The Solar Wind in the Outer Heliosphere: Physical Processes in the Termination Shock and Heliosheath

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The Solar Wind in the Outer Heliosphere
Physical Processes in the Termination Shock and Heliosheath

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Abstract  The solar wind evolves as it moves outward due to interactions with both itself and with the circum-heliospheric interstellar medium. The speed is, on average, constant out to 30 AU, then starts a slow decrease due to the pickup of interstellar neutrals. These neutrals reduce the solar wind speed by about 20% before the termination shock (TS). The pickup ions heat the thermal plasma so that the solar wind temperature increases outside 20-30 AU. Solar cycle effects are important; the solar wind pressure changes by a factor of 2 over a solar cycle and the structure of the solar wind is modified by interplanetary coronal mass ejections (ICMEs) near solar maximum. The first direct evidences of the TS were the observations of streaming energetic particles by both Voyagers 1 and 2 beginning about 2 years before their respective TS crossings. The second evidence was a slowdown in solar wind speed commencing 80 days before Voyager 2 crossed the TS. The TS was a weak, quasi-perpendicular shock which transferred the solar wind flow energy mainly to the pickup ions. The heliosheath has large fluctuations in the plasma and magnetic field on time scales of minutes to days.

Keywords  Solar Wind  ·  Termination shock  ·  Heliosheath  ·  Heliopause  ·  Pickup ions  · Interstellar neutral atoms  ·  Anomalous cosmic rays

1 Introduction

We give a brief introduction to the solar wind in the outer heliosphere (HS) and discuss the interaction of the solar wind with the interstellar medium. Figure 1 shows an overview of the heliosphere, the bubble blown into the circum-heliospheric interstellar medium (CHISM) by the solar wind which contains the Sun. Parker (34) developed a theory for a supersonic solar wind at the dawn of the space age. His hypothesis was verified when the solar wind was first detected in the early 1960s (17; 31).

The solar wind is seen in Figure 1 flowing radially outward from the Sun. A corollary to Parker’s theory is that the solar wind goes through a transition from supersonic to subsonic...
Fig. 1 A plot of the equatorial heliosphere from a plasma (top) and neutral (bottom) perspective. The color bar on the top panel shows the plasma temperature. The lines show the plasma flow. The main boundaries, the termination shock, heliopause, and bow shock are labeled. The color bar on the bottom panel shows the H density; the hydrogen wall in front of the heliopause is labeled and the trajectories of the Voyager spacecraft are shown. Figure courtesy of H. Müller.

Flow at the termination shock, where the solar wind senses the CHISM and deflects down the heliospheric tail (56). Figure 1 shows the CHISM moving to the left relative to the Sun. The size of the heliospheric bubble in the CHISM is determined by where the solar wind pressure is equal to the CHISM pressure (35). The boundary between these two plasmas is called the

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heliopause (HP) and is analogous to the magnetopauses of Earth and other planets. The CHISM flow in this model is also supersonic (we don’t know if the real CHISM is super- or sub-sonic), therefore it also goes through a shock so that the flow can divert around the heliosphere. The shock in the CHISM is called the bow shock. The region of shocked CHISM material which flows around the HS is called the outer heliosheath. The region of shocked solar wind where the solar wind diverts down the HS tail is called the inner heliosheath or commonly just the heliosheath.

The neutrals in the CHISM are not affected by the magnetic fields and flow into the heliosphere. Neutral He has few interactions with the plasma, so essentially pristine CHISM He flows into the inner HS where it can be directly measured by spacecraft (57). The CHISM H interacts with the plasma both in the heliosheath (HSH) and in the solar wind via charge exchange. A proton gains an electron from a neutral; the neutral formed from the proton has a speed equal to the plasma speed. The newly created ion, called a pickup ion, is accelerated to the plasma speed and has an initial gyro-energy equal to the plasma flow energy (about 1 keV in the solar wind). The energy for this acceleration comes from the plasma flow energy, so the plasma slows down (46).

One effect of charge exchange in the outer HSH is the formation of the hydrogen wall shown in Figure 1. The CHISM plasma slows down as it approaches the heliopause. The CHISM H is coupled to this plasma via charge exchange, so it also slows down and thus has a higher density (1; 2; 58). This dense region upstream of the nose of the HS is called the hydrogen wall; similar walls are observed at other astrospheres (27).

