Charting the heliosphere in three dimensions

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Introduction

Space physicists continue their exploration of the solar system's home in the galaxy -- that bubble of space, called the heliosphere, carved out of the interstellar medium by the solar wind. Studies of the heliospheric plasma are driven by the search for answers to questions such as: What mechanisms are responsible for the acceleration of the solar wind? How do the properties of the solar wind evolve with distance from the Sun? What is the nature of the interaction of the solar wind with the interstellar medium?

The principal progress made in the last four years has come from data obtained by the Pioneer and Voyager spacecraft moving away from the Sun at roughly 3 AU/year, from the first measurements at high latitudes currently being made. by the joint European-NASA mission named Ulysses, and from continued remote sensing of the inner heliosphere. This review focuses on the average values of the plasma velocity, density, and temperature and the magnetic field in different regions of the heliosphere, leaving discussion of the details of many important structures and processes to other papers.

The Outer Heliosphere

In mid-1994, Pioneer 10 was -60 AU from the Sun, while the solar ranges of Voyagers 1 and 2 *were* -56 and 42 AU, respectively. Even at such great distance.s, the solar wind speed, averaged over a solar rotation or longer, is close to that observed near Earth [*Barnes et al.*, 1992; *Burlaga and Ness*, 1993a; *Belcher et al., 1993; Gazis et al., 1994]. Both* the Voyager and Pioneer data continue to show both solar-cycle variations and -25-day variations associated with solar rotation. Richardson *et al. [1994]* have also reported a 1.3-year periodicity in solar wind speed at both Voyager and Earth over the years 1987-1994; the cause of the 1.3-year variation is not known. The. amplitudes of all these speed variations diminish with distance from the Sun due to the transfer of momentum when fast wind collides with slower wind in its path. Figure 1 shows daily averages of the speed and density of the solar wind observed by Voyager 2 between January, 1990, and June, 1993, when the spacecraft was 31 to 39 AU from the Sun [*Belcher et al., 1993]*. The -70 km/s variations measured at Voyager in 1993 were considerably smaller than the -300 km/s variations measured during the. same period near Earth by IMP *8.* (IMP = Interplanetary Monitoring Platform; IMP 8 has monitored the near-Earth solar wind since 1973.)

The Voyager and Pioneer data have recently been reprocessed using new algorithms which allow the computation of ion temperature to lower values than previously possible [*Gazis et al.*, 1994]. The average proton temperature decreases with increasing solar distance r as $r^{0.7}$ out to 20 AU, and is less well determined but consistent with that power-law cooling rate out to the present distances [*Gazis et al.*, 1994]. When compared to the $r^{-5/3}$ power law expected for adiabatic expansion, it is clear that something continuously heats the protons, but the energy-transfer mechanisms are not yet identified. Interplanetary shocks are important in determining the structure, dynamics, and thermodynamics of the solar wind inside -10 AU [*Whang*, 1991], but both the number and the strength of shocks are strongly diminished at greater distances [*Burlaga, 1994*]. It is not yet known whether the plasma heating in the outer heliosphere is caused by turbulent cascades, by instabilities resulting from the pickup of interstellar ions, or by other mechanisms.

Even less is known about the thermodynamics of electrons in the outer heliosphere. The instruments on Voyager can measure electron energies only above a 10 eV threshold and have therefore obtained little electron data beyond 10 AU. Ulysses is the first spacecraft to be flown beyond 1 AU with the capability of resolving the two components of the interplanetary electron distribution -- namely the thermalized core population and the nearly collisionless, higher energy halo population which carries most of the heat flux from the corona into the wind. *McComas et al.* [1992] reported that the core electron temperature observed by Ulysses between 1 and 4 AU decreased, on the average, as $r^{-0.7}$, which, perhaps surprisingly, is the same as the proton temperature profile measured by the Pioneers. The core electron temperature could also be estimated from noise spectra obtained by the radio science experiment on Ulysses, and from those data *Hoang et al.* [1992] reported that there were different power laws for different [wcs of solar wind flow and that the average core temperature was nearly constant from 1 to 3 AU. A power law of $r^{-0.7}$ can, however, be fit through their published data within the rather large error bars. Other results from *McComas et al.* [1992] are that: (1) the ratio of the core temperature to the energy of the boundary between the core and halo populations remains roughly constant at the value theoretically predicted by *Scudder and Olbert* [1979], (2) the ratio of halo to core densities has roughly a constant value of 0.04, which is not readily understood theoretically, and (3) the heat flux drops off as $r^{-2.36}$, which is consistent with data obtained between 0.3 and 1 AU by the Helios missions [*Pillip et al.*, 1990].

