The Three-Dimensional Structure of the Solar Wind Over the Solar Cycle

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Abstract. Throughout declining and minimum phases of the solar cycle the solar wind displays a simple global structure with fast, tenuous flows emanating from large polar coronal holes filling the interplanetary medium at mid and high latitudes, and slower, denser, and much more variable flows at low latitudes. Approaching solar maximum a complicated mixture of flows from streamers, small coronal holes, and coronal mass ejections extends to higher and higher heliolatitudes, ultimately covering even the poles as the polar coronal holes shrink, fragment, and disappear. The most recent observations have continued through solar cycle 23 maximum with the formation of a mid-sized, circumpolar coronal hole in the northern hemisphere. By April of 2002, Ulysses had again moved back down to ~45° N, however, this hole has not yet grown to nearly the size of those observed in the previous orbit nor pushed fast solar wind down to mid-latitudes. Rather, a complex mixture of solar wind flows is observed below ~70° N in these recent observations. This interval also provided a unique geometry where Ulysses skimmed along, nearly parallel to the boundary of the polar coronal hole over several solar rotations. These times contain substantial intermediate speed solar wind, supporting the previous findings of McComas et al. [2002a] of thin boundary layers (CHBLs) flanking coronal holes.

INTRODUCTION

Over the past decade, the joint NASA/ESA Ulysses mission has made mankind’s first two pioneering orbits through the high latitude heliosphere and unlocked many of the secrets of the three-dimensional (3-D) structure of the solar wind over the solar cycle. This paper briefly summarizes a number of these discoveries and goes on to show the most recent solar wind observations from Ulysses. The majority of the observations described here were made with the Solar Wind Observations Over the Poles of the Sun (SWOOPS) instrument [Bame et al., 1992]. The next three sections describe: 1) the 3-D solar wind around solar minimum; this structure is particularly simple and well ordered by heliolatitude; 2) the much more chaotic 3-D solar wind structure observed during the approach to and through solar maximum; and 3) the most recent, post-maximum observations taken by Ulysses, respectively.

THE 3-D SOLAR WIND SPANNING SOLAR MINIMUM

Throughout Ulysses’ first complete polar orbit the solar wind displayed a remarkably simple three-dimensional structure, with persistently fast, tenuous and uniform solar wind at high heliolatitudes and slower, more variable, and highly structured wind at low latitudes [e.g., McComas et al., 1998]. Figure 1 (adapted from McComas et al. [2002b]) summarizes Ulysses’ two polar orbits in the context of the solar cycle. The bottom panel displays the monthly and smoothed sunspot numbers. The top left panel shows Ulysses’ first polar orbit, beginning in February 1992, when the spacecraft swung past Jupiter, extending through December 1997. This interval also includes the declining phase of solar cycle 22, through solar minimum, and into the very early rise of cycle 23. This panel also indicates the times of fast solar wind (>700 km s⁻¹, shaded), which was consistently observed at high heliolatitudes.

As Ulysses made its first southward sojourn in 1992-1993, it encountered a strong, recurrent co-rotating interaction region (CIR). With each rotation of the Sun, Ulysses alternately encountered both the fast solar wind from the large southern polar coronal hole and the slower and more variable low-latitude solar wind [Bame et al., 1993]. CIRs form because of the rotation of the Sun, which serves to radially align fast wind with the slower solar wind ahead of it. Such interactions are particularly significant at mid-latitudes when there are large, stable polar coronal holes and a significant tilt or warp in the heliospheric current sheet.
Consistent flow deflections across the recurrent CIR indicated a characteristic north-south tilt, which forms as the three-dimensional structure of a CIR develops and propagates outward [Gosling et al., 1993]. Subsequently, the opposite tilt was observed in the northern hemisphere as Ulysses returned to low latitudes, further confirming this simple physical model [Gosling et al., 1997]. An additional ramification of the consistent tilts of CIRs is that in both hemispheres the forward waves, which often steepen into shocks within a few AU of the Sun, propagate equatorward, while the reverse waves (shocks) propagate poleward. This characteristic asymmetry between forward and reverse shocks was also observed throughout Ulysses' first orbit with reverse shocks being seen up to much higher heliolatitudes than were forward shocks [e.g., Gosling, 1996, and references therein].

