss plasma data only from the Voyager 2 instrument (see Bridge et al., 1977). Fig. 2 shows the Voyager 2 plasma data and magnetic field magnitude from days 50 to 110 of 2006. The most noticeable feature is the large shock which occurred in a tracking gap between days 59 and 60. This shock was comparable to the shock observed in October 2001 and is the largest shock observed by Voyager 2 since 1991 (Richardson et al., 2006). The speed increased from 380 to 520 km/s. The density jumped by about a factor of 2 at the shock and another factor of 2 a few days later. The temperature rose by a factor of 4. The magnetic field increased 1–2 days after the plasma parameters increased; this offset in timing is not understood.

The shock was followed by a MIR, a region of enhanced magnetic field magnitudes and enhanced magnetic field fluctuations (see Burlaga, 1995). The shock was coincident with an increase in energetic particles with energies from tens of keV to over an MeV. Behind the shock, the >70 MeV cosmic ray particles showed a decrease in intensity; the increased magnetic field and fluctuations inhibited their inward transport; this relation between increased magnetic field magnitude and fluctuations and decreased cosmic ray intensities has been observed throughout the heliosphere (Burlaga et al., 2003, 1985). After the MIR was a region of very low density, below the PLS threshold of 0.0003–0.0005 (which depends of the speed and temperature of the solar wind). Models suggest this low-density region could be associated with a reverse shock passing Voyager 2 (Richardson et al., 2006). After the MIR, the speeds remained higher than before the shock by 40–50 km/s.

A smaller shock was observed at the end of day 243; this shock passed Voyager 2 while it was being tracked; it is the furthest shock for which we have plasma data (at 80.6 AU). Fig. 3 shows that the speed jump at this shock is about 45 km/s. The density increases by about 20% and the temperature by a factor of 2. The speed slowly decreases over about 13 days; at the end of this period the character of the plasma profiles change, so 13 days seems to be the time period where data is affected by this small shock. The bottom two panels show the >0.5 MeV and >70 MeV particle data. The higher energy cosmic rays are not affected by this event, but the >0.5 MeV ions show an enhancement throughout the region affected by the shock.

These two shocks emphasize that the shocks in the solar wind in the outer heliosphere are not well understood (Ashmall and Richardson, 2005). Models predict a simultaneous rise and slow decrease of all the plasma parameters and the magnetic field. The data show very different behavior. At the Bastille day shock, which arrived at Voyager 2 in January 2001, the density jumped before the speed, temperature, or magnetic field by at least a few hours. Fig. 4 shows high resolution data of the shock crossing; data gaps are present when the spacecraft was not tracked. The density first rose before a data gap, which lasted about 16 h. The other solar wind parameters increased across the data gap; the density stayed high 2 h after the gap then decreased to pre-shock levels (Burlaga et al., 2001; Wang et al., 2001a; Ashmall and Richardson, 2005). Voyager 2 was tracked during the passage of the October 2001 shock; the speed jump at the shock was a step function and occurred at the same time as a step-function jump in the temperature, but the density increase was more gradual and took 3 hours to complete (Wang and Richardson, 2002).

The reason for the strange behavior of these shocks is not known. The main thermal pressure in the solar wind at these distances is in the pickup ions, which are not directly measured; the change in pickup ions near the shock may be disconnected from the behavior of the bulk thermal solar wind plasma. Voyager 2 is approaching the termination shock; the plasma changes at this shock will be interesting to observe in light of the behavior of the interplanetary shocks.