Although the direction of the solar-wind flow is usually close to radially away from the Sun, Voyager 2 observed a period of large-scale, systematic north-south flows near solar-activity minimum [*Lazarus et al.*, 1988]. Two different concepts of the cause of those north-south deflections have been developed. One concept is a vortex street created in the region of strong shear between fast and slow streams at different latitudes [*Veselovsky*, 1989; *Burlaga*, 1990; *Siregar et al., 1992; Siregar et al., 1993*]. Recent three-dimensional magnetohydrodynamic simulations of the interactions of stationary streams caused by the tilt of the Sun's magnetic dipole with respect to the Sun's spin axis are also able to reproduce the north-south flows seen by Voyager [*Pizzo*, 1994a, *b*]. Observations farther out in the heliosphere may be able to distinguish between those two concepts because the vortex street would grow with distance while the stream interactions would die out.

The interplanetary magnetic field is, of course, weaker in the outer heliosphere than closer in, but like the plasma sped and temperature, its strength does not decrease monotonically, but shows local maxima and minima related to solar activity as well as to the interaction of fast and slow streams. The heliospheric current sheet (HCS) which divides regions dominated by the magnetic fields of the northern and southern magnetic poles of the Sun can still be discerned at 50 AU and the latitude of the *HCS* is generally consistent with the latitude inferred from measurements of the magnetic field at the surface of the Sun [*Burlaga and* Ness, 1993*b*]. The north-south component of the field has an average value of zero, even at the Voyager 1 location some 30° north of the ecliptic plane, in agreement with Parker's spiral model. The average azimuthal components were consistent with the expected spiral directions in 1986-7, but were greatly disturbed during 1989 when solar activity was high and transient flows can distort the HCS [*Burlaga and* Ness, 1993 *b*].

There is a continuing debate about whether or not there is a flux deficit in the distant magnetic field which, if it exists, would result from a net plasma flow from the equator toward the *poles [Winterhalter et al., 1990; Burlaga and Ness,* 1993*a*]. When fit to a power-law relation, the Voyager-2 plasma data yield proton density proportional to $r^{-2.10\pm0.03}$ and speed proportional to $r^{+0.05\pm0.01}$ [*Belcher et al.*, 1993], which, if taken at face value, would indicate a divergence of the plasma out of the equatorial region, but time (e.g., solar-cycle) variation may alias the radial fits.

The relations between the heliospheric current sheet, magnetic sectors, and stream interaction regions familiar to observers at 1 AU disappear at large distances to be replaced by several types of "merged interaction regions" [*Burlaga et al.*, 1993]. Sometimes transient streams and quasi -steady corotating streams interact to form compound streams even within 1 AU [*Behannon et al.,* 1991]; sometimes two transient streams collide and interact [Phillips *et al.*, 1992]; while at other times single streams maintain their identity to distances of at least 6 AU [*Siscoe* and *Intriligator*, 1993].

The High Latitude Heliosphere

Before the Ulysses mission, in situ measurements of the solar wind plasma had been limited to heliographic latitudes of ≤16° (Because of an instrument failure, Voyager 1, now at ~32°N latitude, can measure the magnetic field, but not the plasma parameters.). Ulysses reached its highest latitude of 80.2°S in September, 1994.

Figure 2 shows the solar wind speed measured by Ulysses as a function of heliographic latitude from the time of the Jupiter flyby in February, 1992, through September, 1994. From Jupiter to -12°S, Ulysses observed rather slow, highly fluctuating solar wind speeds which are not unusual for near-ecliptic, solar maximum conditions near 5 AU. The change at -12°S was caused by both the increasing solar latitude and changes on the Sun, leading to the spacecraft passing in and out of the quasi-steady high speed flow from the southern polar coronal hole, and crossing the low-speed streamer belt and heliospheric current sheet once per solar rotation [*Bame et al.*, 1993]. The high-speed streams seen by Ulysses between roughly 15 and 20°S are probably the same streams seen by Voyager in 1993 (Figure 1). The stream amplitude of ~350 km/s measured at Ulysses was not only much greater than that measured at Voyager, but also slightly greater than that measured in the ecliptic at 1 AU by IMP 8, despite the greater heliocentric distance (>5 AU) of Ulysses. The decline in stream interactions with increasing heliographic latitude between 0 and -20° is evidently greater than the increasing effect of stream interactions between 1 and 5 AU.

