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Detailed Terms
The Solar Wind in the Outer Heliosphere and Heliosheath

J. D. Richardson · L. F. Burlaga

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Abstract The solar wind environment has a large influence on the transport of cosmic rays. This chapter discusses the observations of the solar wind plasma and magnetic field in the outer heliosphere and the heliosheath. In the supersonic solar wind, interaction regions with large magnetic fields form barriers to cosmic ray transport. This effect, the “CR-B” relationship, has been quantified and is shown to be valid everywhere inside the termination shock (TS). In the heliosheath, this relationship breaks down, perhaps because of a change in the nature of the turbulence. Turbulence is compressive in the heliosheath, whereas it was non-compressive in the solar wind. The plasma pressure in the outer heliosphere is dominated by the pickup ions which gain most of the flow energy at the TS. The heliosheath plasma and magnetic field are highly variable on scales as small as ten minutes. The plasma flow turns away from the nose roughly as predicted, but the radial speeds at Voyager 1 are much less than those at Voyager 2, which is not understood. Despite predictions to the contrary, magnetic reconnection is not an important process in the inner heliosheath with only one observed occurrence to date.

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

1 Introduction

Galactic and anomalous cosmic rays (GCRs and ACRs) move inward to Earth through the solar wind. Their transport rate and observed intensity depends on solar wind conditions. The Voyager spacecraft have sampled solar wind plasma from Earth into the heliosheath; in July 2010 Voyager 1 and 2 were at 113 and 93 AU from the Sun, respectively. The solar

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wind is supersonic and flows radially outward from the Sun. As it moves outward, it inter-
acts with the planets, comets, and other solar system bodies, but these have little effect on
the large-scale flow. The solar wind is not uniform; the flow speed, density, composition,
temperature, and magnetic field all vary in time. The initial source is bimodal, with fast (700
km/s) and slow (350 km/s) solar wind streams. In addition, coronal mass ejections (CMEs)
on the Sun propel large amounts of matter outward at speeds up to a few thousand km/s.
These streams and parcels interact and evolve with distance from the Sun. The solar wind
eventually responds to the outside pressure of the local interstellar cloud (LIC), first going
through a transition from supersonic to subsonic flow at the termination shock, and then
being diverted by the LIC pressure down the heliotail.

Figure 1 shows an overview of the heliosphere. The top panel shows the plasma tem-
perature and flow lines and the bottom panel shows the density of neutral H in the LIC. The
boundary of the heliospheric bubble occurs where the solar wind pressure is balanced by the
LIC pressure. Since both the solar wind and the LIC are magnetized plasmas, they cannot
mix. The boundary between these two plasmas is called the heliopause (HP) and is thought
to be analogous to the magnetopauses of Earth and other planets. If the LIC were supersonic,
a shock would form in the LIC upstream of the HP so that the flow could divert around the
heliosphere. The shock in the LIC in front of the HP is called the bow shock. The region
of shocked LIC material which flows around the heliosphere is called the outer heliosheath.
The region of shocked solar wind where the solar wind diverts down the heliosphere tail is
called the inner heliosheath or commonly just the heliosheath.

The LIC is about 2/3 neutral and 1/3 plasma and is comprised mainly of H and He
with smaller amounts of heavier elements (see review (26)). The neutrals in the LIC are not
affected by the magnetic fields and flow into the heliosphere. Neutral He has few interactions
with the solar wind plasma, so essentially pristine LIC He flows into the inner heliosphere
where it can be directly measured by spacecraft and used to determine the LIC speed and
temperature. The original LIC H is removed mainly by charge exchange with solar wind
protons as it moves inward and little remains at 1 AU.

This chapter describes the solar wind environment in the outer heliosphere. We describe
the evolution of the solar wind plasma and magnetic field from 1 AU through the heliosheath.
We discuss solar cycle variations and the impact of interplanetary CMEs (ICMEs) on the
solar wind structure. The interaction of the LIC neutrals with the solar wind is described.
We focus on how these structures affect cosmic ray propagation through the heliosphere.

