The solar wind in the third dimension

M. Neugbauer

Jet Propulsion Laboratory, California Institute of Technology, Pasadena,CA91109

Abstract. For many years, solar-wind physicists have been using plasma and field data acquired near the ecliptic plane together with data on the scintillation of radio sources and remote sensing of structures in the solar corona to estimate the properties of the high-latitude solar wind. Because of the highly successful Ulysses mission, the moment of truth is now here. This talk summarizes the principal differences between the Ulysses observations and expectations.

This paper is a review of what we now know about the solar wind at high latitudes compared to what our expectations were before the Ulysses mission. Rather than being exhaustive, the comparison is necessarily brief and focusses on those things most closely related to my own work.

The expectations for what Ulysses would find in the solar polar regions were heavily influenced by the fact that the polar passages would occur during a period of declining and minimum solar activity. At those phases of the solar cycle, the polar regions are covered by large coronal holes, so the expectations were largely based on previous near-ecliptic studies of the properties of the solar wind from polar coronal holes which extended down to near-equatorial regions. One of the most prominent properties of the solar wind from coronal holes is that it is fast, with speeds usually exceeding 600 km/s. Remote sensing of the latitude distribution of solar wind speed using radio techniques has revealed that during periods of declining solar activity and near solar minimum, the solar wind speed increases with increasing latitude to values between 600 and 650 km/s for the 15° bins centered on $\pm 60^{0}$ latitude [*Rickett and Coles*, *1991]*. Ulysses found the polar solar wind speed to be 750-800 km/s, which is somewhat greater than predicted from the radio data, This is not really very surprising because the solar wind from some of the largest near-ecliptic coronal holes has had speeds approaching 800 km/s and because the radio techniques are known to often under-estimate the highest solar-wind speeds, probably because of the effect of integration along the line of sight through both high- and low-speed plasmas [Grail et al., this meeting].

Wang et al. [1990] had the courage to make a quantitative prediction of the speed-versus-latitude variation to be observed by Ulysses, The dashed line in Figure 1 shows the predicted speed profile if the solar magnetic field were dipolar, whereas the solid line shows the same profile based on the solar magnetic field observed in 1983, one solar cycle before the Ulysses polar passage. The dots are 12-hour averages of the speed observed by Ulysses from Jupiter flyby in 1992 through June 15, 1995. *Wang et al.'s* prediction was based on an empirical relation between solar wind speed measured near the ecliptic and the rate of expansion of magnetic field lines between the photosphere and a source surface at 2.5 solar radii. The principal differences between the predicted and the observed speeds are that the observed high-latitude speeds were somewhat higher than predicted and that the latitudinal profile observed by Ulysses did not display a local maximum at mid-latitudes.

One cannot conclude from the differences between the expectations and observations shown in Figure 1 that the empirical and theoretical relations between the speed and the field-expansion factor are wrong. The problem almost certainly lies in the difficulty in predicting the solar field and its extrapolation from the photosphere, where it can be observed, out into the solar wind. Different assumptions about how to carry out that extrapolation can lead to very different results. For example, in comparing the latitude of the last (i.e., highest latitude) appearance of the low-speed streamer belt plasma with expectations based on different methods of calculating the latitude of the heliospheric current sheet, *Phillips et al. [1994]* found an uncertainty of -20° in the predicted location of the heliospheric current sheet.

It has been known for quite some time that the solar wind from coronal holes fills much more of the heliosphere than would be expected on the basis of the fraction of the solar surface covered by coronal holes. Whereas a dipole magnetic field is strongest at the poles, the wind and field from the polar coronal holes expands to lower latitudes with the result that the interplanetary magnetic field is not as dipolar as the field at the surface of the Sun. Comparison of data obtained by Ulysses with near-Earth data obtained by IMP 8 has shown that the spreading out of the polar magnetic field occurs such that the radial component of the heliospheric magnetic field is independent of heliographic latitude [*Balogh et al*,, 1995; *Smith and Balogh*, 1995].

In the quasi-stationary solar wind near the ecliptic plane, corotating interaction regions (CIRs) form where the fast solar wind from coronal holes overtakes slower, streamer-belt wind in its path. As the wind continues out beyond 1 AU, forward and reverse shocks often form at the leading and trailing edges of the interaction regions [*Smith and Wolfe, 1976],* Many such CIRs and shocks were observed by Ulysses, especially as it passed through latitudes at which the spacecraft was alternately, once each solar rotation, embedded first in plasma from the south polar coronal hole and then in plasma from the near-equatorial streamer belt. What was not expected was that no forward corotating shocks (with one exception) were seen poleward of -25°S, whereas reverse corotating shocks continued to be detected until nearly 60°S *[Gosling et al., 1995].* This assymmetry can be explained as the result of a simple tilted-dipole model of the solar magnetic field which results in the forward shock moving into the near-equatorial band of slow wind while the reverse shock moves poleward into the high speed wind.

