Ulysses Solar Wind Plasma Observations at High Southerly Latitudes

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Solar wind plasma observations made by the Ulysses spacecraft through −80.2° solar latitude and continuing equatorward to −40.1° are summarized. Recurrent high-speed streams and corotating interaction regions dominated at middle latitudes. The speed of the solar wind was typically 700 to 800 kilometers per second poleward of −35°. Corotating reverse shocks persisted farther south than did forward shocks because of the tilt of the heliomagnetic streamer belt. Sporadic coronal mass ejections were seen as far south as −60.5°. Proton temperature was higher and the electron strahl was broader at higher latitudes. The high-latitude wind contained compressional, pressure-balanced, and Alfvénic structures.

The solar wind is an ionized gas flowing from the solar corona and consisting primarily of free electrons, protons, and doubly ionized helium. It has been measured at low solar latitudes for more than 30 years. Inferences about the high-latitude solar wind have been drawn from in situ in-ecliptic measurements (*1*) and remote sensing techniques (*2*). The high-speed (600 to 900 km s^{-1}) solar wind flows from coronal holes, whereas the low-speed (300 to 450 km s^{-1}) wind flows from open field regions above or adjacent to the heliomagnetic streamer belt, a closed magnetic field region encircling the sun at the heliomagnetic equator. The nature of the boundaries between sources of fast and slow wind, and the source of medium-speed wind (450 to 600 km s^{-1}), are not well understood. As the solar magnetic cycle nears sunspot minimum, the streamer belt has a moderate (~10° to ~30°) tilt relative to the solar equator and separates large coronal holes which cover the solar poles. Thus, the expected solar wind configuration includes slow wind near the heliomagnetic equator and fast wind near the poles. At intermediate heliographic latitudes, and sometimes at low latitudes, solar rotation and the tilt of the heliomagnetic axis can produce alternating regions of slow and fast wind.

The solar wind plasma experiment on board the Ulysses spacecraft measured the solar wind throughout the southern hemisphere mission phase with separate ion and electron spectrometers (*3*). Here we present observations and analysis starting after the outbound Jupiter bow shock crossing on 16 February 1992, at 5.40 astronomical units (AU) from the sun and −6.4° heliographic latitude, through the peak southerly latitude of −80.2° on 13 September 1994 at 2.29 AU, and continuing through 7 January 1995, when Ulysses reached 1.52 AU and −40.1°.

Wind speed was slow and irregular through June 1992, with little discernible stream pattern (Fig. 1). Beginning in July 1992, a well-defined recurrent high-speed stream was observed, with a location indicating a coronal source at an equatorward extension of the south polar coronal hole (*4*). This stream was observed 15 times, recurring every ~26 days through early July 1993. A coronal mass ejection (CME) in November 1992 resulted in instantaneous wind speeds approaching 1000 km s^{-1}. The two-decade variations in plasma density resulted from alternating encounters with coronal hole and streamer belt wind and from corotating interaction regions (CIRs), compression regions driven by fast wind overtaking slow wind. In April 1993 the minimum wind speed increased from ~400 to 550 km s^{-1}, roughly coincident with the last encounter with the heliomagnetic current sheet, a magnetic field reversal located within the streamer belt plasma (*4*).

Beyond ~2 AU from the sun, the forward and reverse waves bounding CIRs commonly steepened into pairs of fast magnetosonic shocks. The CIRs observed by Ulysses at low latitudes were generally bounded by leading forward shocks and trailing reverse shocks. After the spacecraft passed a latitude corresponding to the tilt of the streamer belt (29°), only one additional CIR-driven forward shock was observed, whereas the reverse shocks persisted. Furthermore, the forward shocks produced northward flow deflections, whereas the reverse shocks produced southward deflections. This pattern was interpreted as resulting from equatorward (poleward) propagation of the forward (reverse) shocks, resulting from solar rotation and the tilt of the streamer belt relative to the rotational equator (*5*). The reverse shocks trailing the CIRs can propagate substantially poleward of the actual interface between fast and slow wind and can influence high-latitude cosmic ray propagation and solar wind particle energization.