2 Solar Wind Evolution

The Parker equation predicts that the solar wind speed asymptotically approaches a con-
stant value, the density decreases as $R^{-2}$, and B in the ecliptic decreases as $R^{-1}$ at large
distances (46). At the termination shock (TS) the plasma slows and is compressed, so the
density, temperature, and magnetic field magnitude all increase. Figure 2 shows 25-day run-
ning averages of the plasma speed, normalized density, and proton temperature observed by
Voyager 2 (V2) from 1 - 93 AU. The TS location is labeled and is evident from the sharp
transition in the plasma parameters. To first order, upstream of the TS the speed is constant
and averages 440 km/s. $NR^2$ is also constant on a large scale before the TS. The temperature
decreases until 20-30 AU, then increases. Figure 3 shows 1-year averages of the magnetic
field magnitude at Voyager 1 (V1) compared to predictions from the Parker equation (11).
The magnetic field depends on the solar field, which is time dependent, and the solar wind
speed (11). The V1 plasma experiment is not functional, so speeds are derived from the
Wang-Sheeley model (65). The upper and lower lines give values for upper and lower limits to the solar wind speed. The Parker model fits the data well.

Time variation is observed in these parameters on all scales. At solar minimum the solar wind has large latitudinal gradients, with speed increasing and density decreasing with heliolatitude. Near the equator, solar wind speeds average 350 km/s and densities 7 cm$^{-3}$. At high latitudes the speeds are 700 km/s and densities 3 cm$^{-3}$. The transition region occurs at 10-30$^\circ$ solar magnetic latitude, but covers a larger range of heliolatitude since the Sun’s
Fig. 2 Running 25-day averages of the radial speed, density normalized to 1 AU, and thermal proton temperature observed by V2. The dashed line shows the TS and the shaded regions show the 1986 and 1996 solar minima.

dipole is tilted. The solar minima in 1986 and 1996 are shaded in Figure 2. In 1986 V2 was at low heliolatitudes, so the speed was lower than average and the density higher. In 1996, V2 was at $20^\circ$ heliolatitude and it observed a mix of solar wind from high and low-speed streams, so the average speed increased and the average density decreased. The magnetic field was low at these solar minima. At solar maximum the solar wind is relatively slow and dense. The magnetic field is large; the solar cycle variation in solar magnetic field strength results in the solar cycle intensity variation of the GCRs and ACRs observed at Earth.

Shorter scale features are also observed, the most notable the 1.3-year period speed variations observed from 1987-1998 (50). This variation in speed was observed throughout the heliosphere (33) and has been an occasional feature observed in historic solar wind data (61?). A similar period has been observed in convection patterns in the Sun and may be related (35). These variations in the solar wind cause similar periods in cosmic ray intensities (7).

The neutral H in the interstellar medium flows into the heliosphere until it eventually is ionized, predominately via charge exchange with solar wind protons. The newly created ion,
called a pickup ion, is accelerated by the Lorentz force to the solar wind speed and has an initial energy equal to the solar wind energy, about 1 keV. The new neutral (the former ion) retains the solar wind speed as it leaves the heliosphere. The energy gained by the pickup ion comes from the bulk motion of the solar wind. This decrease is partially compensated for by the outward pressure gradient of the pickup ions, which accelerates the solar wind $\sim 5$ km/s by 100 AU (31). The decrease in solar wind speed due to these pickup ions has been derived by comparing speeds at V2 to those observed by Ulysses and at 1 AU (64; 56). Just inside the V2 TS crossing at 84 AU, the speed had decreased by almost 20% and the hot pickup ions comprised about 20% of the solar wind density. Thus the pickup ions from the LIC remove about 35% of the flow energy before the solar wind reaches the TS.

Fig. 3 Yearly averages of the V1 magnetic field (squares) magnitude compared to those predicted by the Parker model (solid line). The solar wind speed is not measured on V1, so the Wang-Sheeley model (65) was used to determine the speed at V1; the dashed lines shows predictions for other speeds.
The solar wind temperature observed at V2 does not decrease adiabatically; in the inner heliosphere some of the heating comes from interaction of the solar wind streams, but beyond 10 AU pickup ions are the main heat source (30; 59). These ions are formed with a ring distribution (the particle trajectories are perpendicular to the field) which is unstable, driving magnetic fluctuations which isotropize the distributions. The waves transfer a small amount (∼4%) of their energy to the thermal protons, which can heat the solar wind sufficiently to match the observations (59; 37).