CIRS were no longer observed in the field and plasma data once Ulysses reached a latitude of -40”S, beyond which the spacecraft was continuously immersed in the flow from the polar coronal hole. All systematic longitudinal variations in the solar wind plasma died away by a latitude of -650S [Phillips GRL paper). It was therefore quite surprising to find that the flux of galactic cosmic rays reaching Ulysses continued to be modulated at the solar-rotation frequency all the way to the highest latitude (80°) reached by Ulysses *[Simpson et al., 1995].* Lower energy particles (<8 MeV) accelerated at the CIRS also continued to be detected by Ulysses up to latitudes of -70°, well after the CIRS themselves were no longer detected *[Simpson et al., 1995],* A likely explanation is that the CIRs continue to modulate the galactic cosmic rays and to accelerate interplanetary particles at distances well beyond those sampled by Ulysses such that the effects observed at Ulysses are caused by processes further out in the solar system on the same field lones as those connected to Ulysses.

The high-latitude solar wind was not completely without structure, however. Earlier Helios observations of the wind from coronal holes had revealed structures in which magnetic and thermal pressures varied out of phase with each other such that the total pressure remained constant [*Thieme et al.,* 1988; 1990]. When observed between 0.3 and 0.5 AU, those pressure-balance structures subtended an angular size of 1-2°, which is consistent with an origin associated with the solar supergranulation structure. By the time the pressure-balance structures reached 1 AU, however, they had broadened out to 3 or 4°. It was therefore somewhat surprising that Ulysses detected similar pressure-balance structures at distances of 3 AU or greater with the occurrence of the pressure-balance structures became more frequent with decreasing solar distance and increasing solar latitude [*McComas et al,,* 1995], The widths of the high-latitude pressure-balance structures were typically 7-100. *McComas et al.* [1995] have suggested that these structures originate in the polar plumes visible in white-light images of the solar corona *[Fisher and Guhathakurta, 1995].*

A different kind of structure observed in the high-latitude wind by Ulysses is the "microstream" which appears as a local peak or dip in the speed profile with a time scale of about a day. The microstreams exhibit increased density and temperature in regions of positive speed gradient [*McComas et al.,* 1995; *Neugebauer et al., 1995]. The* proton temperature and the alpha-particle abundance were both higher at the peaks than at the dips, while the proton flux was the same for the peaks as for the dips [*Neugebauer et al., 1995].* The widths and frequency of occurrence of the microstreams did not change with latitude, which means that the source(s) of the microstreams cannot be longer lived than about a day or two. Although no notice had been paid to microstreams in coronal hole flow at low latitudes, such structures are probably not unique to the high-latitude solar wind; two papers at this conference [Cohen et al., Paularena et al.,] report on similar structures in the early observations by the WIND spacecraft. Further work is clearly required to link the pressure-balance structures and the microstreams to specific solar features.

1(has been known for a long time that the solar wind often contains a strong flux of outward-propagating Alfvén waves [*Belcher and Davis, 1971]* which are strongest in the high-speed, quasi-stationary wind from coronal holes [*Tu et al., 1990].* As expected, the high-latitude solar wind from the polar coronal hole had a very strong flux of such waves [*Balogh et al., 1995; Smith et al., 1995].* The intensity of the waves appears to be a much stronger function of radial dist'ante from the Sun than of solar latitude [Balogh, this conference].

Marsch et al. [1982] reported that in the high-speed wind observed by Helios, the alpha particles often "surfed" on the Alfvén waves, That is, the alphas streamed through the proton fluid at approximately the Alfvén wave speed, so they did not participate in the wave motion. Because the differential streaming between alphas and protons was known to decrease with increasing distance from the Sun [*Marsch et al.*, 1982; *Neugebauer et al.*, 1994], alpha-particle surfing was not expected during the Ulysses polar pass at >2 AU. In actuality, a variety of alpha-particle behaviors was found *[Goldstein et al., 1995].* Far from the Sun or close to the ecliptic there was little differential streaming, as expected, and the alphas participated in the wave motions similarly to the protons. Closer to the Sun at high latitudes, the alphas sometimes surfed. But more surprisingly, the alpha-proton differential streaming speed was often significantly greater than the propagation speed of the Alfvénic oscillations, so in the refererence frame of the alphas, the waves appeared to be propagating back toward the Sun and the alpha-particle oscillations were -180° out of phase with the proton oscillations. The observed wave speed was only -0.6 times the Alfvén speed. *Goldstein et al.* [1995] have proposed that such a significant decrease of the wave speed below the Alfvén speed may be caused by an anisotropic distribution of pickup ions, but that hypothesis is controversial.

