The three-dimensional solar wind around solar maximum

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[1] Ulysses is now completing its second solar polar orbit, dropping back down in latitude as the Sun passes through its post-maximum phase of the solar cycle. A mid-sized circumpolar coronal hole that formed around solar maximum in the northern hemisphere has persisted and produced a highly inclined CIR, which was observed from ~70°N down to ~30°N. We find that the speed maxima in the high-speed streams follow the same slow drop in speed with decreasing latitude observed in the large polar coronal holes around solar minimum. These results suggest a solar wind acceleration effect that is related to heliolatitude or solar rotation. We also find that the solar wind dynamic pressure is significantly lower in the post-maximum phase of this solar cycle than during the previous one, indicating that while the heliosphere is larger than near solar minimum, it should be smaller than during or after the previous maximum. *INDEX TERMS:* 2164 Interplanetary Physics: Solar wind plasma; 2102 Interplanetary Physics: Corotating streams; 2139 Interplanetary Physics: Interplanetary shocks; 2162 Interplanetary Physics: Solar cycle variations (7536); 2199 Interplanetary Physics: General or miscellaneous. **Citation:** McComas, D. J., H. A. Elliott, N. A. Schwadron, J. T. Gosling, R. M. Skoug, and B. E. Goldstein, The three-dimensional solar wind around solar maximum, *Geophys. Res. Lett.*, *30*(10), 1517, doi:10.1029/2003GL017136, 2003.

1. Introduction

[2] The three-dimensional structure of the solar wind varies dramatically over the solar cycle, as summarized in Figure 1. The top two panels show polar plots of the solar wind speed measured with the SWOOPS (Solar Wind Observations Over the Poles of the Sun) experiment [*Bame et al.*, 1992] on the Ulysses spacecraft. The top left panel is essentially a replot of the figure by [*McComas et al.*, 1998], summarizing Ulysses' first polar orbit. The top right panel shows a comparable plot for Ulysses' second orbit. In both of these panels, time starts on the left side of the plot and progresses counterclockwise over the orbit. Underlying the SWOOPS data are composite images of the Sun and corona characteristic of solar minimum and maximum conditions, respectively. The bottom panel of the Figure displays the monthly and smoothed sunspot numbers for the time interval covered by Ulysses' first two polar orbits. Over this time, the Sun completed a full 11-year cycle from the declining phase (Orbit 1 South), through solar minimum (Orbit 1 North), the rise to solar maximum (Orbit 2 South), and most recently through solar maximum and immediately post-maximum (Orbit 2 North).

[3] Throughout Ulysses' first orbit, the solar wind displayed a remarkably simple bimodal 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, 2000]. The fast flows arose from large coronal holes that covered both solar poles throughout these portions of the solar cycle. At mid latitudes, Ulysses observed a co-rotating interaction region (CIR) with each solar rotation [e.g., *Gosling*, 1996, and references therein]. CIRs form because the rotation of the Sun radially aligns fast and slow parcels of wind such that the fast wind overtakes the slower wind ahead.

[4] The global structure of the 3-D solar wind is completely different during Ulysses' second, near solar maximum, orbit (upper right panel). Near maximum, highly variable flows are observed at all heliolatitudes. These flows arise from a mixture of sources including streamers, coronal mass ejections (CMEs), small low latitude coronal holes, and possibly active regions [*Neugebauer et al.*, 2002]. Fast coronal hole solar wind observed in the ecliptic plane near solar minimum comes largely from equatorward extensions of polar holes, while during more active parts of the solar cycle, fast ecliptic flows also arise from multiple smaller distributed low and mid latitude coronal holes [*Luhmann et al.*, 2002]. Because of the variety of types of solar wind observed at all heliolatitudes, the solar wind exhibits little average latitudinal variation around solar maximum [*McComas et al.*, 2002a].