3. Shock origins

Large shocks in the outer heliosphere are rare; thus they can usually be traced back to events at the sun or in the inner heliosphere with little ambiguity. The Bastille day CME occurred when Earth and Voyager 2 were aligned in heliospheric longitude; the arrival time of the shock and the speed jump were predicted very accurately (Wang et al., 2001b). In this case, a single large CME resulted in a large shock being formed in the inner heliosphere, which then decayed as it propagated to Voyager 2. The October

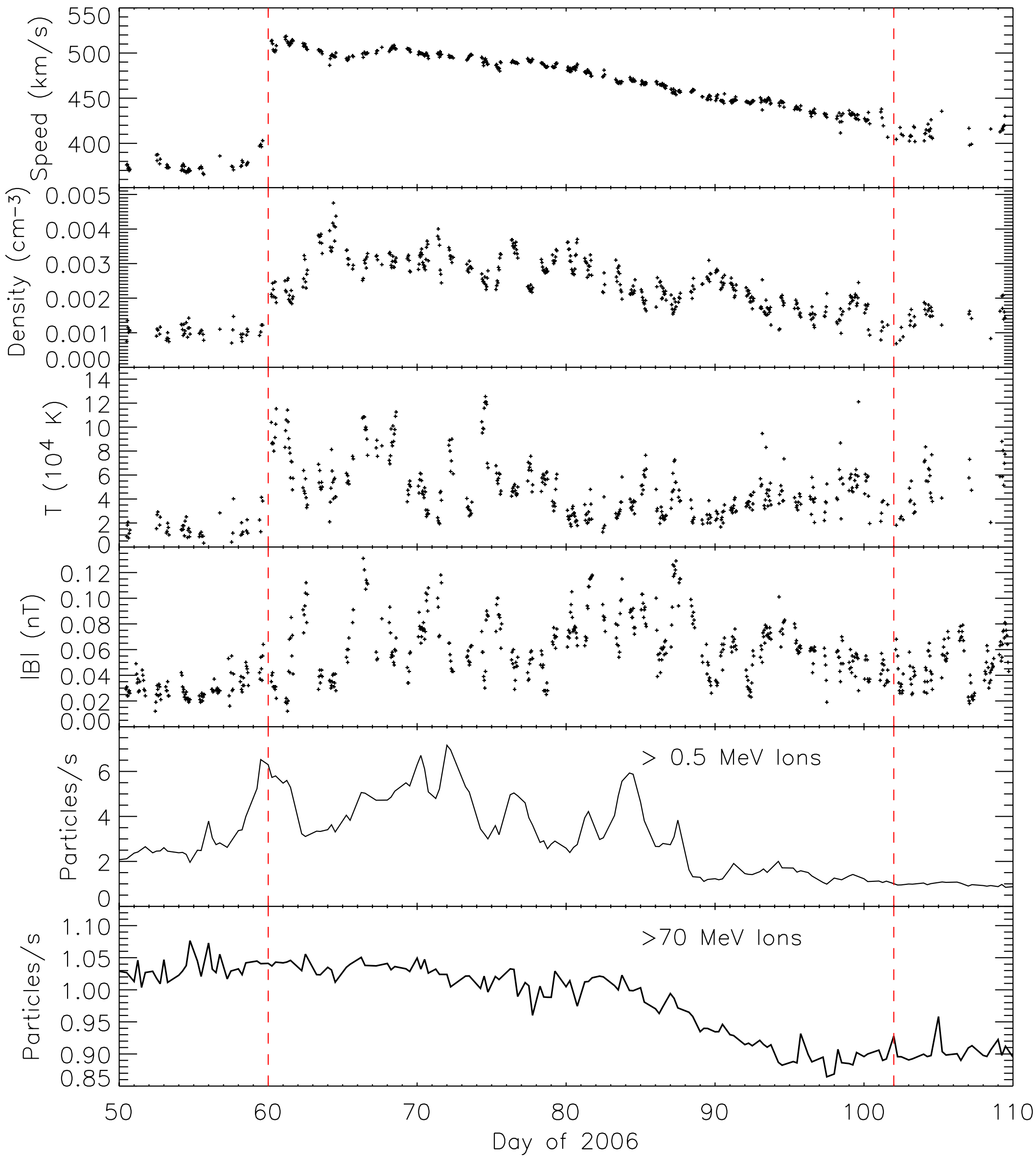

Fig. 2. Shock observed on day 60 of 2006. The panels show hourly averages of plasma speed, density, temperature, magnetic field magnitude, and counting rates of >0.5 MeV and >70 MeV particles. The dashed vertical lines show the extent of the MIR. The red line in the density panel is a running 7-point average to make the density rise more obvious. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2001 and May 2004 shocks were produced by a series of events on the Sun which overtook each other and merged as the solar wind moved outward (Wang and Richardson, 2002; Richardson et al., 2005). As successive forward shocks merged, the leading shock was strengthened, counteracting the shock dissipation which occurs with distance. The shock observed in March 2006 was formed from two different mechanisms. Ulysses was at the same heliolatitude as Voyager 2 in mid-2005; it saw a speed increase at this time probably due to the equatorward movement of polar coronal holes (Richardson et al., 2006). Propagation of the Ulysses data to Voyager 2 using the 1-D model showed that a shock would form and arrive at Voyager 2 near the time observed, but that the magnitude of the speed jump predicted was a factor of 2 too small. For previous shocks, the 1-D model has done a good job of predicting the propagation time (Wang et al., 2001a; Wang and Richardson, 2002), so we do not think 3-D effects could explain this discrepancy. The Sun was very active in September 2005, with many large flares and CMEs. These flares and CMEs were directed roughly in the direction of Voyager 2, but were more than 90° from the direction of Ulysses. Thus these events should affect Voyager 2 much more than Ulysses. If an artificial ICME were superposed on the Ulysses data, then a good fit to the speed and arrival time of the shock at Voyager 2 was obtained (Richardson et al., 2006). So this shock was formed by a superposition of a speed increase from high-speed streams moving equatorward