The Alfvén waves in the polar regions apparently had an unexpectedly large effect on both galactic cosmic rays and solar wind electrons, The entry of cosmic rays into the inner heliosphere is believed to be controlled or modulated by diffusion, convection, adiabatic cooling, and drifts in the interplanetary magnetic field [*Jokipii, 1986]*. At the present phase of the solar cycle, the drifts would be expected to lead to relatively easy access and a consequent increase in the flux of cosmic-ray ions relative to the flux of cosmic-ray electrons into the polar regions of the heliosphere. This was not what was found. As summarized by *Simpson et al. [1995],* "The increase in the flux toward the poles was modest for most nuclei, much smaller than had been hoped based upon ideas of magnetic field lines open to the interstellar medium that were current prior to the launch of Ulysses", and " The lack of variation of the electron-to-proton ratio with latitude appears to be in clear contradiction to the predictions of models which include a significant role for gradient and curvature drifts [*Jokipii et al., 1977]"*. It had previously been suggested, however, that waves and other structures, such as might be caused by convection-driven motions of the solar footpoints of the polar magnetic field, might considerably slow the access of galactic cosmic rays to the polar heliosphere [*Jokipii and Kota, 1989],* as was apparently the case,

Another surprise was the shape of the electron distribution function at high latitudes. In the high speed wind, the electron distribution typically shows a "strahl" or beam of superthermal electrons aligned with the magnetic field, Helios data showed that in the near-equatorial, high-speed wind the width of the strahl increases with increasing distance from the Sun [*Pilipp et al., 1987].* Table 1 gives some representative results obtained by the solar-wind electron spectrometer on Ulysses. Despite the polar observations being much closer to the Sun than the low-latitude observations, the strahl was wider at -80° than it was at -15°. Something, presumably collisions, must be scattering superthermal electrons out of the strahl; the presence of large amplitude Alfvén waves in the polar flow could perhaps account for the increased scattering by lengthening the path between the Sun and the spacecraft.

Table 1. Width of the electron strahl at two heliospheric locations. Data from *Phillips et al. [1995]*

	Equatorial	Polar
Latitude	-15°	-80°
Distance	5.3 AU	2.2 AU
FWHM of strahl	56°	81°

Next, let us consider the latitudinal dependence of the heavy ions in the solar wind. From UV and X-ray observations, it is well established that the corona is cooler in coronal holes than elsewhere. The coronal temperature at the heliocentric distance where ion-electron collisions effectively cease determines the charge state of the heavy ions in the solar wind. Thus it was expected that the ionization temperature T_{ion} would be lower at high latitudes than at lower latitudes where a variety of solar sources contribute to the flow. That expectation was confirmed by Ulysses [*Geiss et al.*, 1995]. A result that had not been anticipated, however, was the strong correlation between solar-wind abundances and T_{ion}. In the high-latitude wind, the enhancement of elements with low first ionization potential (FIP), or more accurately, first ionization time, was found to be less than in the average low-latitude wind. A strong correlation was found between T_{ion} and the ratio of the densities of Mg (low FIP) to O (high FIP) ions [*von Steiger*, *1993; Geiss*, *1995].* This result reveals a previously unknown relation between the physical processes in the chromosphere where the first ionization occurs and in the corona where the final ionization state is determined,

Finally, we consider the properties of the interplanetary plasma clouds (IPCs) resulting from solar mass ejections (SMEs) at high latitudes (following the nomenclature suggested by Sch wenn [this conference] to clarify the different aspects of what is commonly called a coronal mass ejection or CME). On the basis of coronagraph data from the Solar Maximum Mission, *Hundhausen [1993]* concluded that most SMES originate within 15° of the heliomagnetic equator, which was inclined to the heliographic equator by <30° during the period when Ulysses was exploring the high southerly latitudes. The mean width of the SMEs as they moved through the corona was -40° [*Hundhausen*, *1993]*. Thus one might logically expect that Ulysses would detect the interplanetary manifestations of SMEs at latitudes as high as perhaps 70°. This was, in fact the case; Ulysses observed IPCS at latitudes up to 61 OS. A quote from *D. Sime [1985]* summarizes the expectations concerning the properties of high-latitude SMES and IPCs: "The high latitude events are not expected to be different in average properties from their ecliptic counterparts". That prediction turned out to be inaccurate.