In late July 1993 the minimum wind speed at Ulysses increased again, to ~675 km s^{-1}. Since that time, the spacecraft has been continuously immersed in fast solar wind from the south polar coronal hole (Fig. 2). Evidence for equatorial stream interactions persisted in the Ulysses observations until April 1994. The last reverse shock was observed at −58.2°, with a flow deflection and position in solar longitude indicating a source at the main equatorial CIR (*6*). After May 1994 the solar rotation periodicity in wind speed vanished, giving way to an irregular pattern within a speed range of 700 to 800 km s^{-1}. Average speeds increased and variability in density decreased slightly near the highest latitudes. Typical values for speed and scaled density near −80° latitude were 770 km s^{-1} and 2.7 cm^{-3}, respectively, similar to those for flows from the broadest coronal holes in the ecliptic plane (*7*). The continued absence of CIRs and reverse shocks in the most recent data as the spacecraft returned to mid-latitudes may be due to two factors. First, the orbit is eccentric, with mid-latitudes transited northbound at 1.5 to 2 AU

Table 1. Solar wind milestones for the Ulysses out-of-ecliptic mission through 7 January 1995.

Event	Date	Heliocentric distance (AU)	Heliographic latitude (degrees)
Highest wind speed (990 km s^{-1} in CME)	9 Nov 1992	5.17	−19.9
Last slow wind ($v < 450$ km s^{-1})	6 Apr 1993	4.84	−28.3
Last CIR-driven forward shock	29 Jun 1993	4.58	−33.6
Last medium wind ($v < 600$ km s^{-1})	25 Jul 1993	4.49	−35.4
Last CIR-driven reverse shock	3 Apr 1994	3.34	−58.2
Last CME	21–22 Apr 1994	3.24	−60.5

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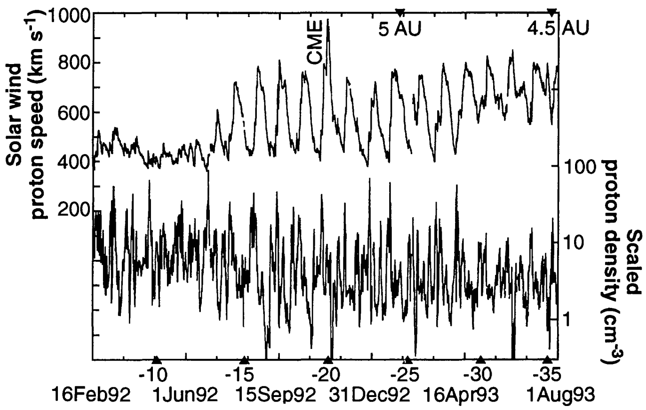

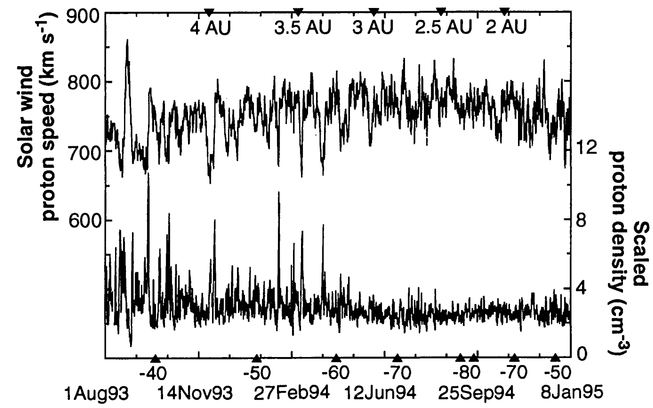

Fig. 1 (left). The 6-hour-averaged solar wind proton speed (top trace, scale at left) and proton density (scaled to 1 AU; bottom trace, scale at right) observed by the Ulysses solar wind plasma experiment from 16 February 1992 through 31 July 1993. Solid triangles at the top mark heliocentric distance; triangles at the bottom indicate heliographic latitude in degrees. **Fig. 2 (right).** Same as Fig. 1, but for the interval from 1 August 1993 through 7 January 1995, when Ulysses was constantly immersed in the high-speed solar wind. Scales have changed from Fig. 1.

as compared with 4 to 5 AU southbound. The waves bounding CIRs generally do not steepen into shocks until roughly 2 AU. Second, the continued evolution of the sun toward its sunspot-minimum configuration resulted in a decrease in the maximum southerly extent of the heliomagnetic current sheet, as inferred from Wilcox Solar Observatory photospheric field measurements, from ~25° to ~12° during April through September 1994 (*8*).