Figure 2 shows the densities of ion and neutral populations in the heliosphere. The CHISM ion density increases at the bow shock where the flow speed decreases, but these ions do not enter the HS. The neutral density also increases at the bow shock, forming the hydrogen wall. The CHISM neutrals flow into the HS and are the HS population with the highest density outside 10 AU. The solar wind density decreases as \( R^{-2} \) out to the TS, increases at the TS, and again increases approaching the HP. The pickup ions, the ionized interstellar neutrals, make up an increasingly large fraction of the solar wind with distance and comprise about 20-30% of the solar wind at the TS (46). Since the pickup ions are hot, they dominate the thermal ion pressure outside 30 AU. Thus the CHISM not only stops the solar wind and diverts it down the tail, but also penetrates deep into the HS. This chapter discusses the outward flow of the solar wind and how it is affected by the CHISM.

2 Solar Wind Evolution

The slow solar wind reaches an asymptotic speed of about 400 km/s and, to first order, maintains that speed until the TS. Figure 3 shows 101-day averages of the solar wind speed, density, temperature and dynamic pressure at V2. The top panel also shows 101-day averages of the solar wind speed at 1 AU. Near the Sun (out to 30 AU) the speeds at Earth and those at V2 are very similar. The solar wind parameters have a lot of variation, but to first order the speed is constant, the density decreases as \( R^2 \), and the temperature decreases out to 20-25 AU and then increases.

The solar wind changes over a solar cycle (25). The dynamic pressure, which determines the distance to the TS and HP, is least near solar maximum, increases for 2-3 years after solar maximum, then decreases to the next solar maximum (42). At solar maximum, the solar wind is slow and dense at all heliolatitudes. At solar minimum, the solar wind is slow and dense near the equator but fast and tenuous near the poles, with a transition region near 20 - 30° heliolatitude. This gradient in speed with heliolatitude at solar minimum causes the
The density of the plasma and neutral components from 1 to 1000 AU. The solar wind ions come from the Sun. The pickup ions are interstellar neutrals which have been ionized in the solar wind. The densities of the solar wind and of the pickup ions jump at the termination shock. Outside the heliopause, the ions are part of the CHISM. Both the ion and neutral density increase in front of the heliopause (in the hydrogen wall). The interstellar neutrals dominate the mass density outside 10 AU. Figure courtesy of V. Izmodenov.

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difference in solar wind speeds at Earth and V2 in 1986-87 and 1995-97. In 1986-87, V2 was at a lower average heliolatitude than Earth and observed lower speeds whereas from 1995-97 V2 was at a higher heliolatitude than Earth and observed much higher speeds. Variations also exist from solar cycle to solar cycle; the current solar minimum has a smaller solar wind dynamic pressure than in the previous two cycles (29). Other shorter scale features are also observed, such as the speed variations with a 1.3-year period observed from 1987-1998 (41). This variation in speed was observed throughout the heliosphere and has been an occasional feature observed in historic solar wind data (15; 55). A similar period has been observed in convection patterns in the Sun and may be related (18).

Solar activity varies over a solar cycle, with many more ICMEs at solar maximum than at solar minimum (8). As the ICMEs move outward, they expand until they reach 10-15 AU (48); during solar maximum as much as 40% of the SW observed by V2 is from ICMEs. At times of high solar activity the Sun sometimes emits a series of ICMEs over time periods of days to months. The latter ICMEs catch up to earlier ICMEs and merge, compressing the solar wind ahead of them to form regions of high magnetic field and (often) density called
merged interaction regions (MIRs) (3; 5; 43). Near solar maximum these structures dominate the solar wind profile; from 2001-2005 the MIRs observed in the outer solar system evolved so that the magnetic field, speed, density, and dynamic pressure were all correlated, resulting in large pressure pulses which reached the TS roughly twice each year and pushed it outward (45).

3 Effects of the neutral CHISM on the Solar Wind

The first effects of the CHISM on the solar wind are those of the neutral H and He which penetrate into the heliosphere. The solar wind contains stationary structures called pressure-
balanced structures across which the pressure (thermal plus magnetic) is constant. By 20 AU, the observed structures could only be in balance if the plasma had a hot pickup ion component (4). The next observed effect of the CHISM neutrals was an increase in the thermal proton temperature starting between 20 and 30 AU, which overwhelmed the adiabatic cooling which would occur without a heat source. The pickup ions are the heat source; they are formed with a ring distribution (the particle trajectories are perpendicular to the field). These distributions are unstable and generate magnetic fluctuations which isotropize the distributions. The waves transfer a small amount (4%) of their to the thermal protons, which is enough to heat them as observed (51; 19).