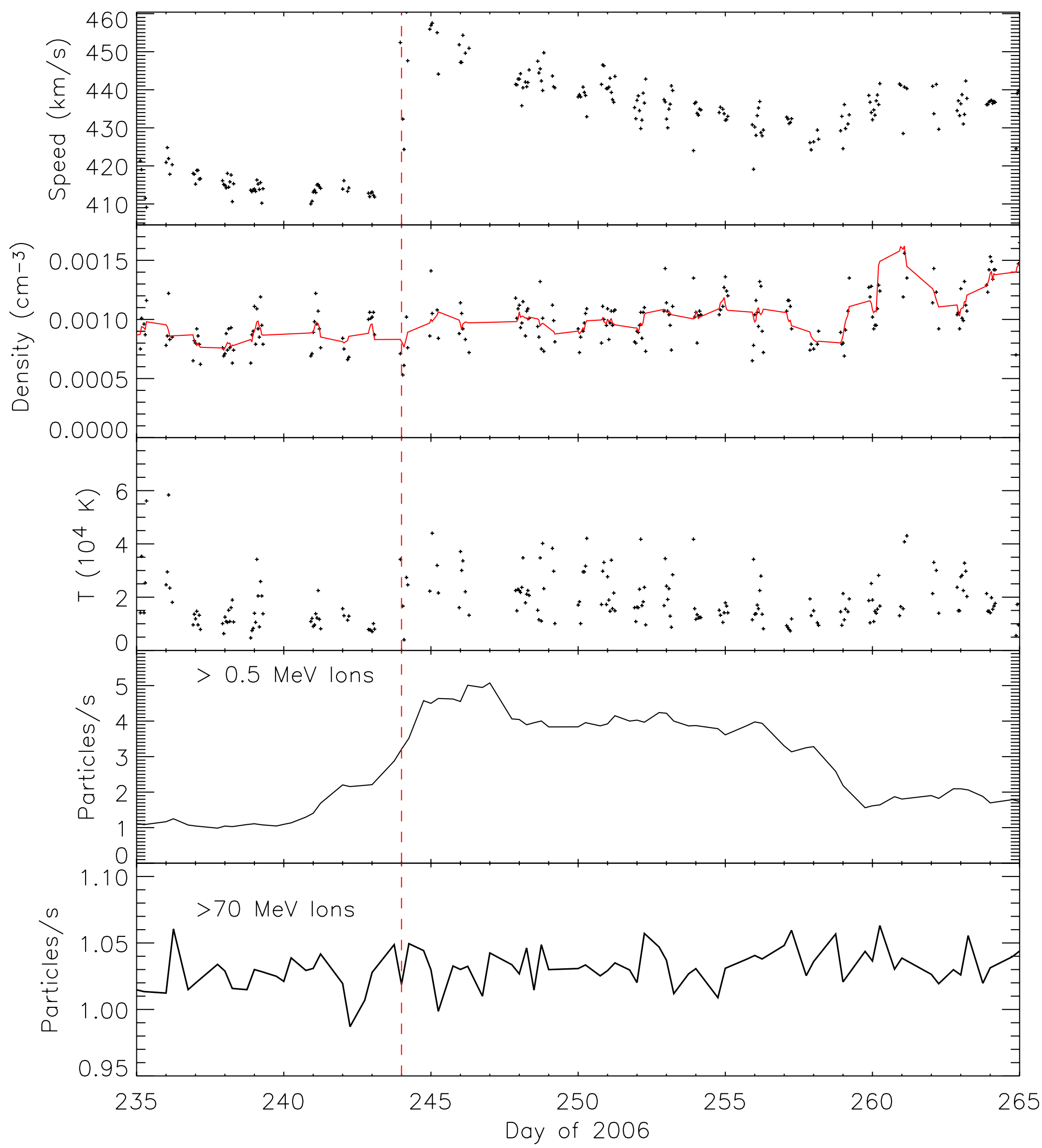

Fig. 3. Shock observed on day 244 of 2006. The panels show plasma speed, density, temperature, and counting rates of >0.5 MeV and >70 MeV particles.

and solar activity combining to form a very large structure in the outer heliosphere.

These shocks and the MIRs which trail them affect not only the energetic particles but the location of the termination shock. Fig. 5 shows daily averages of the solar wind dynamic pressure from 2001 onward, covering all the large shocks discussed above, and 25-day averages of the solar wind pressure over the entire Voyager 2 mission. The pressures are normalized to 1 AU. The period from 2001 to 2004.5 is dominated by large pressure pulses; these pulses generally last a few months with pressure increases of a factor of 5–10. They are driven by CMEs and by the time they reach the outer heliosphere the density, speed, temperature, and magnetic field strength are all correlated, producing the large pressure increase (Richardson et al., 2003). The pressure pulse in 2006 is the first in 21 months but also the largest. We note that, comparing 25-day averages, the March 2006 pressure pulse is the largest observed all mission by Voyager 2. Although the termination shock responds to these small scale events, the large scale features drive the large-scale motions.

Fig. 6 shows the location of the termination shock as a function of time. We use a 2-D magnetohydrodynamic (MHD) model which includes pickup ions to determine the shock location. The Voyager 2 data are used as input for this model, since these data are observed nearest to the termination shock. The interstellar H density at the shock is set equal to 0.09 cm^{-3}, which gives good agreement with the solar wind slowdown. Since the total interstellar pressure is not known, we use the V1 crossing of the termination shock in December 2004 at 94 AU (Stone et al., 2005; Decker et al., 2005; Burlaga et al., 2005) to normalize the model positions. The large scale, 12 AU in and out, termination shock motion due to solar cycle changes