[5] Mass and ion charge state composition of solar wind heavy ions provide important information about the solar wind sources because they are fixed in the chromosphere and lower corona, respectively [*von Steiger et al.*, 1997]. *Geiss et al.* [1995] showed a clear anticorrelation between the freezing-in temperatures of ion charge states with the solar wind speed and a First Ionization Potential (FIP - energy required to ionize the first electron) effect where low FIP ions are enhanced relative to higher FIP ions in coronal holes. *McComas et al.* [2002b] examined the variation between fast and slow winds at the edges of the nine small coronal holes and found that the rarefaction regions map back to a coronal hole boundary layer (CHBL). In the

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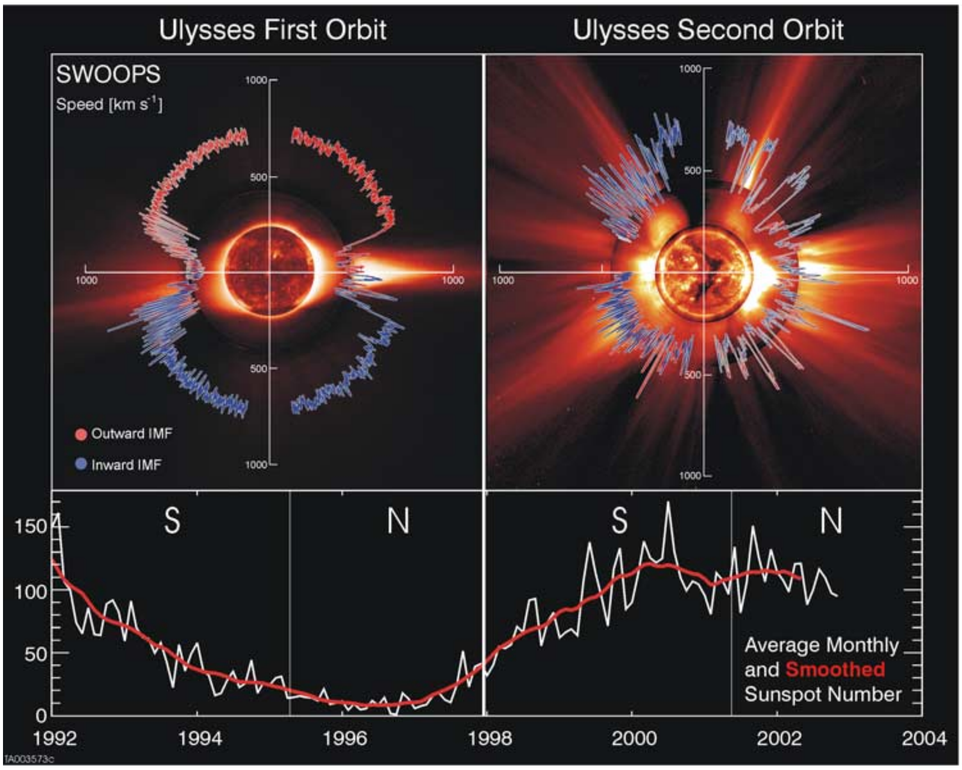

Figure 1. Polar plots of solar wind speed as a function of latitude for Ulysses' first two orbits. Sunspot number (bottom panel) shows that the first orbit occurred through the solar cycle declining phase and minimum while the second orbit spanned solar maximum. Both are plotted over solar images characteristic of solar minimum (8/17/96) and maximum (12/07/00); from the center out, these images are from the Solar and Heliospheric Observatory (SOHO) Extreme ultraviolet Imaging Telescope (Fe XII at 195 Å), the Mauna Loa K-coronameter (700–950 nm), and the SOHO C2 Large Angle Spectrometric Coronagraph (white light).

CHBL oxygen and carbon freezing-in temperatures drop in concert with increasing solar wind speed; however, the Fe/O ratio (low/high FIP) stay depressed throughout the bulk of the CHBL. Such boundary layer flow is responsible for much of the intermediate speed wind seen in the rarefaction regions behind CIRs.