Another important aspect of the mid-latitude CIRs observed in Ulysses first orbit was characteristic ion composition variations. In particular, the fast wind from the large polar coronal holes exhibited low ion freezing-in temperatures and a diminished difference between the low-FIP and high-FIP abundances [Geiss et al. 1995]. These results showed that solar wind from this polar coronal hole was fundamentally distinct from the slower, low latitude solar wind, both 1) in the corona, where the electron density rapidly drops and sets the charge state distributions of the solar wind heavy ions and 2) wherever the elemental composition is determined (probably down in the chromosphere).

The solar wind plasma observations covering Ulysses' first complete polar orbit were quantitatively examined by McComas et al. [2000a]. These authors provided statistics on over 20 solar wind parameters in the coronal hole flows and investigated their characteristic variations with radial distance, heliolatitude, and over the solar cycle. They found that the solar wind from the large polar coronal holes was extremely uniform. Once the radial variations were determined and accounted for, only a very weak heliolatitude dependence remained in most of the

FIGURE 1. Ulysses' first (left) and second (right) polar orbits mapped to the sunspot number (bottom) over the past solar cycle, adapted and extended from McComas et al. [2002b]. Fast solar wind (daily average speed >700 km s⁻¹) is indicated by shading. The highest latitude regions are left blank as Ulysses' orbit did not sample above |80.2°| heliolatitude.
parameters. One example of this residual latitude variation is the slight increase in solar wind speed with heliolatitude. From 36°-80° the speed is very well characterized by a linearly increasing speed, which is 760 km s⁻¹ at 60° and has a slope of +1 km s⁻¹ deg⁻¹. If the characteristic speed is an inverse function of a magnetic expansion factor [Wang and Sheeley, 1992], then these observations indicate that throughout the main portion of polar coronal holes, the expansion factor is only slightly increasing with decreasing latitude.

Comparison of the fast solar wind from southern and northern hemispheres showed much smaller differences across the fast latitude scan as compared to the more distant portions of Ulysses’ orbit. Since the observations were taken over only ~10 months out of the nearly 6 year orbit, smaller differences from this scan indicate that the observed north-south asymmetries were more likely due to temporal variations over the solar cycle instead of a quasi-permanent hemispheric asymmetry. Thus, observations of ~40% lower mass flux in the northern than the southern hemisphere, indicates that there is much more energy going into the polar solar wind during the declining phase of the solar cycle than near minimum. Further, the average values of the solar wind speed are extremely similar between the hemispheres. This combination suggests that the additional energy needed to accelerate the higher mass flux must have been deposited below critical point down in the lower corona [Holzer and Leer, 1981].

A new class of forward-reverse shock pairs was also identified in the high latitude solar wind on Ulysses. These shock pairs were shown to be driven by “over expansion” of some high latitude coronal mass ejections, which travel out with a speed comparable to the surrounding high speed solar wind [Gosling et al., 1994; 1998]. Over expansion most likely occurs because these CMEs start out with an excess of initial pressure, causing them to expand as they propagate outward. This expansion forms a compressive wave (which eventually steepens into shock) that encircles the CME and is observed as a forward shock on the upstream side and a reverse shock on the downstream side as it passes over the spacecraft. Finally, a rarefaction forms in the center of the CME as the compressions propagate outward, effectively leaving a region depleted in plasma.

The left panel in Figure 2 (from McComas et al., 2002b) summarizes the near minimum configuration of solar wind speed (polar plot), overlaid on a set of coronagraph images, which show the characteristically simple coronal configuration typical of solar minimum. The Ulysses data were taken over its first fast latitude scan, which occurred just before solar minimum (September 1994 – July 1995). Comparison of this figure with a similar plot covering the entire first orbit [McComas et al., 1998] shows the same macroscale structure persisted over much of the declining phase and the near minimum portions of past solar cycle. Thus, a simple picture of the declining phase and near-minimum solar wind structure emerges: fast, tenuous flows emanate from large polar coronal holes to fill the interplanetary medium at mid and high latitudes, while slower, denser, and much more variable flows are present at low latitudes.