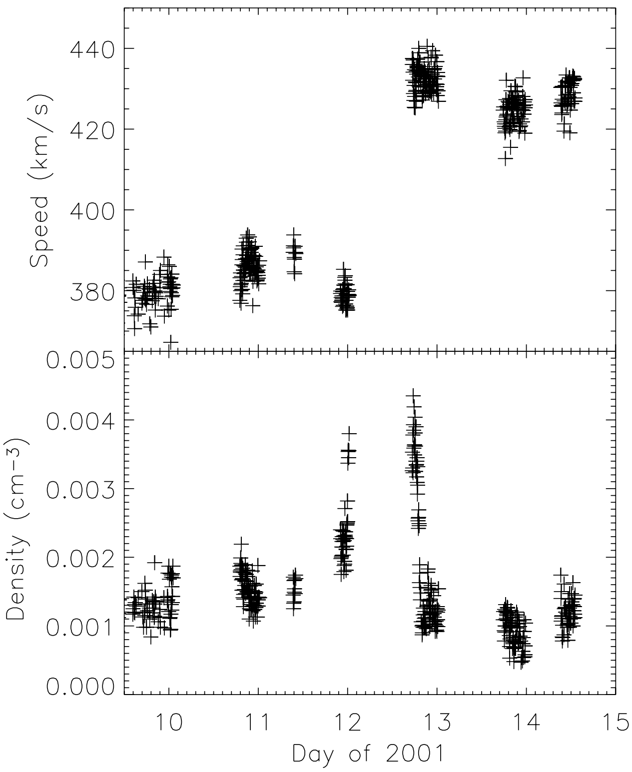

Fig. 4. Fine resolution solar wind speeds and densities near the Bastille day shock.

is the primary feature. After the minimum termination shock distance of 82 AU was reached in 1999, the termination shock moved outward, paralleling the trajectory of V1 until the peak termination shock distance of 96 AU was reached in 2004. The termination shock then moved inward past V1. The large shock in March 2006 had only a small affect on the shock location, pushing the termination shock out about 1 AU, after which the termination shock resumed its inward motion. The dashed line shows the termination shock location if we assume the solar wind pressure from last solar cycle repeats next solar cycle. In that case Voyager 2 would cross the termination shock in 2007. However, recent observations and models suggest that the heliosphere and termination shock are asymmetric. Observations of in-flowing H constrain the LIC magnetic field direction (Lallement et al., 2005).

Models show that the LIC magnetic field can break the symmetry of the system (Opher et al., 2006; Pogorelov, 2006); using directions consistent with the Lallement data the termination shock and HP are much closer in the south than the north as the tilted magnetic field shifts the whole heliosphere northward. Voyager 2 entered the termination shock foreshock region about 9 AU closer than V1, consistent with the termination shock being closer in the south. The bottom trace in Fig. 6 shifts the termination shock inward 10 AU; if the termination shock were this much

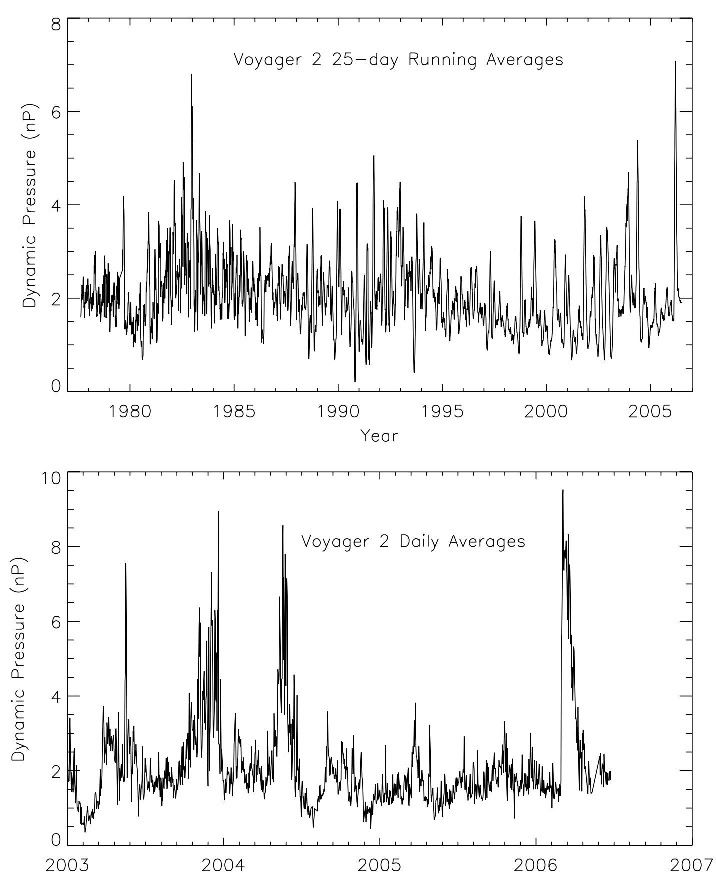

Fig. 5. Pressure of the solar wind: Daily averages (top) from 2001 to 2007 and (bottom) 25-day averages over entire mission.

