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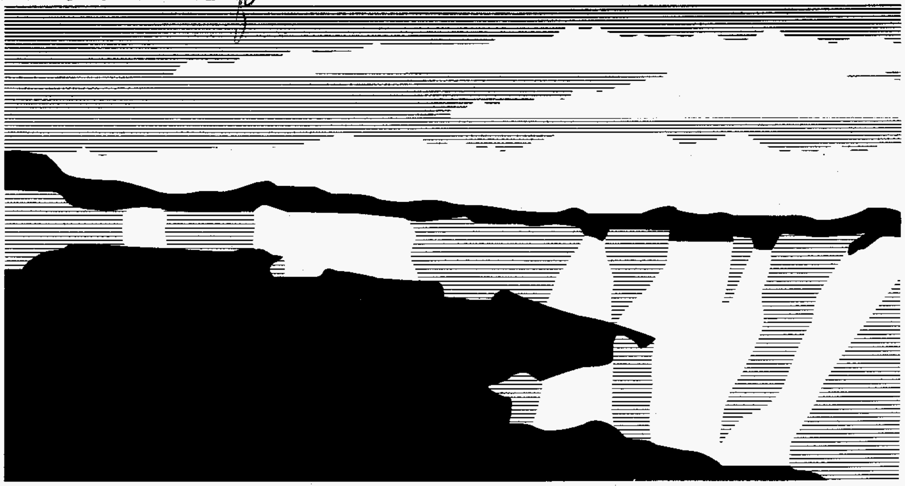

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ULYSSES SOLAR WIND PLASMA OBSERVATIONS AT HIGH LATITUDES

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ABSTRACT

Ulysses reached its peak northerly heliolatitude of 80.2°N on July 31st, 1995, and is now moving towards aphelion at 5.41 AU which it will reach in May, 1998. We summarize measurements from the solar wind plasma experiment, SWOOPS, emphasizing northern hemispheric observations but also providing southern and equatorial results for comparison. The solar wind momentum flux during Ulysses' fast pole-to-pole transit at solar minimum was significantly higher over the poles than at near-equatorial latitudes, suggesting a non-circular cross section for the heliosphere. Furthermore, modest asymmetries in wind speed, density, and mass flux were observed between the two hemispheres during the fast latitude scan. The solar wind was faster and less dense in the north than in the south. These asymmetries persist in the most recent high- and mid-latitude data but are less pronounced. As of July, 1996 the northern fast solar wind has lacked any strong stream interactions or shocks and, although a comprehensive search has not yet been made, no CMEs have yet been identified during this interval. On the other hand, Alfvénic, compressional, and pressure-balanced features are abundant at high latitudes. The most recent data, at 4 AU and 32°N, has begun to show the effects of solar rotation modulated features in the form of recurrent compressed regions.

INTRODUCTION

The solar wind plasma experiment on board the Ulysses spacecraft, SWOOPS (Solar Wind Observations Over the Poles of the Sun), consists of two electrostatic analyzers which independently measure electron and ion distribution functions as a function of energy per charge and direction (Bame *et al.*, 1992). From these measurements moments are calculated, including density (n), velocity (v) and temperature (T). Additionally, it is useful to construct mass flux ($n\ v\ r^2$) and momentum flux ($n\ v^2\ r^2$), where r is heliocentric distance. The variation of these parameters with latitude during Ulysses' fast latitude scan and beyond forms the central theme of this report.

Ulysses was launched in October, 1990 and, after obtaining a gravity assist from Jupiter in February, 1992, proceeded towards the southern polar regions, reaching a maximum southern latitude of 80.2° in September, 1994, at a distance of 2.3 AU. The subsequent phase of the mission - commonly referred to as the "fast latitude scan" - took Ulysses from 80°S to 80°N and into 1.34 AU in a little over ten months. Currently (July, 1996), Ulysses is at 4 AU and 32°N proceeding towards aphelion at 5.41 AU and will cross the ecliptic plane (–7° heliographic latitude) on May 10th, 1998.