Cosmic ray transport is inhibited when magnetic fields are strong, such as at solar maximum. But smaller scale magnetic field increases also decrease the cosmic ray flux. Two major generators of enhanced field regions are ICMEs and fast solar wind streams. The Sun has regions of fast and slow flow; as it rotates the flows in some radial directions alternate between slow and fast wind. The fast wind streams overtake the slow wind streams; a compression region, called a corotating interaction region or CIR, with higher density and field, forms between these two solar wind streams. By 2-3 AU a forward-reverse shock pair forms at the stream boundary and moves away from the interaction region. These corotating shocks are observed out to about 35 AU and modulate cosmic ray fluxes and accelerate lower energy particles (see review (2)).

ICMEs are ejected from the Sun with a range of speeds (see review (39). High speed ICMEs compress the solar wind ahead of them and drive leading shocks which can form very near the Sun. ICMEs are characterized by large magnetic field strengths. The compressed sheath region between the shock and ICME also has an enhanced magnetic field. ICMEs produce the largest Forbush decreases observed at Earth. Solar activity varies over a solar cycle, with many more ICMEs at solar maximum than at solar minimum (24). As the ICMEs move outward, they expand until they reach 10-15 AU (55); during solar maximum as much as 40% of the solar wind 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 later ICMEs catch up to earlier ICMEs and merge, compressing the solar wind to form regions of high magnetic field and (often) density called merged interaction regions (MIRs) (6; 12; 52).

The density enhancements observed in Figure 2 near solar maximum from 2000-2004 are MIRs. These features become better developed and larger with distance and dominate the solar wind structure in the outer heliosphere near solar maximum. The magnetic field, speed, density, and dynamic pressure in these MIRs were all correlated, resulting in roughly two large pressure pulses per year (53). These MIRs produce decreases in the cosmic ray flux due to their enhanced magnetic field. The pressure pulses associated with these MIRs should push the TS outward; for example, the pressure pulse which passed V2 in late 2002 pushed the TS outward so that V1 was no longer in the TS foreshock region (54).

3 Cosmic Rays: The CR-B Relation

A quantitative relationship between the change in the > 70 MeV/nuc cosmic ray intensity (I) and the strength of the magnetic field (B) was discerned by Burlaga et al. (7) in the Voyager observations made near 11 AU. This empirical relationship is dI/dt = - D(B/B_{av}) for B > B_{av} and dI/dt = R for B < B_{av}, where B is the daily average of the magnetic field strength, B_{av} is the average B over one year or more, D and R are constants, and t is time. The CR-B relation does not explain every detail of the cosmic ray variation, but does describe the observations that the cosmic ray intensity decreases when B is greater than average and increases at a constant rate when B is less than average. This relationship has been observed from 10 AU
in 1983 to 83 AU in 2007, with D fluctuating about \( \sim 0.003 \) and R decreasing linearly with increasing time from \( \sim 0.002 \) in 1983 to \( \sim 0.0006 \) in 2001 (14).

The large-scale fluctuations in B that enter the CR-B relation can be viewed in two ways (14): 1) a deterministic point of view, where one considers regions with \( B > B_{av} \) as interaction regions, and 2) a statistical point of view where one treats the time series as a multifractal time series. Burlaga et al. (9) show that the magnetic field fluctuations observed at different phases of the solar cycle can be simulated with just a few parameters derived from the observations of multifractal spectra. The following discussion uses the deterministic language.

Interaction regions were defined by Burlaga and Ogilvie (5) as regions in which B and the total pressure (magnetic and thermal pressure) are significantly higher than average. Interaction regions can be produced by the steepening of corotating streams, shocks, magnetic clouds, and other ejecta, as well as by the interaction among these flows (in which case they are called “merged interaction regions”, MIRs). Burlaga et al. (10) define three classes of MIRs: 1) corotating merged interaction regions (CMIRs), produced by interactions among corotating streams, 2) global merged interaction regions (GMIRs) produced by interaction among a series of transient streams and other flows over a period of only a few solar rotations or more, and 3) local merged interactions (LMIRs) produced by the interactions among a few transients. The density and temperature as well as B are enhanced in CMIRs. The density is often, but not always, enhanced in GMIRs (51). The structure and dynamics of MIRs is discussed in detail in the book by Burlaga (12).