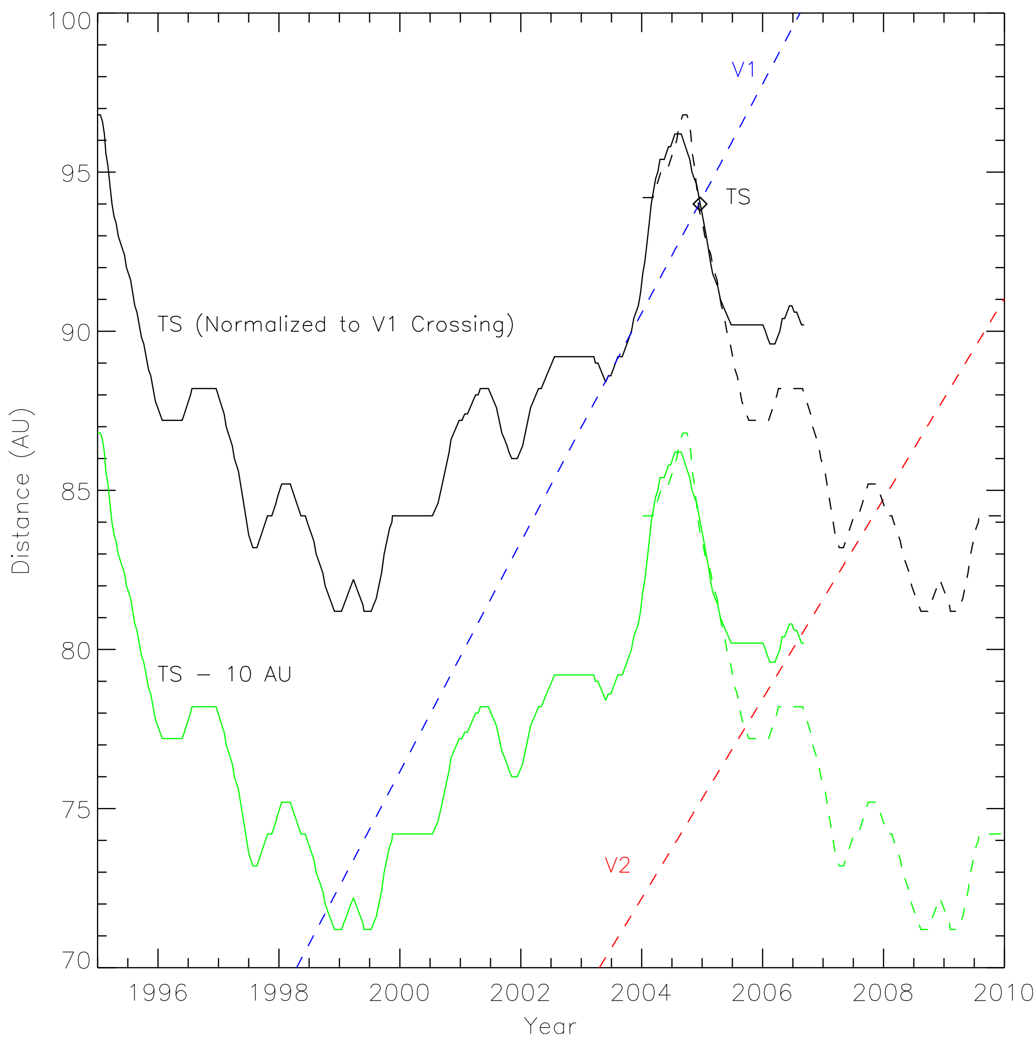

Fig. 6. The location of the termination shock predicted by 2-D model using Voyager 2 data as input and normalized to the observed Voyager 1 termination shock crossing at 94 AU. Data from the past solar cycle are used to extend the plot forward in time. Also shown are the same locations shifted 10 AU inward.

closer at the heliospheric latitude of Voyager 2, then Voyager 2 would be very close to the termination shock in late 2006.