The slowdown of the solar wind due to pickup of CHISM neutrals increases with distance and was first reported near 30 AU (41), although the slowdown was not observed in Pioneer 11 data at similar distances (14). By the time V2 neared the TS in 2007, the solar wind speed was about 83% of its speed at Earth, so the pickup ions made up about 19% of the total solar wind density (46). We note that the 17% decrease in speed represents a roughly 30% decrease in flow energy. Thus the neutrals from the interstellar medium acquire a substantial fraction of the solar wind energy well before the TS crossing.

4 The Termination Shock

The first direct sign of the approaching TS was a fairly sudden increase in tens of keV to MeV ions and electrons in mid-2002 observed at V1 but not at V2, which was 18 AU closer to the Sun (23; 30). Figure 4 shows that these ions streamed along the magnetic field lines in the outward direction, as if they were generated at the Sun. Although the approach of the TS seemed a likely source for these particles, the outward direction was initially confusing. An MIR passed V1 and V2 in early 2003, at which time the V1 particle fluxes decreased. The increased dynamic pressure associated with the MIR pushed the TS outward so the field lines at V1 became disconnected from the TS. The MeV particles were again observed starting in mid-2004, but the keV ions and electrons did not return until the start of 2004. This difference in particle energies suggests the connection to the TS was more distant, so that only the more energetic particles had time to make it to V1 before they were convected back to the TS with the solar wind flow.

Another decrease, again likely due to an MIR, was observed in late 2004. Throughout this time period the particle intensities were highly variable and highly anisotropic (moving along the magnetic field away from the Sun). During a data gap on day 316, 2004, at 94 AU, V1 crossed the termination shock. The particle intensities jumped, became steady and isotropic, and the magnetic field magnitude increased (6; 9; 53).

The V1 TS crossing revealed the scale size of the heliosphere, roughly 90 AU for the TS and (based on models) 120-140 AU for the HP. Since V1 crossed the TS in a data gap, the TS strength (the ratio of downstream to upstream density and magnetic field, which is 4 for a strong shock) could only be estimated and was of order 2-3 (6; 53). The HSH speeds derived from the particle data were very low just after the TS, -50 to 50 km/s (9), consistent with an inward-moving TS (22). The keV particles seem to have their source at the TS, with a peak just outside the TS. However, the anomalous cosmic rays (ACRs), which were thought to be accelerated at the TS (37), had intensities at the TS less than the peak values observed upstream in the solar wind and the flux of ACRs continued to increase after the TS crossing (9; 53).

Let us return to the foreshock particles which were streaming the wrong way. They were telling us that the TS is blunt, with a larger radius of curvature than the Parker spiral field
Fig. 4 Panels 1, 2, and 4 show 5-day smoothed V1 40-53 keV ion, 3.4-17.6 MeV proton, and 0.35-1.5 MeV electron intensities. Panel 3 shows the direction that particles are traveling. The bottom panel shows speeds estimated from the low-energy ions (since the plasma instrument is not working).

If the TS were blunt, the field line would first intersect the TS near where the TS is closest to the Sun, but would be in the solar wind on both sides. V1, as shown in the figure, would then see particles flowing from the TS in the direction outward along the field line because this field line is connected to the TS. This hypothesis predicted that V2, on the other side of the closest point of the TS, would see particles streaming in the opposite direction. V2 entered the TS foreshock region in late 2004 and particles were streaming in the opposite sense (sunward) from those at V1, consistent with the blunt shock hypothesis (10).