Beyond -28°S the spacecraft remained above the current sheet [*Smith et* al., 1993], while after -35°S, it was permanently in the high-speed polar flow [*Phillips et* al., 1994]. Beyond -40°S, the speed observed by Ulysses was usually between 700 and 800 km/s, which is -100 km/s higher than the highest yearly-average speeds measured at high latitudes by remote sensing using interplanetary scintillation (IPS) techniques over the 16-year period 1972-1987 [*Rickett* and Colts, *1991]. The* difference is perhaps not surprising because direct comparisons of IPS data with in-ecliptic spacecraft data have previously shown that 11'S often underestimates the highest speeds.

Even though the origin of coronal mass ejections (CMEs) which cause transient solar wind flows are highly concentrated near the Sun's magnetic equator (i.e., the heliospheric current sheet) [*Hundhausen*, 1993], Ulysses continues [o observe CME flow at high latitudes. There arc some interesting differences between CMEs near the equator and at high latitudes. First, a wide range of solar-wind speeds (from 200 to 1000 km/s, including the spike seen in Figure 2 near 20°S) is observed in near-equatorial CME flows, whereas all the CMEs observed by Ulysses above 40°S latitude had speeds between 650 and 800 km/s [*Gosling et al., 1994a].* Second, some of the high-latitude CMEs were preceded by a forward shock and followed by a reverse shock; such shock pairs driven by the rapid expansion of CME material had no[been previously identified in the solar wind [Gosling *et al.,* 1994*b*].

Solar-rotation averages of the proton flux, normalized to 1 AU, showed a decrease from --4x10s $cm^{-2}s^{-1}$ equatorward of -10° to a fairly steady value of $-2.5x10^{8}cm^{-2}s^{-1}$ between 40° and 60°S [*Goldstein et al., 1995; McComas et al.,* 1995]. The proton temperature observed by Ulysses poleward of 40°S is significantly lower (1 .5x10^5 K) than that in higll-speed streams near the ecliptic (2.3x1@ K) [*McComas et* al., 1995].

To latitudes of 45°S, Ulysses observations of the radial component of the magnetic field, which is the component which comes closest to characterizing the field strength in the source region of the solar wind, remained constant with latitude. At the same time, the relative amplitude of Alfvén waves (propagating changes in the direction of the magnetic field) propagating outward from the Sun increased strongly with increasing latitude and showed longer periods or longer wavelengths than the Al fvén waves seen in high-speed streams in the ecliptic [*Smith et al.*, 1995].

Close To The Sun

There has been no opportunity for in situ measurements of the properties of the solar wind at solar distances less than the 0.3 AU perihelia of the Helios spacecraft. All recent observations of the inner heliosphere have therefore been obtained by remote sensing. Using radio scintillation techniques, *Woo and Gazis [1993]* found that inside 0.3 AU, the variation in the solar wind structure is more pronounced than it is farther out, with most of the fluctuations occurring in the slow wind near the heliospheric current sheet, rather than on the leading edges of high-speed streams. In another study using IPS, Colts *et al.* [1991] were able to study the profiles of velocity versus solar distance between 11 and 90 solar radii (0.05 to 0.42 AU) for 16 solar wind streams. Half the streams had velocity profiles in good agreement with theoretical solar wind models that included moderate amounts of acceleration by hydromagnetic waves, but four of the streams had profiles which were too steep and four others had profiles which were too flat 10 be explained by such models. In a later study [*Coles and Esser, 1992],* it was shown that the wave energy required to explain the acceleration of the streams with normal pro files is consistent with the upper bounds determined from other 11'S observations.

Woo and Goldstein [1994] used spectral broadening of spacecraft radio signals to probe the solar wind in the range of 3 to 8 solar radii (0.01 100.04 AU) under conditions of minimum solar activity. They found that the solar wind speed was approximately 2.2 times greater at -60° latitude than it was near [he solar equator; their result is consistent with earlier 11'S data obtained at solar distances >0.5 AU.

Other data in the inner regions of the solar wind were obtained by the Spartan 201, a spacecraft carrying a while-fighl coronagraph and an ultraviolet coronal spectrometer during a Space Shuttle mission in April, 1993 [*Kohl et* al., 1994; *Strachan et al., 1994; Fisher et al., 1994].* Although velocity, density, and temperature data were obtained out to 3.S solar radii in both coronal streamers and coronal holes, the final results from those experiments arc not yet available. Other flights of Spartan 201 arc scheduled to coincide with the Ulysses passages over the solar polar regions.