4. Solar wind slowdown

The solar wind ionizes interstellar neutrals, mostly via charge exchange. These new pickup ions are then accelerated to the solar wind speed and heated to a thermal energy equal to the solar wind energy, about 1 keV. The energy for this acceleration and heating comes from the bulk motion of the solar wind and causes the solar wind to decelerate. Determination of the solar wind deceleration requires a difference measurement between the solar wind speed in the inner heliosphere (at Ulysses or a spacecraft near Earth) and at the distance of Voyager 2. Magnetohydrodynamic modeling is used to predict the speed expected at Voyager 2 based on solar wind parameters in the inner heliosphere, then the density of the interstellar H is adjusted so that the model results match the observations. These calculations can be performed only when two spacecraft are at the same heliolatitude or near solar maximum, when heliolatitudinal speed gradients are small. In 1999–2000, near solar maximum, the speed at Voyager 2 was 12–14% below that expected in the absence of pickup ions which implies an interstellar H density of 0.09 cm^{-3} at the termination shock (Wang and Richardson, 2003). In mid-2005, Ulysses and Voyager 2 were both at 25°S heliospheric latitude; this alignment allowed the slowdown in the solar wind between 5 and 79 AU to be determined (Richardson et al., 2007). The interaction of the solar wind with the foreshock particles ahead of the shock could further slow the solar wind in this region.

A complication for determining the solar wind slowdown in 2005–2006 is the large set of ICMEs in September 2005 which were directed 120° from Ulysses but <30° heliospheric longitude from Voyager 2. These transients must be removed to provide a reliable estimate of the solar wind slowdown. One way to do this is to only look at data from before the shock passage at Voyager 2, since the solar wind upstream of the interplanetary shock is not affected by the