V2 entered the foreshock region at 75 AU, about the same time V1 crossed the TS in late 2004. Since V1 entered this region at 85 AU, 10 AU further out, either the HS was asymmetric or the foreshock was much thicker in the V2 direction than the V1 direction. Models do suggest the foreshock is thicker at the V2 location because of the geometry of the crossing locations (32), but only by a few AU. Models also show that, if the CHISM magnetic field were tilted from the CHISM flow direction, the heliosphere would be asymmetric (26; 40). Similar asymmetries are observed in Earth’s magnetosphere (36; 12) and in ICME models (50). The difficulty for global heliospheric models is to determine the actual CHISM field direction. Observations of a difference between flow directions of H and He coming into
the HS provide constraints on this direction (24; 20). Use of these field direction constraints in models gives HS asymmetries with the TS and HP closer in the south than the north, although the amount of the asymmetry varies between models (33; 38). V2 crossed the TS on day 242 of 2007 at 84 AU; calculations of the TS motion based on V2 solar wind data upstream of the TS and a 2-D model indicate the TS moved inward 2-3 AU between the V1 and V2 TS crossing, giving an asymmetry of 7-8 AU in the TS locations in the V1 and V2 directions (7; 11; 47; 52).

Figure 6 shows daily averages of the plasma and magnetic field parameters before the TS crossing. The TS crossing is very obvious in the plasma data, marked by a sharp decrease in speed, an increase in temperature, and a change in flow angle. The density and magnetic field strength both increase, but these increases are comparable to increases observed in the solar wind. At the TS the solar wind begins to turn into a flow down the heliotail. The directions are as expected for this deflection, in the T and -N directions (the RTN coordinate
Fig. 6 Daily averages of the plasma speed, density, temperature, flow angles, and magnetic field magnitudes near the TS.

The solar wind begins to slow at about day 160, eighty days before the TS crossing, when a step-like decrease was observed. Two more downward speed steps were observed at days 190 and day 232, reducing the speed to near 300 km/s just before the TS. SW speeds of 300 km/s are sometimes observed near 1 AU, but V2 had not observed speeds this low since 1978, which suggests that these decreases are associated with the TS. The speed decrease from 380 to 300 km/s corresponds to a loss of about 40% of the solar wind flow energy before the TS. The first two speed decreases are associated with large increases in B. We do not yet understand the physics behind these speed decreases.

Figures 7 and 8 show the three crossings of the TS which occurred while V2 was being tracked. The first and fifth crossings occurred in data gaps. The third and fourth crossings at 244.0 and 244.11 have the classic foot ramp structure of a quasi-perpendicular, supercritical shock (7). At the foot, the magnetic field increases and the speed decreases; this region formed by ions which reflect from the shock. At the ramp the speed decreases and the
temperature, density and field all increase. The second TS crossing at 243.84, a few hours earlier, looks very different. The speed steadily increases over about 30 minutes. The density does not have a clear increase but the temperature does jump. The magnetic field decreases across the foot region and two increases in the field were observed, both of which look like ramps. These data may show the TS in the process of reforming with the ramp moving upstream by an ion gyroradius (7).

Another surprise was the low thermal proton temperature in the heliosheath. Magnetosheaths of the outer planets all have proton temperatures of a few million degrees K and electron temperatures which are a factor of roughly 2 hotter. Models also predicted the HSH temperature would be a few million degrees. The models which predict these temperatures assume that almost all the SW flow energy goes into heating the thermal plasma, which is the case at the planetary magnetospheres. The observed HSH temperatures are about an order of magnitude less than these predictions, a few hundred thousand degrees K for protons (47). Electron temperatures are below the 10 eV instrument threshold; occasionally tails of the

Fig. 7 The plasma speed, density, thermal speed, and magnetic field magnitudes near the TS.
The magnetic field magnitude, standard deviation of the magnetic field over 4-minute intervals, the azimuthal field angle, the elevations angle, and the plasma speed.

Fig. 8 The magnetic field magnitude, standard deviation of the magnetic field over 4-minute intervals, the azimuthal field angle, the elevations angle, and the plasma speed.

electron distributions are observed which allow us to estimate that the electron temperature is 3–4 hundred thousand degrees K.

What happens to the flow energy? We discussed above that about 40% of the flow energy is lost before the TS, probably heating energetic particles. The drop in speed at the TS is not a factor of 4 as at the planetary bow shocks but a factor of 2, so less energy is available for heating. But the major difference seems to be that most of the energy at the TS is going not to the thermal plasma but to the pickup ions. Based on V1 observations, Gloeckler et al. (16) inferred that 80% of the flow energy transferred at the TS went into the pickup ions, which is consistent with the V2 plasma observations.