[6] Finally, *Smith et al.* [2001] examined Ulysses magnetic field observations from 1999 and 2000, and found that two magnetic sectors were present up to a latitude of −78°. These authors argued that the field observations were consistent with there being a single warped current sheet at solar maximum. Such a configuration is consistent with the large solar wind variability seen to high latitudes.

2. Additional Observations

[7] The latest solar wind observations from SWOOPS are shown by the black lines in Figure 2. These data cover the interval from 11 October 2001, when Ulysses was at 80°N through the most recent observations on 25 January 2003 as Ulysses approached 20°N. In each panel, the observations are compared to those taken six years earlier, at the equivalent locations during Ulysses' first polar orbit, under nearly solar minimum conditions (red). Around solar minimum, the band of solar wind variability was narrow, and confined to low latitudes (~30° to 10° north) [*Gosling et al.*, 1995, 1997; *McComas et al.*, 1998]. This was indicative of small dipole tilt angles and confinement

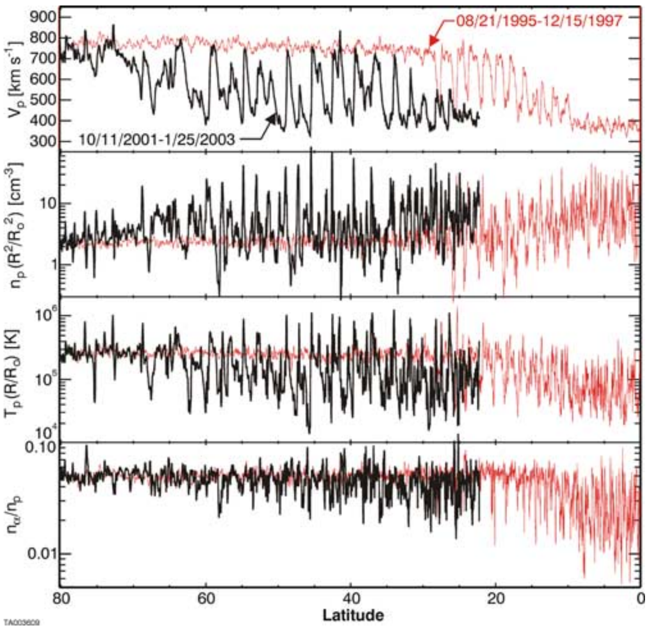

Figure 2. Twelve-hour running averaged solar wind proton speed, scaled density and temperature, and alpha particle to proton ratio as a function of latitude for the most recent part of the Ulysses orbit (black line) and the equivalent portion from Ulysses' first orbit (red line).

of the helmet streamers to low latitudes around solar minimum.

[8] In contrast to the solar minimum configuration, the recent post-maximum observations indicate that slower solar wind flows extend to very high latitudes (at least ~70°N). The associated band of solar wind variability extends over a much broader range of latitudes (nearly 50° of Ulysses' orbit). These data indicate that the heliospheric current sheet and streamer belt were highly inclined, consistent with the findings of *Smith et al.* [2001], although the solar wind structure is not as periodic as the simple recurrent CIR observed during Ulysses' first orbit. Interestingly, the highest peak speeds seen in the most recent data lie very close to those from the earlier epoch, and even follow the small decrease in speed with decreasing latitude observed in the previous polar coronal hole observations [*McComas et al.*, 2000].

[9] D. J. McComas (The three-dimensional structure of the solar wind over the solar cycle, submitted to *Solar Wind 10, AIP Conference Proceedings*, 2003) showed Ulysses observations of fast wind from a circumpolar coronal hole that had newly formed in solar cycle 23 in the northern hemisphere. These authors demonstrated that as of April 2002, when Ulysses was approaching 45°N, this hole had not yet grown to the size of those at solar minimum and had not pushed fast solar wind down to mid-latitudes at all heliolongitudes. The continuing observations provided here show that the southern-most extension of the fast coronal hole flows was observed only down to ~32°N. These observations indicate that a large polar coronal hole, similar to those that dominated solar wind flows in both hemispheres during Ulysses' first orbit, still has not fully developed in the northern hemisphere.