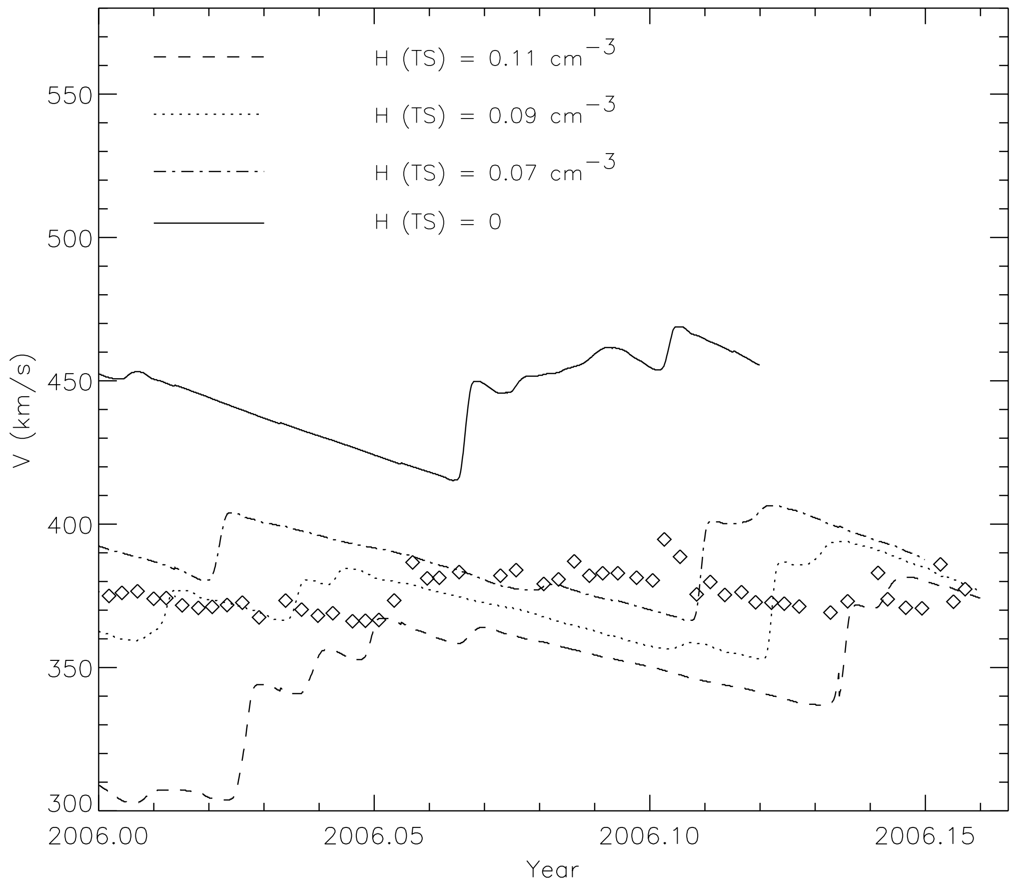

Fig. 7. Observed solar wind speeds (diamonds) and speed profiles predicted using models with different values of LIC H at the termination shock.

approaching ICME. We take the Ulysses data, propagate it to the location of Voyager 2 using a 1-D MHD code which includes pickup ions, and vary the value of the LIC H density at the termination shock to determine which values best match the data. Fig. 7 shows the daily average data points (diamonds) and five profiles corresponding to H densities at the termination shock of 0, 0.07, 0.09, and 0.11 cm^{-3}. The profiles end at the shock arrival time, which differ for each profile since the shock propagation is affected by the pickup ions. The average observed speed is 376 km/s. The speed with no pickup ions is 443 km/s so the slowdown is 67 km/s, or about 15%. The model speeds for H densities of 0.07, 0.09, and 0.11 cm^{-3} are 388, 373, and 357 km/s, respectively. The best match to the average speed is for H = 0.086 at the termination shock, consistent with values derived previously (Wang and Richardson, 2003; Gloeckler et al., 1993, 1997). We see no evidence yet for slowing of the solar wind associated with the foreshock region; such slowing would produce simultaneous rises in the density and magnetic field strength.

5. Summary

We have reviewed and discussed plasma structures including shocks and MIRs in the outer heliosphere. Solar maximum in the outer heliosphere is dominated by MIRs; these are formed by ICMEs compressing material ahead of them. In the outer heliosphere these features have evolved to have strongly correlated speed, density, temperature, dynamic pressure, and magnetic field magnitudes. The shocks preceding these MIRs are often large, formed from the merger of several ICME shocks, but the shock structure is often different from that expected. The density and magnetic field increase are not always coincident with the speed jumps and the structure behind the shocks is more complex than that predicted by MHD models. The MIRs behind the shocks do affect the termination shock location, but the effects are relatively small compared to longer time-scale changes such as those occurring over a solar cycle. The solar wind is slowed by its interaction with the interstellar neutrals as it moves outward. The most recent determination of the speed decrease between Ulysses at 5 AU and Voyager 2 at 79 AU found a decrease of 67 km/s, about 15%, consistent with a interstellar neutral H density at the termination shock of 0.09 cm^{-3} derived from previous work.

Acknowledgements

We thank the Voyager CRS (E. Stone, P.I.) and MAG (N. Ness, P.I.) teams for providing data used in this study. The work at MIT was supported under NASA contract 959203 from the Jet Propulsion Laboratory to the Massachusetts Institute of Technology. C. Wang received support from NNSFC Grants 40204009 and 40325010 from China. Research also supported by the CAS International Partnership Program for Creative Research Teams.

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