This paper follows several others which have summarized various stages and milestones in the Ulysses mission (e.g. Phillips *et al.*, 1993, McComas *et al.*, 1995, Phillips *et al.*, 1995a, Phillips *et al.*, 1995b). Because of space limitations we restrict our discussion, for the most part, to a description of large-scale variations in the plasma parameters. Several other recent reviews have provided summaries of related topics. In particular, Feldman *et al.* (1996) reviewed much of the out-of-ecliptic mission (up to July, 1995), with emphasis on solar wind structures and ion and electron distribution functions. Gosling (1994)

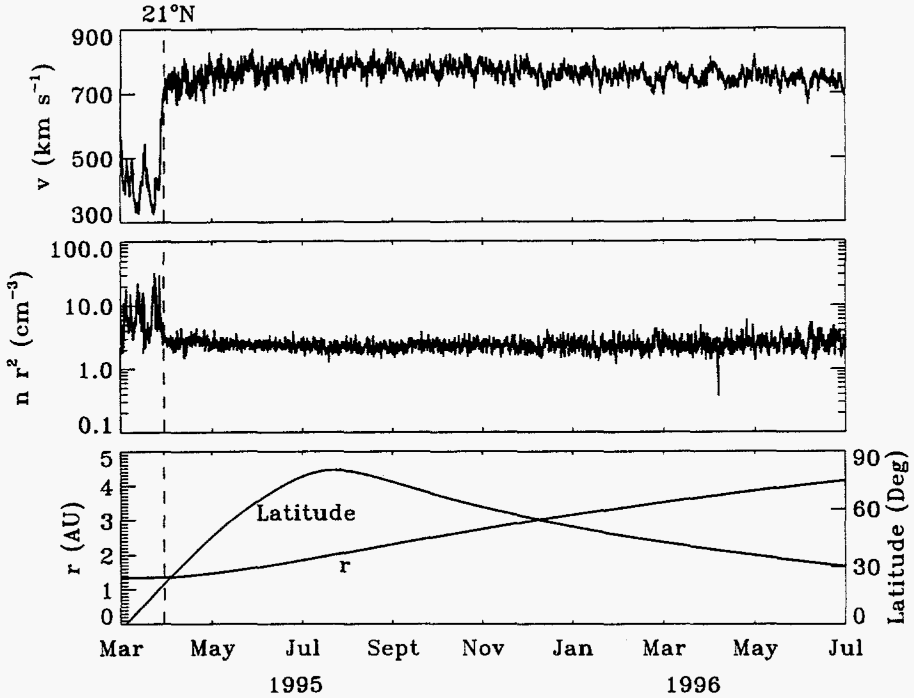

Fig. 1. One-hour averages of solar wind speed (upper panel) and proton density (middle panel) from March, 1995 to July, 1996. The density has been normalized to 1 AU. Also shown are the heliocentric distance and heliographic latitude of Ulysses (bottom panel).

provided an overview of coronal mass ejections (CMEs) at high latitudes, and Gosling (1996) discussed corotating and transient flows in the solar wind within the context of a three-dimensional heliosphere. A more quantitative analysis of the latitudinal and radial variations of Ulysses plasma parameters, particularly solar wind temperature, has been provided by Goldstein *et al.* (1996).

PLASMA PARAMETERS FROM POLE TO POLE AND BEYOND

Ulysses' unique polar trajectory has allowed the examination of solar wind parameters over almost all heliographic latitudes (80.2°S to 80.2N°) and heliomagnetic latitudes (88°S to 85°N). Figure 1 shows one-hour averaged solar wind speed (top panel) and proton density (middle panel) for the last sixteen months (March, 1995 to July, 1996) which began with Ulysses' traversal into the northern hemisphere. Density has been normalized to 1 AU by multiplying by $(r/r_0)^2$, where $r_0 = 1$ AU. The bottom panel shows the latitude and heliocentric distance (r) of Ulysses during the interval these measurements were made. At low latitudes (±21° about the ecliptic plane) Ulysses sampled both the coronal streamer belt marked by low speed, high density, and large variability and high speed flows from coronal holes. This interval has been discussed in detail by Gosling *et al.* (1995a,b). Following a sharp transition (dashed line), Ulysses became continually immersed in high speed/low density solar wind. By early July, 1996 Ulysses was located at 4 AU from the Sun at a latitude of 32°N. The most striking feature of this high latitude portion is the near constancy of the flow. Since 21°N, we have observed exclusively fast solar wind. No forward shocks have been identified, and only a few reverse waves (which may have been weak shocks) were seen at equatorial latitudes. Although a detailed search has yet to be performed, no CMEs have been identified in the northern hemisphere. There appears to be a small positive poleward speed gradient, and a very slight negative poleward density gradient in the northern high-latitude data set. Energy flux increases at high latitudes, and mass flux shows very little variation with latitude. Including all high-latitude measurements to date, the median speed of the high-latitude solar wind is 776 km s^{-1} and the median density scaled to 1 AU is 2.38 protons cm^{-3}. Feldman *et al.* (1996) summarized the bulk flow parameters for the southern high-latitude solar wind. We note that small systematic differences in the plasma parameters occur in the opposite solar hemispheres (see below). For example, the northern high latitude solar wind speed was observed to be typically 10 - 20 km s^{-1} faster than solar wind measured at the same heliographic latitude in the southern hemisphere.