First, the high-latitude IPCs had higher speeds than did their average equatorial counterparts. By comparing the speed distributions of equatorial and high-latitude IPCs, *Gosling et al. [* 1994] concluded that, on the average, the speed of an IPC does not strongly depend on the speed at which the material is observed to move through the corona, but is close to the ambient speed of the plasma in which it is embedded,

There were also differences in IPC properties other than speed, Figure 2 [Gosling *et al.*, *1995]* compares the time profiles of a single IPC observed both near Earth by IMP 8 (on the left side of the figure) and by Ulysses (on the right) at a latitude of -47° and a solar distance of 3.53 AU. One of the more obvious differences is that at IMP, the IPC (labelled CME) was preceded by a forward shock, driven by the large speed difference between the IPC plasma and the low speed wind in its path, while the IPC observed by Ulysses had both a forward shock ahead of it and a reverse shock behind it. Since there was little difference in speed between the Ulysses IPC and the plasma ahead of or behind it, the shocks are believed to have been driven by the expansion of the IPC plasma into the surrounding medium [Gosling *et al,*, 1994]. Such expansion-driven reverse shocks had not been identified in IPC events in the low-latitude solar wind.

Another striking difference between the properties of the IPC seen at IMP and at Ulysses is the helium abundance (labelled "α fraction", in the third panel of Figure 2). The alpha to proton density ratio reached -0.2 at IMP, but never exceeded 0.08 at Ulysses. None of the high-latitude IPCs showed the significant helium enhancements which are often observed in equatorial IPCs. Another, and perhaps related, difference is in the ion charge states; at low latitudes, T_{ion} is usually higher in IPCs than in the ambient wind, whereas no such increase of T_{ion} was observed in the high-latitude IPCS [Calvin, this conference]. Other differences between the IMP and Ulysses observations include the temporal profiles of the proton density (top panel), the temperature (second panel) and the field strength (fifth panel). Some of the smoothing out of those profiles between 1 and 3.53 AU may have resulted from an evolution with increasing distance from the Sun.

SUMMARY

All told, some things turned out as expected, while others did not. A summary of some of the major results is given in Table 2.

Table 2, Summary of Properties of the Polar Solar Wind

Things that turned out as expected:

High-speed flow

Large flux of Alfvén waves

Low ionization temperature

Transient events observed to *-60°* latitude

Things we should have thought of:

Reverse CIR shocks observed at higher latitudes than forward CIR shocks

Surprises:

21 R-accelerated particles poleward of observed CIRS

B_R| independent of latitude

$V_{\alpha p} > V_{wave}$; alphas don't surf

Electron strahl width increases with latitude

Small latitudinal gradient of cosmic rays (intensity and e:p ratio)

Correlation of ionization temperature with elemental abundances

Interplanetary plasma cloud speed ≈ ambient wind speed

Forward and reverse shock pairs around interplanetary plasma clouds

4(high latitudes, plasma in interplanetary clouds not enriched in helium and doesn't have increased T_{ion}

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FIGURE CAPTIONS

Figure 1, Twelve-hour averages of the solar wind speed observed by Ulyses (Dots) plotted versus heliographic latitude and compared to latitude profiles predicted by *Wang et al., [1990]* for a solar dipole field (dashed line) and for the solar field observed at the previous solar minimum (solid line).

Figure 2. Comparison of observations of an interplanetary plasma cloud at two different locations (near-Earth on the left and Ulysses at a latitude of -61° on the right). From *Gosling et al.* [1995].

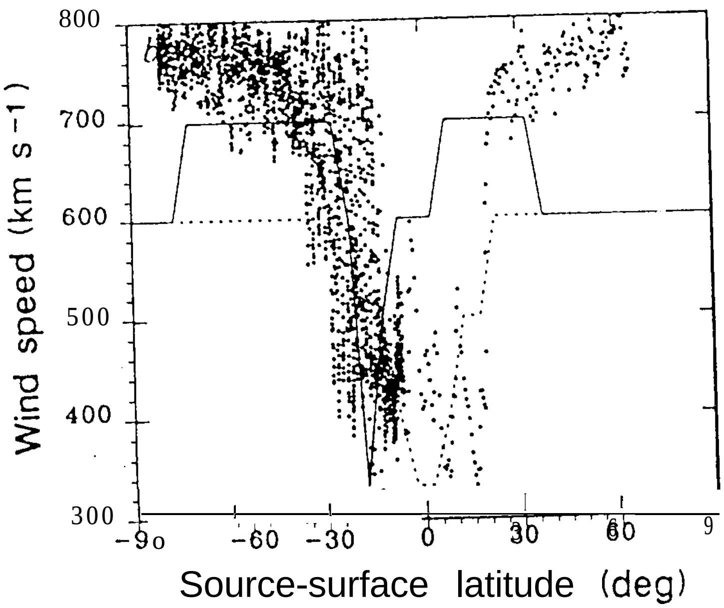
Wind speed (km s −1)
800
700
600
500
400
300
−90
−60
−30
0
30
60
Source-surface latitude (deg)