In addition to the average energy of the ions being low, some spectra look like they are not heated at all by the TS. Figure 9 shows examples of two ion spectra from the heliosheath which were fit to convected isotropic Maxwellian distributions. The first has a temperature of 22,000 K and the second a temperature of 228,000 K. The density and magnetic field go up by a factor of two at the shock, so the temperature should increase by a factor of two by conservation of the first adiabatic invariant. As shown in Figure 9, some spectra in the HSH have temperatures of only 20,000 K, twice the average solar wind temperature. These protons were essentially unheated at the shock, they gained only the energy from compression of the plasma as it slowed at the shock. These cold spectra are seen sporadically throughout the heliosheath data encountered through August 2008. They could be plasma
Fig. 9 Two ion spectra from the heliosheath. Best fits of convected isotropic Maxwellian distributions to the histogram of observations of current versus energy are shown by the curves. For the left spectrum the temperature is 22,000K and for the right spectrum it is 228,000K.

which has passed through the TS when it is in the process of reforming, or could have passed through the shock at a time when only hotter ions were effected by the shock (58). The TS is strongly time dependent based on the variations observed in the HSH.

Since data are available across the TS, the Rankine-Hugoniot equations can be solved to find the shock speed and normal (47). The shock normal angle is consistent with zero in the N direction but slightly off-radial in the T direction suggesting the shock has a smaller radius of curvature than a circle, opposite of the blunt shock hypothesized above. But this measurement is for one crossing of a very dynamic surface and so is not in real conflict with having a blunt TS. The TS was quasi-perpendicular and had compression ratios of 2.2-2.5 at TS-2 and 1.0-2.3 at TS-3. The shock moved at speeds of 50-100 km/s, similar to the speeds of planetary bow shocks. The upstream Mach numbers are 4.9 and 8.8 and the downstream Mach numbers are 1.1 and 2.8. These downstream Mach numbers highlight the lack of heating of the thermal plasma; this component of the plasma remains supersonic downstream of the TS. Thus the waves that convey information about the interstellar plasma upstream must propagate at speeds determined by the pickup ion sonic speed.

Figure 10 shows the plasma properties in the HSH. The average velocity components are 140 km/s in the radial direction, 47 km/s in the T direction, and -15 km/s in the -N direction. The average speed is 144 km/s, density is 0.002 cm$^{-3}$, and $T = 144,000$ K. All the parameters are highly variable. These variations probably arise both from fluctuations in the shock speed, normal, and structure and from changes in the upstream solar wind. One feature which may be a solar wind feature is the increase in speed, density, and temperature beginning at about day 350 and lasting roughly 15 days. This increase is qualitatively similar to those observed in MIRs in the solar wind and is associated with a decrease in energetic particle fluxes, also analogous to a solar wind MIR. The N component of the speed changes from southward to northward at this time and remained northward for almost 40 days. This direction change suggests that a transient in the south pushed the flow ahead of it northward as it expanded.
Fig. 10 The plasma speed, EW flow angle, NS flow angle, density, temperature, and Mach number of the thermal plasma.

5 Anomalous Cosmic Rays

Before the TS encounters, the TS was thought to be the source of anomalous cosmic rays (ACRs), singly ionized particles with energies of 20 - 100 MeV. These source of the ACRs are neutrals from the CHISM which are ionized, form pickup ions, and then are accelerated to high energy. The TS seemed a likely place for this acceleration to occur and pre-crossing expectations were that ACR intensities would peak at the TS and that the spectra would be power laws. The data from the TS in Fig. 4 shows that the low energy, tens of keV particle intensities peak at the TS but that the MeV particle intensities do not. Inspection of the particle spectra shows that the ACRs are modulated at the TS at both V1 and V2, so the ACRs are not accelerated where these spacecraft crossed the TS (53; 52). Subsequent suggestions have been that the acceleration occurs in the flanks of the heliosphere (28; 49) or further out in the heliosheath (13).

6 Summary

The Voyager spacecraft are providing in situ observations of the interaction between the solar wind and the interstellar medium. The interstellar neutrals penetrate deep into the
heliosphere and slow and heat the solar wind, removing about 35% of the solar wind energy before the TS. Upstream of the TS, a foreshock region of field-aligned streaming particles was observed. Ahead of the TS the solar wind slowed substantially starting 0.7 AU before the TS crossing. At the TS, little heating of the thermal plasma occurred with most of the energy going into the pickup ions. The HSH is a highly variable region due probably both to changes in the upstream solar wind and to motion of the TS.

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