Figure 4 shows the relationship between B and the cosmic ray intensity observed by Voyager 2 at 31 AU (12). When transient flows carrying strong magnetic fields moved past the spacecraft, a relatively large decrease in the cosmic ray intensity was observed, as shown in intervals 0, 1 and 2. The cosmic ray intensity started to recover in the weaker magnetic field after the passage of each MIR, but the second and third MIRs arrived before this recovery was complete. The result was a significant net depression in the cosmic ray intensity during an interval of \( \sim 100 \) days. A series of MIRs moved past Voyager 2 during intervals 3 through 9 in Figure 4. Each MIR produced a decrease in the cosmic ray intensity which was followed by a recovery to nearly the initial value. The net result was little change in the cosmic ray intensity from DOY 100 through 365, 1990. This situation tends to occur during the declining phase of the solar cycle when corotating streams are dominant (8), as reported in the V2 observations from 2001 - 2005 (53), during 1994 (13) and during 1984 (8).

Transient flows sometimes dominate the solar output for several solar rotations, most often near solar maximum. These flows form extended regions with strong magnetic fields which are barriers to inward cosmic ray transport and produce a long-lasting decrease in the cosmic ray intensity. Near solar minimum, the magnetic field is weak and the cosmic ray intensity increases for several years. The recovery term then dominates the CR-B relation, but isolated MIRs produce localized depressions in the overall recovery of the cosmic ray intensity (8), or a decrease in the rate of recovery (21).

In the heliosheath, the simple CR-B relationship does not hold at either V1 or V2. For example, Figure 5 (21) shows V2 observations of B and the cosmic ray intensity before and after V2 crossed the termination shock. In the supersonic solar wind, two MIRs (MIR-1 and MIR-2) stopped the recovery of the cosmic ray intensity and produced local depressions in the cosmic intensity profile, consistent with the CR-B relation. In the heliosheath, on the other hand, the strong and weak magnetic fields did not produce changes in the cosmic ray intensity consistent with the CR-B relation. The strong magnetic field from DOY 309-320 produced no decrease in the cosmic intensity. The relatively weak B in region F was associated with a decrease in the cosmic ray intensity (rather than the expected increase). And the
strong fields from DOY 370-430 were associated with increasing (rather than decreasing) cosmic ray intensity. It is not known why the CR-B relation does not describe the observations in the inner heliosheath. Perhaps the lack is causally related to a change in the nature of the turbulence (from nearly incompressible in the supersonic solar wind to compressible in the heliosheath) as discussed below.

4 The Termination Shock

The first evidence that the Voyager spacecraft were near the TS was the observation of foreshock particles streaming into the heliosphere from the heliosheath along the magnetic field lines (41). These particles are observed when the connection distance along the magnetic field line from the spacecraft to the TS is short enough that particles streaming along field lines from the TS reach V2 before they are convected downstream by the solar wind. These particles are analogous to the foreshock particles observed upstream of Earth. Variations in plasma pressure and magnetic field direction affect the intensities observed in the foreshock since they change the distance along the field lines between the TS and the spacecraft. At planetary foreshocks these streaming particles affect the plasma flows, but no changes in solar wind parameters produced by these particles have been reported at the Voyagers.
The first evidence of the TS in the solar wind plasma data was a decrease in the V2 solar wind speed from 400 to 300 km/s starting 80 days before the TS crossing (57). This decrease occurred in three distinct steps; the first two steps are associated with large increases in the magnetic field strength but their cause is not understood. The third decrease, from 350 - 300 km/s, is coincident with an increase in the low-energy charged particle flux; this precursor effect had been predicted (25). The observed inward pressure gradient force due to these particles is equal to that needed to slow the solar wind (32). Thus the TS is the first example of an energetic particle moderated shock, where the particles accelerated at the shock modify the shock structure.