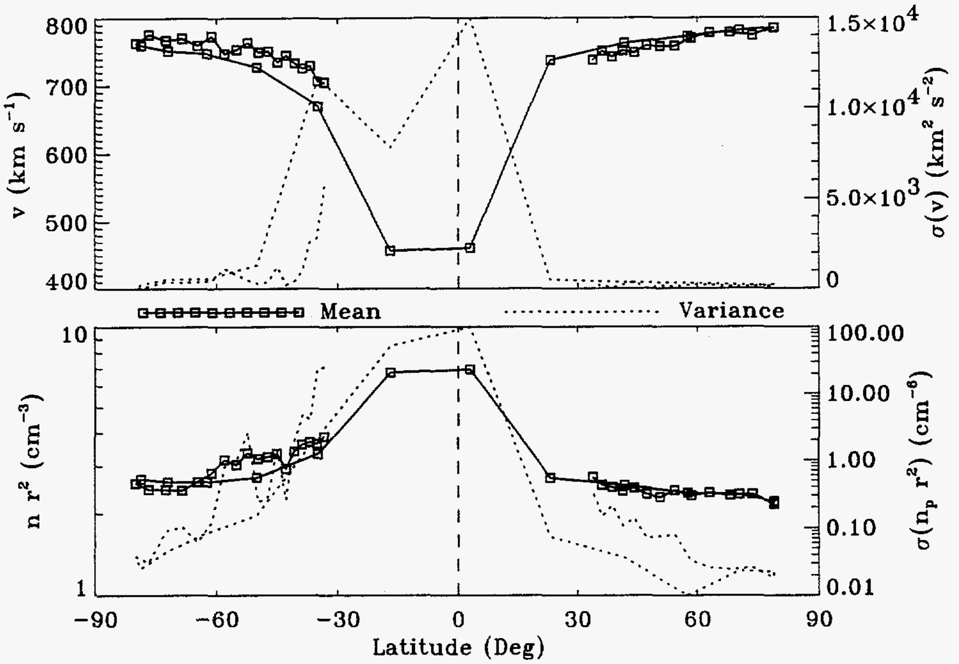

Fig. 2. Solar wind mean speed (upper panel) and proton density (lower panel) binned by solar rotation. Variances are shown as dashed traces. Latitude varied from 33°S to 80°S, to the equator, up to 80°N, and back down to 33°N.

LATITUDINAL VARIATIONS

We now turn our attention to the variation of the solar wind plasma with latitude. Figure 2 shows the mean values for speed and scaled density, binned by solar rotation, as a function of latitude. Variances are superimposed as dashed traces. The plot is centered around the equatorial crossing during the fast latitude scan and extends beyond both polar regions to ~32°, corresponding to the interval; April, 1993 to July, 1996. Note that the southern mid- and high-latitude region was more variable (in both speed and density) than the north. This is likely a temporal effect as the Sun was evolving towards solar activity minimum. During this interval, the tilt of the solar dipole decreased from ~30° to ~10° with respect to the Sun's spin axis. One must view the inferred asymmetries close to the equator with caution as only a few solar rotations contributed to these profiles.

The abundance of helium relative to hydrogen, [He], is shown in the upper panel of Figure 3. At low latitudes the [He] is highly variable, ranging from 0.3% to almost 30%. The periods of low [He] are associated with the coronal streamer belt plasma and intervals of high [He] have been identified with transient CMEs (e.g., Barraclough *et al.*, 1995). At high latitudes, the [He] is fairly constant. The average helium abundance at high latitudes is 4.3±0.6% (Barraclough *et al.*, 1995). This is approximately half the value inferred for the cosmic helium abundance and within the core and throughout the solar convective zone of the Sun (e.g. Feldman *et al.*, 1996 and references therein).