**FIGURE 2.** Comparison of solar wind speed profiles observed over Ulysses’ two fast latitude scans [taken from McComas et al., 2002b]. The IMF polarity is color coded for inward (blue) and outward (red) fields. Each plot has been overlaid on a composite of three concentric solar images from SOHO-EIT (195 A Fe XII, inner), Mauna Loa (middle), and SOHO-LASCO/C2 (outer) for context. The near minimum and near maximum images are from 17 August 1996 and 18 June 2001, respectively.

In contrast to the relatively simple conditions described above, the right panel in Figure 2 shows that the three dimensional solar wind is much more complex around solar maximum. At these times Ulysses observed an irregularly structured mixture of
mostly slow and intermediate-speed flows. Coronal mass ejections and fast CME-associated transient shocks were much more common during the second orbit and occurred at high as well as low heliolatitudes, although their frequency of occurrence still dropped off with increasing latitude [McComas et al., 2000b]. The \textit{in situ} observations of more CMEs around maximum is consistent with coronagraph observations of about ten times higher rates of CMEs around solar maximum as compared to solar minimum [Webb and Howard, 1994].

Throughout the southern half of Ulysses’ second polar orbit (top right panel of Figure 1), there were no flows from large, stable coronal holes. However, short intervals of relatively faster wind from a variety of smaller holes were observed at high southern latitudes using a combination of SWOOPS and Ulysses SWICS data [McComas et al., 2002a]. Flows from these small coronal holes were identifiable from their low coronal freezing-in temperatures and relative depletions in low-FIP ions. While these composition signatures indicate that coronal holes produce a unique type of solar wind, variations in the acceleration process produce a wide range of solar wind speeds from these holes. Further, these authors showed that high-speed wind (>700 km s\(^{-1}\)) can be produced in small as well as large holes, although the very highest speed non-transient winds do come from the centers of the largest holes.

Figure 3, relabeled slightly from McComas et al. [2002a], shows the composite variation between fast and slow winds at the edges of the nine small coronal holes examined (inset). These authors found that the rarefaction regions map back to a coronal hole boundary layer (CHBL). In the CHBL oxygen and carbon freezing-in temperatures drop in concert with increasing solar wind acceleration (and ultimately solar wind speed in interplanetary space). In contrast, the Fe/O ratio (low/high FIP) tends to stay depressed throughout the bulk of the CHBL indicating that this boundary layer originates from within the edges of the coronal holes back at the Sun (as indicated schematically in Figure 3).

\textbf{HIGH LATITUDE SOLAR WIND SHORTLY AFTER MAXIMUM}

Just after the first peak in sunspot number, Ulysses rose above \textasciitilde60° N heliolatitude in its second polar orbit (Figure 1). Extended and solar rotation ordered intervals of high speed wind were again observed, arising from a circumpolar coronal hole that was reforming around the Sun’s northern pole [McComas et al., 2002b]. Thus, it appeared that the complex heliospheric structure around solar maximum, was short lived, and that the simple bimodal structure observed throughout Ulysses first orbit represented the vast majority of the solar cycle [McComas et al., 2002b].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Schematic diagram of a coronal hole, from McComas et al. [2002a]. The inset shows composite coronal freezing-in temperatures binned as a function of solar wind speed at the edge of fast streams. These regions map back to a coronal hole boundary layer (CHBL), with steep gradients in the solar wind acceleration (speed) and freezing-in temperatures.}
\end{figure}

Subsequent SWOOPS observations, however, indicate a somewhat more complex picture. Figure 4 shows the solar wind speed since October 2001, when Ulysses crossed its highest northern heliolatitude, as a function of latitude and Carrington longitude (using constant velocity mapping back to the Sun). The gray bar indicates a solar wind speed ranging from 300-760 km s\(^{-1}\), the typical fast solar wind observed over Ulysses first orbit. The height of the black bar indicates the observed solar wind speed.