[10] The lower three panels of Figure 2 display the proton density and temperature and alpha to proton ratio, respectively. In order to remove the dependence on heliocentric radial distance, the proton density was scaled as R^2 and temperature as R [*McComas et al.*, 2000]. All of the bulk plasma parameters basically follow the structure demonstrated in the solar wind speed plots. The recent observations, associated with the lower and much more variable speeds reveal higher densities and lower temperatures compared to the fast wind seen at mid and high latitudes closer to solar minimum. These parameters also have larger ranges of variability than observed at low latitudes near solar minimum, consistent with the large variability of solar wind sources around solar maximum. The alpha to proton ratio has higher average values and less variability than observed at low latitudes around minimum. Occasional brief excursions to very high alpha to proton ratios are commonly associated with coronal mass ejections (CMEs), which are much more frequent around solar maximum than minimum.

[11] CMEs were encountered at a rate of ~1.5/month throughout Ulysses' recent traverse back down to low latitudes. When Ulysses was predominantly embedded in flow from the northern coronal hole at latitudes above 70°N, at least two, and possibly four, out of the five CMEs observed had the same over-expanding character as observed within the polar coronal hole flows during the first orbit [*Reisenfeld et al.*, 2003; *Gosling et al.*, 1994]. Also, as in the first orbit, no CMEs of this nature have been identified in the more variable flows at lower latitudes.

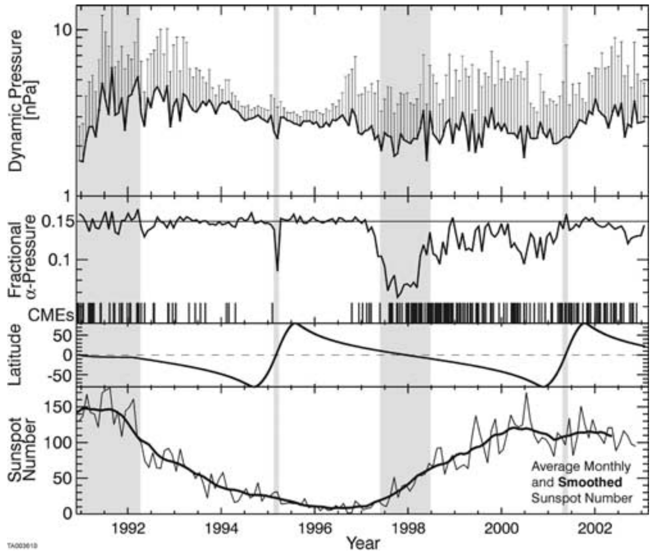

Figure 3. Total dynamic pressure (momentum flux), fraction of alpha to proton pressures, identification of CMEs, spacecraft latitude, and sunspot number over the entire 13-year Ulysses mission. In the top two panels, the data were binned by solar rotation and mean values are plotted; +1σ bars in the top panel show the variability. Grey bands highlight low latitude (<10°) intervals.

Counterstreaming suprathermal electron beams, indicating closed magnetic field lines, were present throughout significant portions of most of the CMEs encountered in the northern hemisphere during the second orbit.

[12] The solar wind dynamic pressure (momentum flux) is given by $m_p(n_p v_p^2 + 4n_\alpha v_\alpha^2)$ as the heavier ions contribute negligibly to this parameter. This is a particularly interesting quantity since the solar wind dynamic pressure "inflates" the heliosphere and, in combination with the surrounding local interstellar medium, determines the shape, size, and structure of the heliosphere. Using early SWOOPS results for Ulysses' first partial orbit, [*Phillips et al.*, 1996] showed that the momentum flux appeared to be lower near the equator compared with higher latitudes and suggested that this variation would cause the heliosphere to be pinched-in at low latitudes. Three-dimensional simulations of the heliospheric interaction with the LISM [*Pauls and Zank*, 1996] incorporated this reduced ram pressure near the equatorial plane and generated the hour-glass shaped cross-section of the heliosphere. These simulations showed that even a modest decrease in the equatorial dynamic solar wind pressure has substantial effects on the structure of the termination shock and heliopause.