The variation of proton temperature with latitude is shown in the lower panel of Figure 3. Radial effects have not been removed, hence the measurements made prior to and following the fast latitude scan do not overlap their counterpart measurements made during the fast-latitude scan. Although proton temperature varies in a similar manner to speed as expected, Goldstein *et al.* (1996) found that the temperature asymmetry is larger than can be explained by the north-south speed difference. Specifically, for a radial power law dependence of the form $T \alpha r^{-\delta}$, they found $\delta = 0.81 \pm 0.02$ for the southern hemisphere and $\delta = 1.03 \pm 0.03$ for the northern hemisphere.

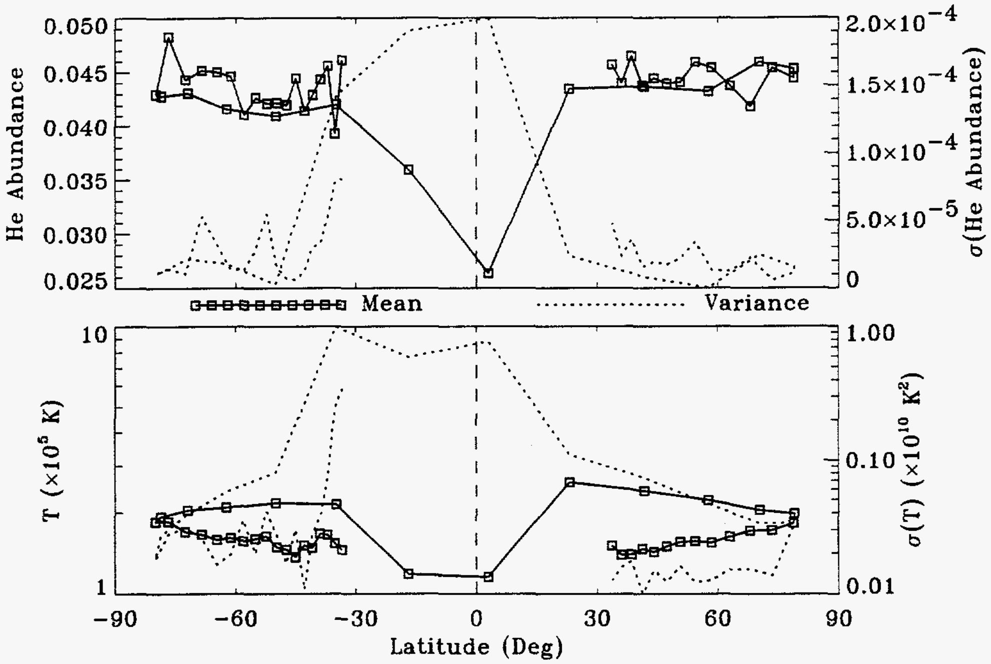

Fig. 3. Solar wind mean Helium abundance (upper panel) and proton temperature (lower panel) are binned by solar rotation. Variance are shown as a dashed trace. Latitude ranges from 33°S to 80°S to the equator, up to 80°N, and back down to 33°N.

Mass and momentum flux are generally the least variable of all solar wind fluid parameters due to the negative correlation commonly observed between density and speed. Mass flux is, however, higher at low latitudes. Specifically, averaged over a solar rotation, the mean mass flux is 2.91 × 10^{12} amu m^{-2} s^{-1} at the equator, whereas the value is 1.74 (1.98) × 10^{12} amu m^{-2} s^{-1} over the north (south) pole. Thus the mean equatorial value is ~47% higher than at the highest southerly latitudes . (A similar comparison using median values yields ~14% difference). This is consistent with mass flux variations deduced from Lyman-alpha measurements (e.g., Summanen *et al.,* 1993) which show an enhancement about the solar equator. For the entire interval centered around the fast latitude scan and extending beyond both polar regions to ~32°, (i.e. April, 1993 to July, 1996) the mean mass flux is 2.10±0.82 × 10^{12} amu m^{-2} s^{-1}.