Fig. 1

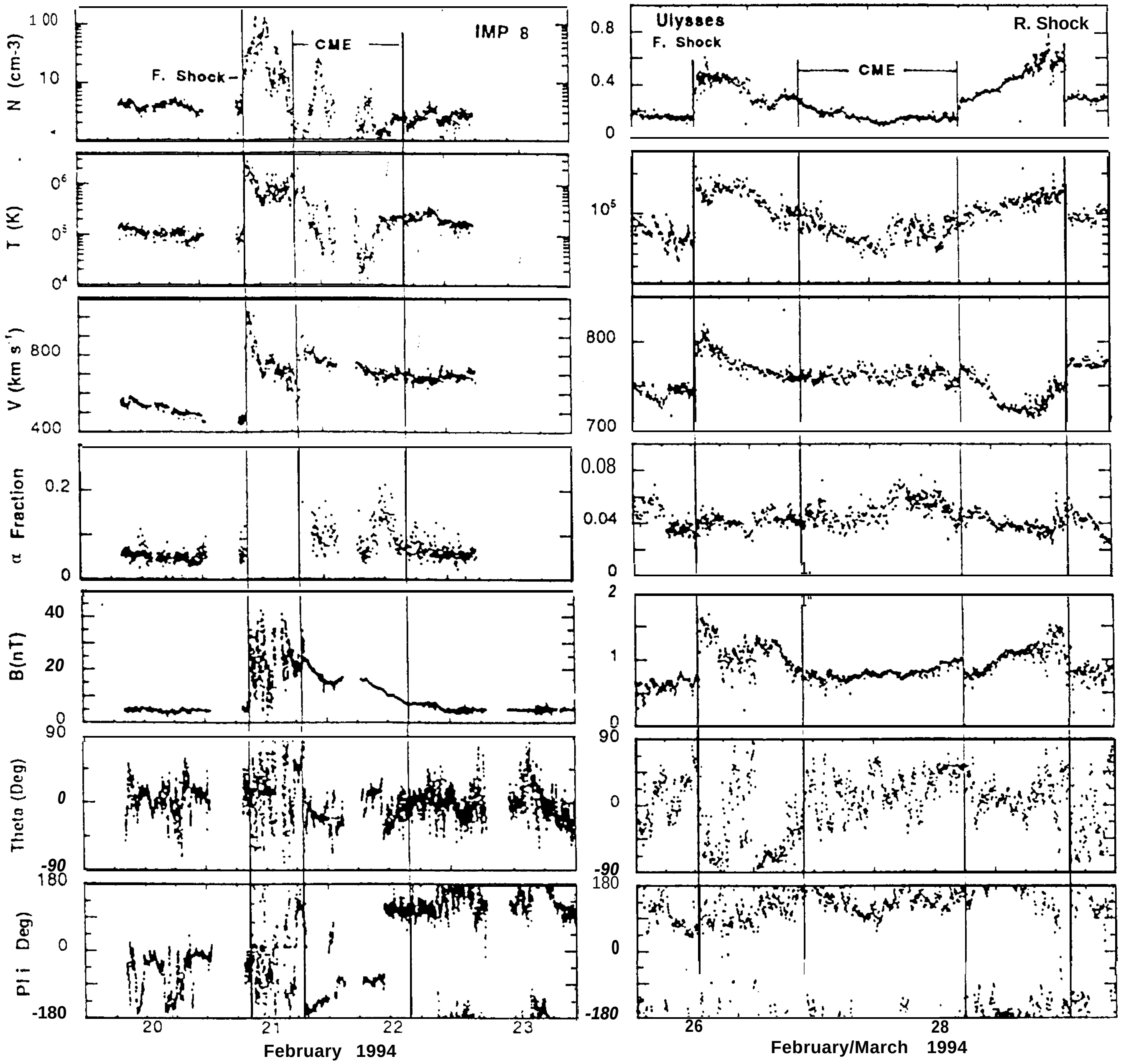
IMP 8
F. Shock
CME
N (cm-3)
T (K)
V (km s-1)
α Fraction
B(nT)
Theta (Deg)
Phi Deg
20
21
22
23
February 1994
Ulysses
F. Shock
CME
R. Shock
26
28
February/March 1994

Fig. 2