V1 crossed the TS during a gap in the tracking of the spacecraft on 16 Dec. 2004 at 94 AU, but despite this gap several signatures indicated that V1 had entered the heliosheath. Figure 6 shows that the magnetic field strength increased by a factor of ~3 across the data gap, consistent with crossing the termination shock (15). A more distinctive signature of the heliosheath is the large increase in the variability of B in heliosheath, which is illustrated by the spread of the 48 sec averages of B(t) in Figure 6 and by the relatively large values of the SD16 (the daily average of the standard deviation of 1.9 sec averages with respect to the 16 minute averages of B) behind the shock. Although the plasma instrument on V1 does not work, the LECP instrument can estimate plasma speeds using the Compton-Getting effect and found a decrease in speed across the TS (28).
The first V2 TS crossing also occurred in a data gap, but then the TS was finally observed when the TS moved across V2 three times in a 5 hour period on 30 Aug. 2007 when V2 was at 84 AU. The shock is very dynamic and reforms on the scale of several hours. In two of the three crossings, the shock had the classic structure of a super-critical, quasi-perpendicular shock (20). The TS had a foot region, formed by reflected ions, with increased B and lower V. The main change in plasma and field occurred in the ramp region, followed by an overshoot in B and then fluctuations downstream of the TS. The magnetic field high-resolution, 2.08 samples/s, data resolved the structure in the ramp, showing quasi-periodic fluctuations with length scales of about 1000 km (20). The third crossing looked very different, with two regions which looked like ramps, and Burlaga et al. (20) suggest that the TS was observed as it was reforming. The shock strength was 2-3 and the TS speed was 60-100 km/s, similar to the speeds of planetary bow shocks (57). An increase in the variability of B at small scales was also observed behind the termination shock by V2.

The TS differs from planetary bow shocks in that most of the flow energy is not transferred to the thermal plasma. The temperature in the heliosheath ranges from 50,000 - 150,000 K, well below the few million K temperatures observed in planetary magnetosheaths. The difference is caused by the pickup ions. When a substantial fraction of pickup ions are present (at the TS they comprise ~20% of the total density (56)) they dominate the thermal pressure of the solar wind. At the TS, almost all the thermal ions pass directly through the shock potential (66), unlike planetary bow shocks where up to 50% of the thermal ions are reflected (?) . The pickup ion distribution is much broader than the thermal ions in energy so some of these ions are reflected. The flow energy of the solar wind thus goes mainly to the pickup ions; they gain about 65% of the energy, thermal ions get 20%, and more energetic
ions get 15% (27). One consequence of the low heliosheath plasma temperature is that the flow in the heliosheath remains supersonic with respect to the thermal plasma. The sound speed of the pickup ions is greater than the flow speed, so it is these waves which convey information about the LIC upstream.

The TS is not symmetric. The first clear evidence of the asymmetry was the location of the inner boundary of the foreshock. V1 entered the foreshock at 85 AU. When V1 crossed the TS at 94 AU, V2 was entering the foreshock region at 75 AU. The V2 TS crossing also occurred 10 AU closer to the Sun than at V1, at 84 AU (20; 57; 27; 60). Models of the TS location using the solar wind dynamic pressure to drive the TS motion show that the TS should move inward only 2-3 AU between the two TS crossings, so TS motion cannot account for the asymmetry. The asymmetry can be reproduced in models if the LIC magnetic field is of order 3-5 nT, much larger than pre-Voyager estimates of \( \sim 1 \) nT, and is at the right orientation to the LIC flow (although models differ on what that orientation should be) (36; 44; 45; 47; 48). These models predict that the HP should also be closer in the V2 than V1 directions.