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Figure. 1. One-day averages of the solar wind sped and density observed by Voyager 2 between January, 1990, and June, 1993 [*Belcher et al.*, 1993].

Figure. 2. Twelve-hour averages of the solar wind speed observed by Ulysses versus heliographic latitude from February, 1992 through September, 1994 (after [*Phillips et al.*, 1994]).

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Fig

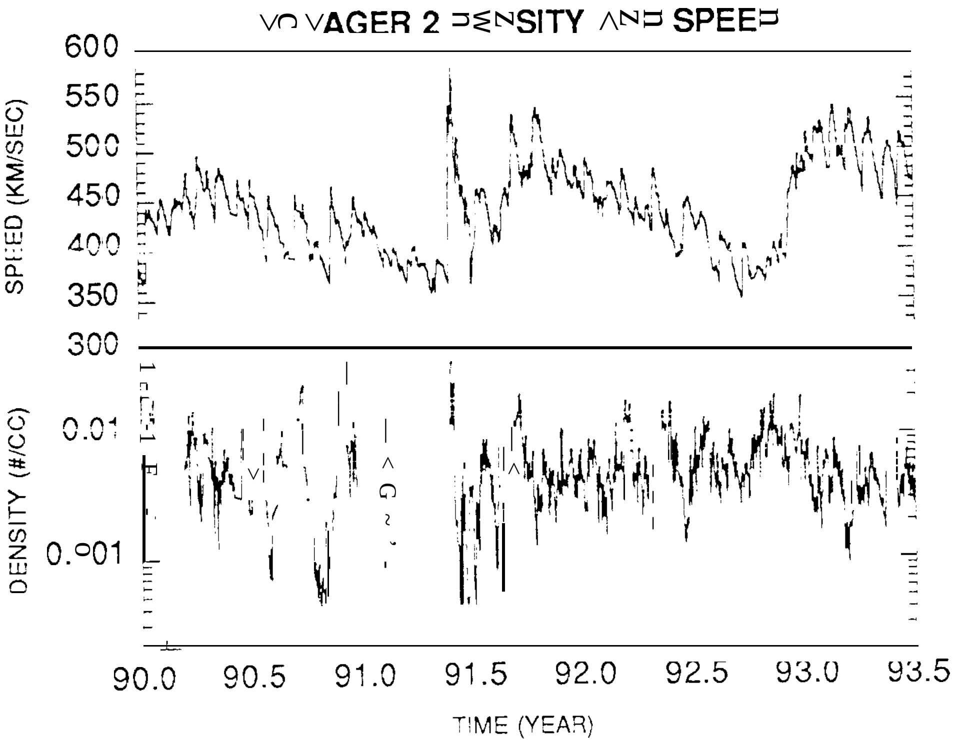
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Fig. 1

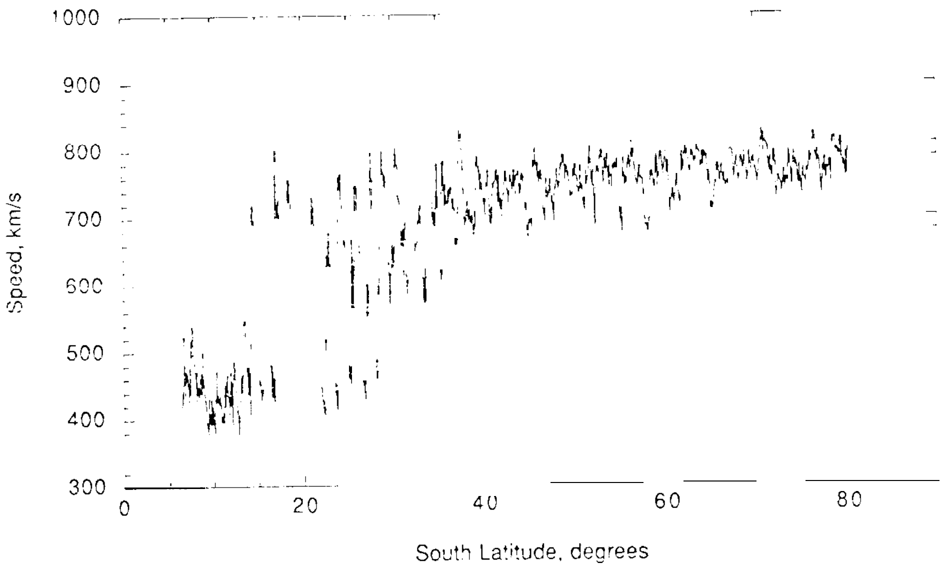
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Fig 2