One mid-latitude CME supported a scenario of coronal magnetic reconnection behind the ejection, on the basis of a flux-rope magnetic topology observed by Ulysses and on a Yohkoh observation of a long-duration soft x-ray event (*9*). The last CME observed to date was in April 1994 at −60.5°. Several CMEs were observed at relatively high latitudes, with some unusual properties when compared with in-ecliptic events. All of the identified high-latitude CMEs had speeds comparable with the ambient wind speeds (700 to 800 km s^{-1}) (*10*). They also had relative abundances of doubly charged helium that were similar to or only slightly higher than those in the surrounding wind (~4% of proton abundance), whereas low-latitude CMEs often have substantially higher helium abundances. Three distinctive events were identified that had leading forward shocks and trailing reverse shocks driven, not by a speed differential between the ejecta and the ambient wind, but rather, by expansion caused by high internal pressure (*11*).

Key solar wind fluid parameters—average speed, density, mass flux, and momentum flux—were highly variable at low latitudes but much less variable poleward of −40° (Fig. 3). The relatively smooth variation in median wind speed from −10° to −40° was due to variation of the sampling of fast and slow wind, even though the separation between these two wind types was quite distinct. The solar rotation–averaged maximum speed changed little with latitude poleward of −15°, whereas the minimum speed increased in two steps, from ~400 to ~550 to ~675 km s^{-1}. Mass flux and momentum flux were much more constant than either speed or density as a result of the well-documented negative correlation between the latter two quantities (*12*). To date there is no clear evidence of substantial differences in prevailing fluid properties during Ulysses' northbound transit when compared with similar latitudes southbound, except perhaps for a narrower range for all parameters from −50° to −60° in the more recent data.

The temperature of the solar wind protons exhibited clear differences between high and low latitudes, similar to in-ecliptic findings of differences between fast and slow wind (Fig. 4). The out-of-ecliptic mission, with its prevailing high-speed wind, had higher temperatures for given heliocentric distances and a steeper radial gradient when compared with the in-ecliptic phase with its slow- and medium-speed wind. The Ulysses temperatures are consistent with fast-wind and medium-wind values for 1 AU determined from measurements from the IMP-6, IMP-7, and IMP-8 missions (*7*).

A prevailing difference in the character of the solar wind electron distribution functions was observed between low and high latitudes (Fig. 5). The suprathermal antisunward field-aligned beam, or strahl, which carries most of the electron heat flux from the hot corona to the cold outer heliosphere, was significantly broader in angle at high latitudes than for high-speed flows at low latitudes. This result is counter to the expectation that the shorter field-aligned path lengths from the corona to the spacecraft at high latitudes should result in less pitch angle scattering and in narrower electron beams. The high-latitude strahl was usually substantially broader in pitch angle than