5 The Heliosheath

Figure 7 shows the plasma data in the heliosheath. The speed is highly variable for the first year after the TS crossing, varying from 100 to over 250 km/s with an average value of about 150 km/s. After 2009.8 the fluctuations were much smaller. In mid-2009 the speed decreased over a few months to 120 km/s and stayed at that value until 2010.5, when the speed increased back to 150 km/s. The density has variations of up to a factor of four before 2009.8. The average density in this time period drops from 0.002 to 0.001 cm\(^{-3}\). The density fluctuations diminish after 2009.8. The temperature and density are closely correlated, with the compressed regions having both higher density and temperature. The average temperature decreases across the heliosheath, from 150,000 K near the TS to 40,000 K in mid-2009, and the fluctuations decrease after 2009.8. Several possibilities could cause the decrease in the fluctuations. One is that the TS motions drive variations in the inner heliosheath and once V2 is far from the TS they damp out. Another is that V2 has entered a region where the upstream solar wind variability is less; Roelof et al. (58) suggest that after the TS crossing an equatorward extension of the southern polar coronal hole creates a series of CIRs which cause variability in the solar wind reaching V2 in the heliosheath.

5.1 Heliosheath Magnetic Fields

5.1.1 Large-scale fluctuations of B

Figure 8 (23) shows a plot of the daily averages of B (a), azimuthal angle \( \lambda \) (b), and elevation angle \( \delta \) (c) as a function of time from 2007.7 to nearly 2009.4 observed by V2 in the heliosheath. The 1 \( \sigma \) uncertainty in B is relatively large, \( \pm 0.05 \) nT, and the uncertainty in each component of B is \( \pm 0.04 \) nT. Thus the uncertainty in the angles is very large, particularly when B is weak. Nevertheless, the “away” polarity becomes more prevalent in the latter half of the interval, which is related to the motion of the heliospheric current sheet (HCS) past V2 toward the solar equatorial plane (23). The decrease in variability observed in the plasma at V2 is not observed in the magnetic field; however, the large-scale variations in B in Figure 8 have a different character before and after 2008.6. Between the crossing of the termination
Fig. 7 Daily averages of the plasma speed, density, and temperature observed by V2 in the heliosheath.

shock and 2008.6 the broad region of intense magnetic fields produces a lognormal distribution of B, which might be related to a compression of magnetic fields by an increase in speed as the HCS moves below the latitude of V2. After 2008.6, the distribution of B is more nearly Gaussian at V2, similar to that observed by V1 in heliosheath. These results are discussed in more detail by Burlaga et al. (23). The character of the large-scale variations in B observed by V1 in the heliosheath is discussed by Burlaga et al. (16; 17; 18; 19).

5.1.2 Compressible turbulence

Figure 9 shows a 6-hour interval which has large variations in the 48 sec averages of B and small variations in the direction of B (16). The constant direction indicates that the “turbulence” in the inner heliosheath is highly compressive. This behavior is opposite to that observed in the supersonic solar wind where the flow is non-compressive.

The 48 sec averages of B have large measurement uncertainties and considerable effort is necessary to remove noise and spurious signals. For this reason, only a fraction of the data
have been reduced to a form that is publishable. Even after the data have been processed to the extent that time and resources allow, uncertainties remain in the data which can lead to false conclusions. For example, the data from DOY 9.2 to 9.4, 2005 in Figure 9 appear to contradict what was said in the preceding paragraph, showing small variability in $B$ and large variability in the magnetic field direction. However, this variability is simply an artifact associated with the weak magnetic fields (0.05 nT) in the interval. In general, the 1-σ uncertainty in each component of $B$, after correcting for noise and spurious signals, is $\sim 0.02$ nT for V1 and $\sim 0.03$ nT for the V2 data resulting from contamination by the highly variable spacecraft magnetic field which is 0.1 - 0.2 nT on average.

Figure 10 shows the magnetic field variations during a 20 day interval. The changes in the magnetic field are primarily in the magnetic field strength which often changes by large amount within several hours, while the direction of the magnetic field changes very little. This indicates that the “turbulence” is highly compressible during this longer interval as well. This behavior is characteristic of the small-scale fluctuations in the heliosheath, in contrast to the nearly incompressible turbulence observed in the supersonic solar wind.