[13] The top panel of Figure 3 shows the 1 AU-scaled solar wind dynamic pressure over the entire Ulysses mission. While the dynamic pressure dipped when Ulysses crossed low latitudes (grey bars) in 1995 and 1997–98, it was not lower for most of the low latitude portion in 1991–92 or 2001. Further, a much larger (nearly factor of 2) variation occurred from 1991 through 2001, with the dynamic pressure rising steeply just after solar maximum and then slowly decreasing over the rest of the solar cycle [*Richardson et al.*, 2001]. The newest, 2002, Ulysses observations do not show this large increase during or just after the latest solar

maximum, but rather a more modest ∼50% increase from ∼2 to ∼3 nPa. Interestingly, the sunspot number was also smaller in the latest maximum (fourth panel).

[14] The second and third panels of Figure 3 show the relative contribution of the alpha particles to the total solar wind dynamic pressure and Ulysses' latitude, respectively. The alpha pressure fraction was remarkably constant at ∼15% throughout most of Ulysses' first orbit; this value appears to be an upper bound for the alpha contribution through Ulysses' second orbit. The alpha/proton ratios observed in the high latitude high-speed streams around solar minimum were nearly constant at 4.4%, so it is not surprising that their relative contribution would be nearly fixed for these high latitude intervals. On the other hand, it is surprising that the highly variable flows observed at all heliolatitudes during Ulysses' second orbit would yield such a similar value. The largest deviations from this value occur at low latitudes near solar minimum (middle two grey bars). Finally, we include the times of CMEs as identified by two or more anomalous plasma and magnetic field signatures such as counterstreaming suprathermal electrons, low proton temperatures, high alpha particle abundances, low plasma beta, smooth magnetic field rotations, etc. across the bottom of the second panel. High alpha densities often observed in CMEs may help account for the additional dynamic pressure provided by the alpha particles, however, numerous CMEs were also observed during the 1997–98 low latitude crossing when the alpha pressure was reduced.

3. Discussion

[15] This study has examined the most recent solar wind observations from Ulysses' second northern polar pass and compared these results with those from Ulysses' first, solar minimum, polar orbit. We found a recurrent CIR that extended over a very broad heliolatitude range from ∼70° down to ∼30°. During this time, the solar dipole and streamer belt were highly inclined and fast flows from northern polar coronal hole had not yet extended down to mid latitudes at all heliolongitudes. It is interesting that the peak speeds observed as Ulysses came down in latitude very closely matched the characteristic speed variation observed previously in the large polar coronal hole flows [*McComas et al.*, 2000]. This relationship suggests that there is an intrinsic latitude dependence of the maximum solar wind speed and other bulk solar wind properties [*McComas et al.*, 2000], independent of coronal hole size or phase of the solar cycle. Because this effect is ordered by the rotational instead of magnetic latitude, it indicates a fundamental relationship to the physical latitude (e.g., dynamo) or rotation of the Sun.

[16] During the period from 1991–2001, the solar wind dynamic pressure was highest just after solar maximum and decreased by nearly a factor of 2 over the rest of the solar cycle as pointed out previously by [*Richardson et al.*, 2001]. These authors suggested that the normal cycle would be for the pressure to return to the previous high value, however, here we found that the pressure only increased ∼50% from the minimum values during the 2000–2002 maximum and post maximum phase. It is interesting that this smaller increase was accompanied by smaller peak numbers of sunspots in the recent maximum compared to the previous one. In any case, the observations reported here indicate that the heliosphere should be significantly smaller now than during the previous post maximum phase. This effect should increase the probability of Voyager 1 reaching the termination shock in the near future.

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