Momentum flux was found to be ~37% lower at near-equatorial latitudes than at high latitudes (Phillips *et al.,* 1995b). (Goldstein *et al.,* (1996) found a somewhat smaller difference by basing their averaging on mean values, rather than medians). Averaged over a solar rotation, we find that the mean equatorial momentum flux is 1.29 × 10^{18} amu m^{-1} s^{-2}, whereas over the north and south poles, it is 1.37 and 1.51 × 10^{18} amu m^{-1} s^{-2}, respectively. Averaged over the entire interval from April, 1993 to July, 1996, the mean momentum flux is 1.53±0.52 × 10^{12} amu m^{-1} s^{-2}. Barnes (1995) predicted that if such asymmetries existed in the average dynamic pressure of the solar wind, the shape of the termination shock would reflect these variations, leading to a prolate or oblate shape for the steady-state shock, depending on the sense of the asymmetry. Since the solar wind pressure is dominated by dynamic pressure (i.e., momentum flux), the distance to the termination shock and heliopause should vary with latitude as the square root of the momentum flux, assuming the momentum flux falls off as $1/r^2$. This led Phillips *et al.* (1995b) to suggest a "peanut"-shaped cross section for the termination shock and heliopause (in the plane normal to the interstellar flow vector), pinched in at the equator by ~20%. Figure 4 shows how the shape of the termination shock and heliopause might have looked during the fast latitude scan phase of the mission. One hour averages of density and velocity were used to calculate the momentum flux. A running boxcar of 624 points (corresponding to ~1 solar rotation) was then applied to these data. The dotted lines are drawn at ±25°, and the dotted semicircle is drawn with a radius equal to the mean value of the data points. This analysis says nothing about the absolute scale size of either the termination shock or heliopause; however, for visualization purposes we have scaled the cross section to roughly expected values. In comparison with Figure 3 of Phillips *et al.* (1995b), our shape appears to be less "peanut"-shaped and more as if a vertical slice has been removed at latitudes < 25°. The difference probably stems from our use of mean values rather

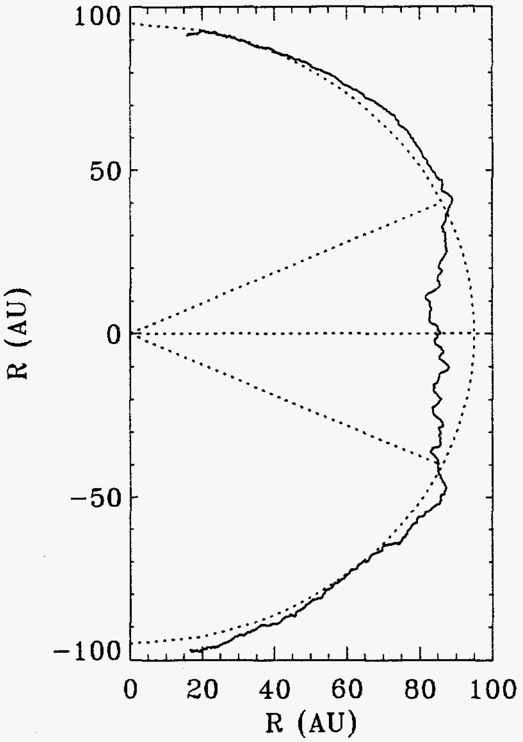

Fig. 4. Shape of the heliosphere in the plane perpendicular to the interstellar flow vector inferred from variations in the measured momentum flux during Ulysses' fast latitude scan. The dotted lines are drawn at 0° and ±25° heliographic latitude.

than medians to construct the averages. Goldstein *et al.* (1996) emphasized that CMEs are likely to modify the momentum flux significantly; thus the shape of the heliosphere may change significantly with solar cycle. In addition, it is likely that the overall coronal expansion looks quite different at solar maximum.

LATITUDINAL ASYMMETRIES

In addition to latitudinal variations in the solar wind plasma parameters, asymmetries have also been observed between the northern and southern hemispheres during the rapid latitude scan. Now that Ulysses has covered a major fraction of the northern high latitude solar wind, we can assess to what extent this asymmetry persists. Figure 5 displays mean speed, scaled density, [He], and proton temperature, binned by solar rotation, versus latitude for the southern and northern hemispheres. It is readily apparent that in all but the [He] profiles, there is a clear asymmetry between the northern (solid line) and southern (dashed line) hemispheres during the fast latitude scan. In the intervals preceding and following the fast latitude scan, however, when Ulysses moved much more slowly with respect to latitude, the asymmetry is less clear: There is still a tendency for the northern hemisphere to have a slightly higher speed and lower density; however, the asymmetry no longer persists in proton temperature. It has been suggested that the Ulysses data indicate a plane of symmetry which is displaced southward by 5°-10°. The most recent solar wind data are still consistent with this hypothesis.

Since normalized density is lower in the northern hemisphere and speed is higher, an important question concerns the variation of mass flux and momentum flux in the two hemispheres. These are shown in Figure 6. Mass flux is consistently lower in the northern hemisphere. Momentum flux, at least during the fast latitude scan, appears to be approximately the same in both hemispheres. The large difference between the curves prior to and following the fast latitude scan may be temporal effects; almost sixteen months passed between the start of the solid line and the end of the dashed line, during which time the Sun evolved significantly in its solar cycle.