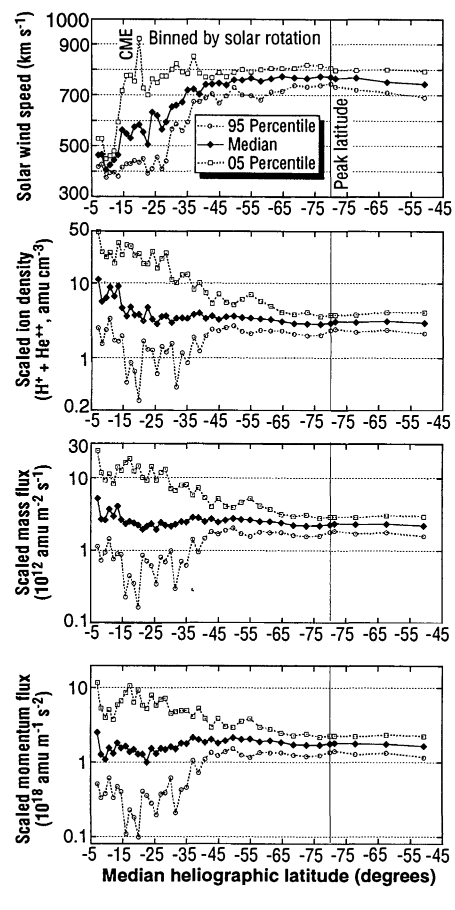

Fig. 3. Median, 5%, and 95% values for solar wind fluid parameters binned by solar rotation and plotted versus heliographic latitude for post-Jupiter observations. Mass-weighting of protons and alphas was used for all parameters. Density, mass flux, and momentum flux were scaled to 1 AU by multiplying by R^2 (AU) (R, distance from the sun). Time runs from left to right; the vertical trace indicates peak southerly latitude on 13 September 1994; amu, atomic mass unit.

those typically observed in the high-speed wind in the ecliptic plane at 1 AU and in the inner solar system (*13*). The mechanism for broadening the high-latitude strahl is currently unknown. The pronounced Alfvén waves observed at high latitudes (*14*) may be a factor, if not through direct interaction with the electron distributions then possibly by lengthening the field-aligned path from the sun and enabling more collisional scattering. Alternatively, the broadening of the strahl may involve nonlinear effects such as turbulence in the inner solar system.

The solar wind at high latitudes exhibited a variety of fine structure; that structure can be characterized as either Alfvénic, pressure-balanced, or compressive. Alfvénic fluctuations were seen as quasiperiodic variations in the nonradial magnetic field and flow components, with periods of 1 hour or greater and often exceeding 10 hours (*14*). In the pressure-balanced structures, as from 23:30 UT on 6 June 1994 through 04:30 UT on 7 June 1994 (Fig. 6), plasma pressure and magnetic pressure changed in opposite directions, whereas total pressure remained relatively constant and plasma beta (the ratio of plasma pressure to magnetic pressure) increased. Structures of this type could be the interplanetary manifestations of polar plumes (*15*), which are ray-like features in the polar solar corona (*16*). Competing models for the evolution of plume plasma predict interplanetary signatures that can be either hotter or cooler than the surrounding plasma but which are always denser (*17*).

In the compressive structure in Fig. 6, from 17:30 UT on 7 June 1994 through 10:30 UT on 8 June 1994, all pressures increased while wind speed was rising, a typical signature of compressions in the solar wind (*18*). The most intense examples of compressional structure are the CIRs encountered at low and middle latitudes. As the spacecraft proceeded southward, the CIRs gave way to an irregular series of small-scale compressions (Fig. 7) (*15*). From −23° to −35° there was an obvious solar longitude structure to dV/dt. From −35° to −62° the fit shape was similar but the amplitude was greatly reduced. For the highest latitude data the fit was essentially flat, indicating that the modulation of dV/dt, and hence of solar wind compressions, by solar rotation had vanished. This effect may be due to a combination of the increasing southerly latitude of the spacecraft and the simultaneous flattening of the heliomagnetic current sheet (*8*). The presence of high-latitude compressional features without a solar-rotation ordering suggests that inhomogeneities within the south polar coronal hole itself were the source of these compressions.

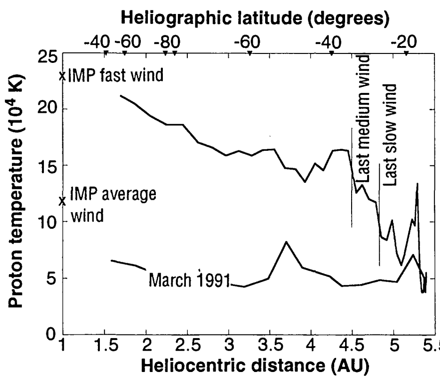

Fig. 4. Solar rotation–averaged solar wind proton temperature versus heliocentric distance for the entire Ulysses mission through 7 January 1995. The lower branch represents in-ecliptic data, with time running from left to right; the upper branch shows out-of-ecliptic data, with time running from right to left. Prevailing proton temperatures at 1 AU for fast and average solar wind are marked at left. CMEs and shocked plasma have been deleted. This process was problematic during March 1991 due to a complex series of shocks and CMEs (*19*); that interval is not plotted. The points on the left axis labeled "IMP fast wind" and "IMP average wind" are based on measurements from the IMP-6, IMP-7, and IMP-8 missions.