Clearly the fast flow from this polar coronal hole has not yet expanded back down to intermediate latitudes. Instead, fast flows are only observed above \textasciitilde70° at most longitudes, and down to \textasciitilde55° for a small range of longitudes (centered at \textasciitilde50° Carrington longitude); He 10830 Å maps of the northern coronal hole back at the Sun indicate that the coronal hole boundary has a small equatorward extension around this longitude at the times that Ulysses observed these fast winds. In
addition, while the mid-sized northern polar coronal hole remained relatively stable in size, no similar polar hole had even begun to form in the south.

**FIGURE 4.** Solar wind speed from October 2001 through April 2002, mapped with a constant velocity back to Sun. The speed is indicated by the height of the black band. The grey band indicates speeds from 300-760 km s\(^{-1}\). While Ulysses observed fast wind above \(\sim70^\circ\), below that the spacecraft skimmed along the boundary of the coronal hole flow, observing both fast and slow winds.

Detailed comparison of the 10830 maps with Ulysses observations for this interval indicates that Ulysses was skimming the boundary of the polar coronal hole flows for several solar rotations as it dropped back down in heliolatitude. Figure 4 shows that for much of this interval, Ulysses consistently observed intermediate speed solar wind in the 500-700 km s\(^{-1}\) range. At these times, Ulysses also observed other unusual plasma properties, such as higher proton temperatures, which is more typical of the fast solar wind. In addition, freezing-in temperatures almost always vary in lock step with the solar wind speed [G. Gloeckler, private communication], suggesting that this interval will display the same characteristic speed and freezing-in temperature variation demonstrated for small coronal holes by McComas et al. [2002a]. These results indicate that as the Ulysses spacecraft skimmed along the edge of the recent mid-sized polar coronal hole, it was sampling a coronal hole boundary layer plasma, similar to the CHBL observations previously documented by McComas et al. [2002a].

**CONCLUSIONS**

This brief paper has reviewed a number of the notable findings from the Ulysses mission about the three-dimensional structure of the solar wind over the solar cycle. Around solar minimum this structure is simple and bimodal with fast, tenuous solar wind emanating from large polar coronal holes, filling the high latitude regions, and slower, denser, and much more variable wind at low heliolatitudes. This configuration, along with the intrinsic tilt of the solar dipole with respect to the Sun's rotation axis, leads to large recurrent CIRs, which have a characteristic equatorward tilt in both hemispheres. In turn, this geometry preferentially drives the CIR-associated reverse shocks to high heliolatitudes. Finally while there is a relative paucity of CMEs away from solar maximum, those that are observed at high heliolatitudes display a unique configuration, consistent with the over-expansion of structures that are initially overpressured back at the Sun.

In contrast, the 3-D solar wind approaching and through solar maximum is remarkably more complex, with a time-varying structure including numerous CMEs, small coronal holes, and slow to intermediate solar wind observed at all heliolatitudes. The most recent, post-maximum Ulysses observations show fast wind from a single mid-sized polar coronal hole in the northern hemisphere, producing intermediate speed flows all along its edge, and a complex mixture of flows persisting at mid-latitudes.

Small coronal holes near solar maximum generate a variety of solar wind speeds, including flows nearly as fast as those coming from the huge, near minimum polar coronal holes. Both these smaller coronal holes and the mid-sized polar hole observed recently as Ulysses dropped back down from its highest northern heliolatitudes seem to be bounded by coronal hole boundary layers. These observations suggest that CHBLs are ubiquitous structures in the solar wind, bounding flows from all coronal holes. Thus, the global solar wind is not simply comprised of fast and slow flows. Rather, a continuous heating and acceleration process exists, at least within the relatively narrow CHBLs.

Finally, all of the observations described in this study have been from a single 11-year interval (spanning the end of cycle 22 and start of 23). The real 3-D structure of the solar wind surely evolves over the full 22 year cycle and varies from one of these cycles to the next. Thus, continuing observations of the high-latitude solar wind are absolutely essential to understanding the full picture of its three-dimensional structure.
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REFERENCES