Figure 11 (22) shows four intervals, each of several hours duration, with large variability in the magnitude of $B$. In general, the profile of $B$ can change from day to day, and on some days $B$ is constant (22). Thus, the profiles are non-stationary and one cannot compute power spectra. The “turbulence” is not homogeneous; rather, it appears to consist of both coherent and stochastic structures. Figure 11 shows that large changes in $B$ occur on a scale of 10 - 20 minutes. From the speeds measured by the V2 plasma instrument, it was determined that the lengths scale of these changes is 60,000 - 120,000 km. The Larmor radius $R_L$ of a 4 keV pickup proton is $\sim 60,000$ km (10 min) and that of a 1 keV pickup proton is 30,000 km (5 min).
The scale of the changes in $B$ is likely determined by the pickup proton population, but we do not know the characteristic Larmor radius of a pickup proton at various positions behind the termination shock. If one had a theory that provides the scale of the changes in $B$ in Figure 10, then one could determine the width in units of $R_L$ and from this one could calculate the effective temperature in heliosheath (22). For example, if the length scale of the jumps in $B$ were $4 \, R_L$, then the characteristic temperature would be $1.3 \times 10^7 \, K$.

Burlaga et al. (21) show that the distributions of the increments of $B$ on scales from 48 sec to 6.8 hr observed by V2 from DOY 245 - 301, 2007 are described by the Tsallis distribution of non-extensive statistical mechanics (62) or, equivalently, the “q-Gaussian” related to the generalized central limit theorem (63). The distribution of increments of daily averages of $B$ on scales from 1 to 128 days, observed by V1 behind the termination shock can also be described by the Tsallis (q-Gaussian) distribution function (19). Thus, the Tsallis distribution describes the variability of $B$ in the heliosheath on a wide range of scales.
Fig. 10 V1 48-sec. averages of the heliosheath magnetic field strength $B$ (a) azimuthal angle $\lambda$ (b) and elevation angle $\delta$ (c).

5.1.3 Magnetic Reconnection Signature

The HCS is carried out with the plasma. At the TS, the plasma flow slows and the HCS crossings become closer together. As the speed further slows and the plasma is compressed against the HP, the HCS crossings may become regions where reconnection occurs. Reconnection and its consequences have been suggested as a possible acceleration mechanism for the ACRs (40; 29). A magnetic reconnection signature was observed near a sector boundary in the heliosheath in the V1 magnetic field data (16). The structure, illustrated in Figure 12, is characterized by a depression in $B$ from $B_1 = 1.0 \text{ nT}$ to $B_{\text{min}} = 0.02 \text{ nT}$ and back to $B_2 = 0.09 \text{ nT}$ at a large change in direction of $B$. Similar structures were first identified in the supersonic solar wind by Burlaga (3) and Burlaga and Ness (4), who called them “D-sheets” and suggested that they might be related to magnetic reconnection. Burlaga and Ness (4) showed that a minimum of $B$ was related to the magnitude of the change of the magnetic field direction, as one would expect if opposite components of the magnetic field canceled, viz., $4 B_{\text{min}}^2 = B_1^2 + B_2^2 + 2 B_1 B_2 \cos(\theta)$. Burlaga (3) showed that in several D-sheets the
depression in B was related to an increase in the density, speed, and temperature. The signature is the same as that observed by Gosling et al. (34) and others in modern high-resolution observations. The event shown in Figure 12 is unique in the V1 data, so reconnection is not important in the inner heliosheath, but it may become more so as the Voyagers get closer to the HP.

5.2 Comparison to models

The basic geometry of the heliosheath flow requires that the flow slow down and turn tailward as it approaches the HP. The magnetic field will be compressed against the HP and increase (1); this increased magnetic pressure will drive the plasma tailward along the magnetic field lines creating a plasma depletion layer comparable to that observed in planetary magnetosheaths. If B in the heliosheath is normalized to B at 1 AU, the field increases across the heliosheath at a rate consistent with model predictions (21; 47).

Figure 13 compares the flow angles observed at V2 with model predictions. Flow angles are in the RTN coordinate system, where R is radially outward, T is parallel to the plane of the solar equator and positive in the direction of the Sun’s rotation, and N completes a right-handed system. Before the TS the flow is close to radial. At the TS the flow diverts in the N and -T directions. For flow directly away from the nose, the flow angles in the RT and RN planes would be roughly equal. The observations show that the RT angles are larger than the RN angles by roughly 10° across the heliosheath, so more of the plasma moves around the side than around the pole in the southern heliosheath. This flow angle difference
Fig. 12  Structure of the D-sheet at the beginning of a sector boundary observed by V1 in the heliosheath. The depth of the depression in B is related to the change in direction of B in the manner predicted by a geometrical model of magnetic reconnection (see text). The panels show 48 s averages of $B$, $\lambda$, and $\delta$. From (16).