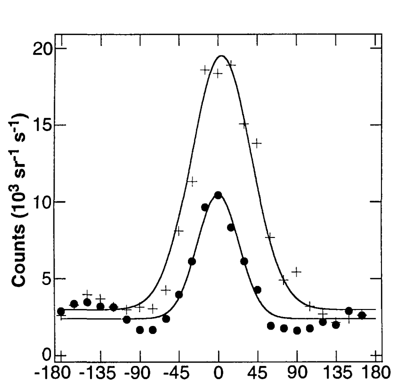

Fig. 5. Counts versus pitch angle for suprathermal electrons from 55 to 65 eV, showing two spectra in the high-speed wind at −15° latitude (heavy dots) and −80° (crosses). Solid traces represent Gaussian fits, yielding full-width-at-half-maximum values of 56° for the low-latitude spectrum and 81° for the high-latitude spectrum.

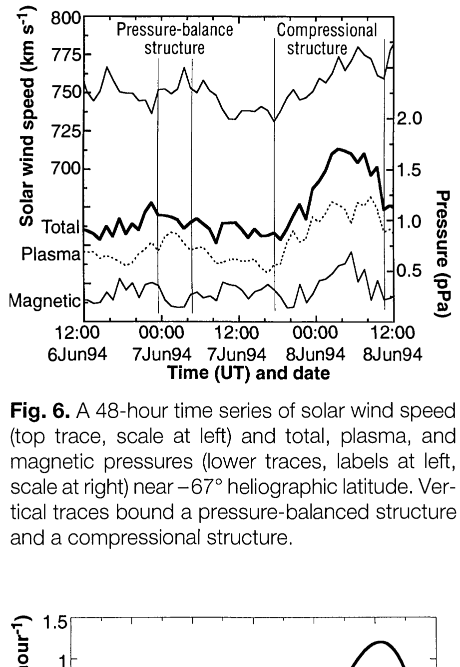

Fig. 6. A 48-hour time series of solar wind speed (top trace, scale at left) and total, plasma, and magnetic pressures (lower traces, labels at left, scale at right) near −67° heliographic latitude. Vertical traces bound a pressure-balanced structure and a compressional structure.

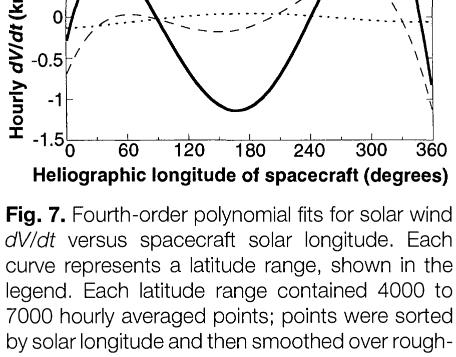

Fig. 7. Fourth-order polynomial fits for solar wind dV/dt versus spacecraft solar longitude. Each curve represents a latitude range, shown in the legend. Each latitude range contained 4000 to 7000 hourly averaged points; points were sorted by solar longitude and then smoothed over roughly 1°. Solid line, −23° to −35°; dashed line, −35° to −62°; dotted line, −62° to −80.2°.

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The Southern High-Speed Stream: Results from the SWICS Instrument on Ulysses

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The high-speed solar wind streaming from the southern coronal hole was remarkably uniform and steady and was confined by a sharp boundary that extended to the corona and chromosphere. Charge state measurements indicate that the electron temperature in this coronal hole reached a maximum of about 1.5 million kelvin within 3 solar radii of the sun. This result, combined with the observed lack of depletion of heavy elements, suggests that an additional source of momentum is required to accelerate the polar wind.