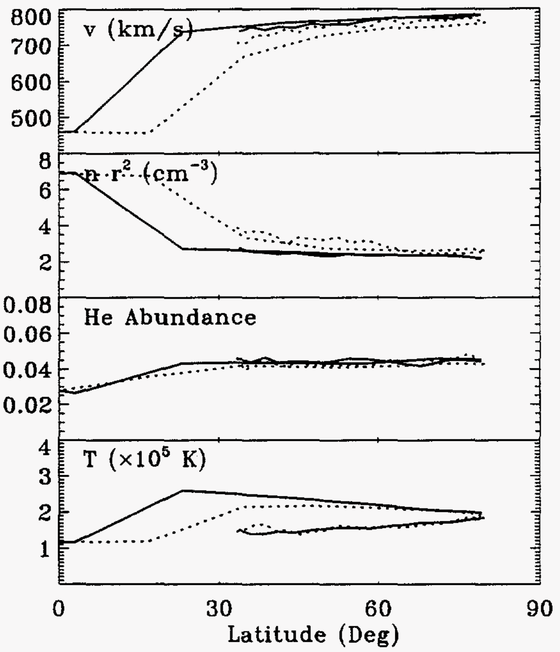

Fig. 5. Solar wind mean speed, proton density, He abundance, and proton temperature, binned by solar rotation. In each panel, the solid curve corresponds to the northern hemisphere, and the dotted curve corresponds to the southern hemisphere.

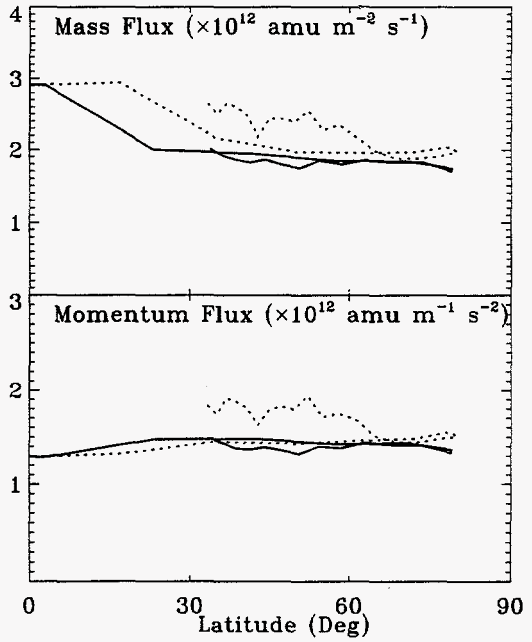

Fig. 6. Solar wind mean mass flux and momentum flux, binned by solar rotation. In each plot, the solid curve corresponds to the northern hemisphere, and the dotted curve corresponds to the southern hemisphere.

SUMMARY AND DISCUSSION

In this report, we have summarized measurements taken with the Ulysses' solar wind plasma experiment over the last sixteen months, commencing with its traversal into the northern hemisphere until the present (July, 1996). In addition, we have compared these results with southern hemispheric measurements. Our analysis supports the previous suggestion of a modest asymmetry between the two hemispheres. Mass flux continues to be the least variable property of the solar wind. Velocity and temperature are higher at high latitudes, while density is lower. The variation of momentum flux suggests an elongated shape for the heliosphere; at least during solar minimum.

So far, the northern fast wind has been devoid of coronal mass ejections, strong stream interactions, or shocks, although solar rotational structures in the form of recurrent compressive events are beginning to reappear in the solar wind plasma data. Alfvénic (e.g., Smith *et al.* (1995)), compressional (e.g., Neugebauer and Ruzmaikin (1996)), and pressure-balanced (e.g., McComas *et al.* (1996)) structures continue to dominate the high latitude solar wind.

The solar wind plasma experiment continues to function nominally, providing an essentially continuous measure of solar wind properties over a wide range of heliocentric distances and heliographic latitudes. Over the next several years, Ulysses will enter a new epoch of observations by sampling the low latitude solar wind at an nearly constant heliocentric distance (~5 AU). Following this, Ulysses will return to the southern polar regions (September, 2000 to January, 2001) and northern polar regions (September to December, 2001). However, owing to a fortuitous orbital period of 6.2 years, the Sun will have evolved to a state of maximum activity when Ulysses returns, thus providing a radically different environment in which to probe the high-latitude solar wind.

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