starts at the TS; assuming the initial flow angles in the heliosheath result from the angle between the radial solar wind flow and the shock normal, the shock must be blunter in the RT than RN direction, so the heliosphere be flattened in the southern pole. The lines show model results from Pogorelov et al. (?); the solid lines show the results for a stationary heliosheath, the dotted lines assume a linear inward heliosheath motion based on the observed decrease in solar wind pressure. These lines are in reasonable agreement with the flow angle data, although we note that no model simulation to date incorporates the observed case of a downstream solar wind with supersonic SW protons and subsonic pick-up ions which determine the pressure gradients which influence the flow direction.

Although model flow angles agree well with the observations, the velocity components do not agree as well and the radial speed $V_R$ observations are difficult to understand. Figure 14 shows the speed components observed by V1 and V2 and model predictions. Since the plasma instrument on V1 does not work, the V1 radial and tangential speeds are derived from the LECP data using the Compton-Getting effect (28). The normal speed is not known. At V2, $V_R$ averages about 130 km/s from 84-89 AU, then decreases to about 100 km/s. The
V1 \( V_R \) is about 120 km/s just after the TS, then decreases to near 0 due to the TS moving inward (38), then increases to an average of about 70 km/s before beginning a monotonic decrease at 104 AU. In mid-2010 at 113 AU, the average V1 \( V_R \) is approaching zero. Thus the radial speeds observed at V1 and V2 in the same region of the heliosheath, as determined by distance from the TS, differ by a factor of 2 or more. The speeds predicted by the model are in between, slower than observed at V2 and larger than observed at V1. The model predicts very similar speeds at V1 and V2, which would be expected as the shock strength was similar at the V1 and V2 TS crossings. The higher speeds observed at V2 are consistent with the weak TS which was observed. The \( V_T \) and \( V_N \) components are in the expected directions but generally larger than the model prediction. The \( V_N \) component on V1 cannot
be measured and much of the flow could be northward at the V1 location; the model shows a northward flow near 50 km/s.
6 Summary and Conclusions

Both Voyager spacecraft have crossed the TS and entered the heliosheath. Inward moving cosmic rays must traverse both regions to reach 1 AU. The supersonic wind in the outer heliosphere has evolved into a region dominated by large-scale (>~ month) structures. The solar wind is slowed when interstellar neutrals are ionized and the resulting pickup ions are swept up by the wind. These pickup ions are hot and dominate the plasma pressure outside 30 AU. At solar maxima, MIRs dominate the plasma structure. These MIRs form when ICMEs merge and create regions of high speed, density, temperature, and magnetic field. Corotating interaction regions form in the declining phase of the solar cycle, driven by fast coronal hole solar wind. These interaction regions have enhanced magnetic fields and are barriers to inward cosmic ray transport inside the TS; when B is high the cosmic ray intensity decreases and vice versa. Beyond the TS, in the heliosheath, this relationship no longer holds.

The plasma and field are highly variable in the heliosheath. The plasma is compressed at the shock, which has a shock strength of 2-3. Most of the flow energy is transferred not to the thermal plasma but to the pickup ions, which dominate the thermal pressure on both in the supersonic solar wind and in the heliosheath. The flow directions are consistent with model predictions at V2, but the radial speeds at V2 are larger than those at V1 by a factor of 2. The magnetic field increases across the heliosheath if the observations are normalized to the decreasing solar field. Variations in the magnetic field strength of factors of 2-5 are often observed on time scales of 5-10 minutes, comparable to the pickup ion Larmor radius. The magnetic field variations are compressive, unlike in the solar wind. Several models hypothesize that reconnection will become an important mechanism for particle acceleration as the solar wind approaches the HP, but only one example of reconnection has been observed to date. The TS and HP should be moving inward in response to the current decrease in solar wind pressure. Combining this inward motion with model results of the heliosheath thickness (47; 45) suggests that the HP crossing could occur as early as 2015 at both V1 and V2.

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References

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