A principal aim of the Ulysses mission was to investigate directly the solar wind coming out of the polar coronal holes. These low-temperature regions of the corona were known to emit high-speed streams (HSSTs), and it was hoped that a dynamically steady and geometrically simple outflow from the corona would be found that would lend itself more readily to theoretical interpretation than the unsteady and geometrically complex solar wind patterns encountered at lower heliographic latitudes. The task was facilitated by the fact that Ulysses is passing over the poles of the sun during the quiet years of the solar cycle, when the coronal holes are largest: The spacecraft collected data for more than a year from an HSST that covered a solid angle of nearly 60% of the southern hemisphere.

We present here results from the Solar Wind Ion Composition Spectrometer (SWICS) on board Ulysses (*1*). For each ion, the instrument measures energy per charge with an electrostatic analyzer and determines—after an acceleration by 23 kV—the time-of-flight and the total energy with solid-state detectors. With this technique, the mass M and charge q are determined separately, so that different ion species can be distinguished even if they have identical M/q ratios. Thus, ion pairs such as C^{6+} and He^{2+}, Mg^{10+} and C^{5+}, or Mg^{8+} and C^{4+} can be separated. This separation allowed measurement of the chemical abundances of C and Mg in the solar wind and ion charge spectra of several elements. Both of these capabilities are important for studying processes in the solar wind source region, that is, the place in the chromosphere and corona from where the solar wind flow originates.

During its voyage to Jupiter, Ulysses detected the typical solar wind, which is quite variable (Fig. 1). Only a few months after the spacecraft left the ecliptic plane, it began to encounter an extension of the HSST emitted by the southern coronal hole. The HSSTs are characterized by high speeds (V > 600 km/s) and low freeze-in temperatures (*2*). From about July 1992 to about May 1993, the spacecraft regularly went into and out of the HSST every solar rotation, and since it has been continuously engulfed in the HSST. The solar wind parameters were much more uniform in the HSST than in the solar wind at lower latitude, and therefore, averages of flow parameters and abundance ratios inside the HSST are an adequate basis for theoretical interpretation.

Differences between abundances in the solar wind and its source reservoir, the outer convective zone of the sun, are created in the chromosphere and the corona. An ion-atom separation mechanism operating at the temperatures prevailing in the chromosphere produces a systematic overabundance of elements with low first-ionization potential (the FIP effect) (*3*). In the corona, a changing efficiency of momentum transfer among the ions or from fields and waves to ions causes variations in solar wind composition (*4, 5*).

In Fig. 2, the relative abundances of nine elements in the slow solar wind and in the southern HSST are plotted as a function of ionization time calculated for solar surface conditions (*6*). A systematic abundance relation is observed, indicating that a competition between the ionization time and a characteristic time for ion-atom separation underlies the FIP effect (*7*). There is a systematic difference between the abundances in the slow solar wind and the HSST: The FIP effect is definitely reduced in the latter (*6, 8*), implying different chromospheric structure or processes below coronal holes.

From mid-1992 to the spring of 1993, Ulysses went into and out of the southern

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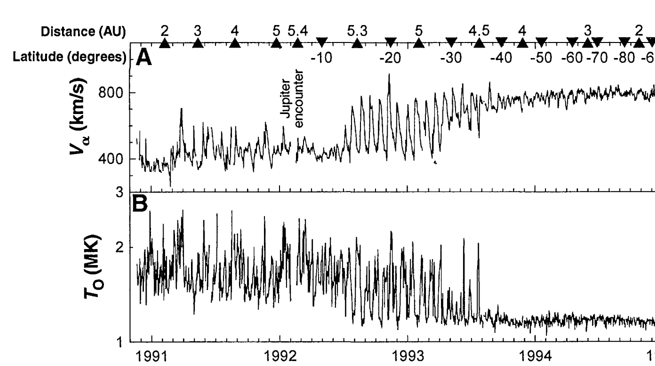

Fig. 1. The changing solar wind conditions encountered by Ulysses during 4 years of observation. (**A**) The speed of the He ions, V_α, and (**B**) the freeze-in temperature (*2*) of O, T_O, as a function of time and the heliographic latitude of Ulysses (distance from the sun in astronomical units is also given). The varying conditions at lower latitude contrast with the quiet flow at higher latitude. During 10 months in 1992 and 1993, the spacecraft regularly went into and out of the HSST from the southern polar coronal hole. The HSSTs are identified by the combination of high velocity and low freeze-in temperatures.