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## Evidence for a high-latitude origin of lower latitude high-speed wind

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**Abstract:** Using low-frequency spectra of the wind speed, density, and magnetic field strength, we show that the near-streamer belt solar wind at solar minimum exhibits many harmonics of fundamental frequencies corresponding to 26- and 34-day periods. Nearly all the low-frequency peaks in the spectra can be explained by these harmonics. The 26-day period is that of coronal hole rotation, and the 34-day period is naturally associated with the photospheric rotation period at about 70° S latitude. Thus we find evidence that the wind flow near 25° S comes from a region poleward of 60° S, consistent with magnetic field models.

flows have been presumed to originate at higher latitude than in the 10° band in the region near 25° S at which they are measured: both the structure of helmet streamers seen in white light photographs and the observed weak variation of field strength over the poles are consistent with an expansion of the flow due to magnetic pressure [Balogh *et al.*, 1995; Fahr and Fichtner, 1991]. It has been something of a puzzle why the flows do not show evidence of the photospheric rotation period at the higher latitude source region. In this paper we use spectra of the time series in Fig. 2 to argue that the longer periods are present, thus providing evidence for the higher latitude origin for the lower latitude flows.

### Introduction

The solar surface rotates faster at the equator than near the poles [Howard and Harvey, 1970] (see Fig. 1), whereas the coronal holes, known to be the source of high speed streams, show remarkably rigid rotation [Timothy *et al.*, 1975; Wagner, 1975]. This is typically attributed to the tying of the holes to the subphotospheric fields that are presumed to be rotating more uniformly than the surface layers. Spacecraft observations of the solar wind in the ecliptic, especially near solar minimum, show the characteristic 26-day period of coronal hole rotation, and often a multiple or two of the basic frequency is evident due to the warping of the heliospheric current sheet that leads to multiple crossings of the solar equator (where the slow wind flows) in a given solar rotation [e.g., Matthaeus and Goldstein, 1982; Burlaga, 1987]. Any time series with a characteristic period but with smaller-scale structure or waveform shape will have a power spectrum that includes many multiples of the fundamental period, but generally solar wind time series are not sufficiently stationary for higher harmonics to be seen.

The Ulysses spacecraft provides a unique opportunity to study low-frequency spectra of the solar wind because it measures very long time series under nearly uniform conditions. For this study we will focus on the interval somewhat after the Jupiter encounter (1992 day 247 to 1993 day 90) in which the spacecraft repeatedly dipped into the streamer belt while spending much of its time in the high-speed flow associated with the south polar coronal hole. Figure 2 presents the density, flow speed, and magnetic field magnitude for this interval. Note the very regular 26-day (624-hr) repetition of many features, including the streams and the compressed plasma at the leading stream interfaces. These

### Data Analysis

Since we are interested only in the low-frequency behavior of the time series, we use hourly averaged data from 208 days of the publicly available portion of the data from the Ulysses mission. Many short data gaps were filled by linear interpolation, and this has essentially no effect on the periods of a day or more relevant here. While we also apply more sophisticated methods [Thomson *et al.*, 1995], the use of a long and regular time series allows us to demonstrate the main results using a simple FFT power spectrum. To maintain the spectral resolution, no averaging of the spectra are performed, and the full 5000 data points are used in the transforms. The resulting spectra have two degrees of freedom per spectral estimate. The conventional statistical error bars for this case are very large, but we believe the peaks are real, as argued below.

The spectra presented in Fig. 3 have the square of the Fourier coefficients multiplied by  $f^{5/3}$ , where  $f$  is the frequency, so that the spectrum is "whitened," making peaks appear more equal despite the general decrease in power with increasing

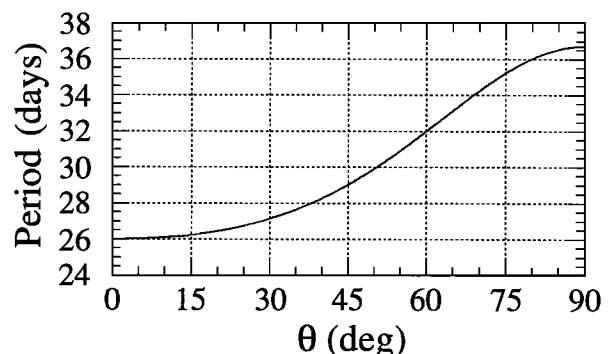


Fig. 1. The rotation period of the solar surface as a function of latitude.

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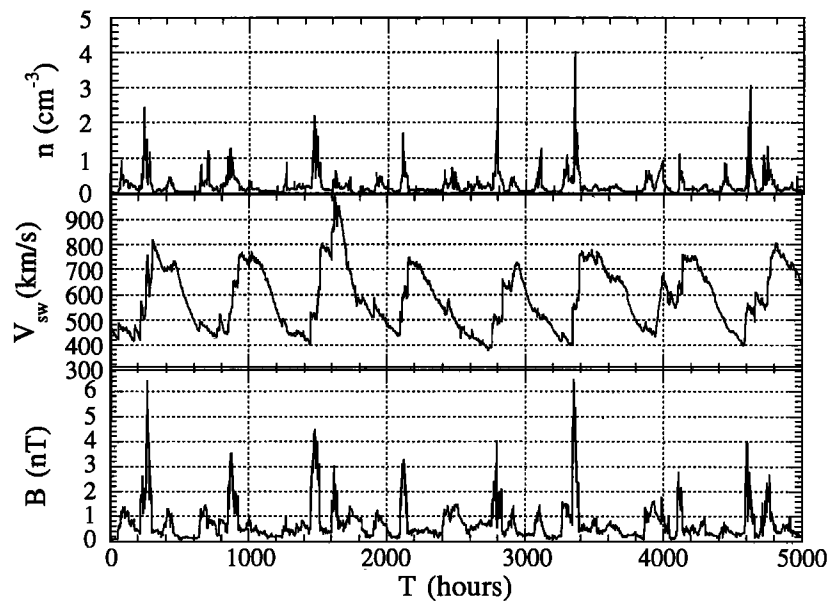


Fig. 2. Time series of Ulysses hourly-averaged data from day 247 of 1992 to day 90 of 1993 for the (top) density, (middle) solar wind speed, and (bottom) the magnitude of the magnetic field.

frequency. The plots are log-linear so that the regular spacing of harmonics is evident. Examination of Fig. 3 reveals that all three quantities, and especially the magnetic field and density, show remarkably similar peaks at low frequencies, although the relative amplitudes are different, leading to the qualitative difference in the large-scale structure of the time series. Two sets of harmonics are apparent; although a few peaks do not appear or are not prominent, generally the first 10 multiples

of two basic frequencies appear in both spectra. (Higher harmonics are sometimes strong as well.) The periods for the fundamentals of these series that give the best fit to each set of peaks are 26.0 and 34.3 days, with an uncertainty of roughly 0.2 days. If we take the width of the peaks to indicate a range of possible periods contributing to the average, we find a range of about  $\pm 1.5$  days. The 26-day peak clearly represents the coronal hole rotation rate, and in this case the range of periods

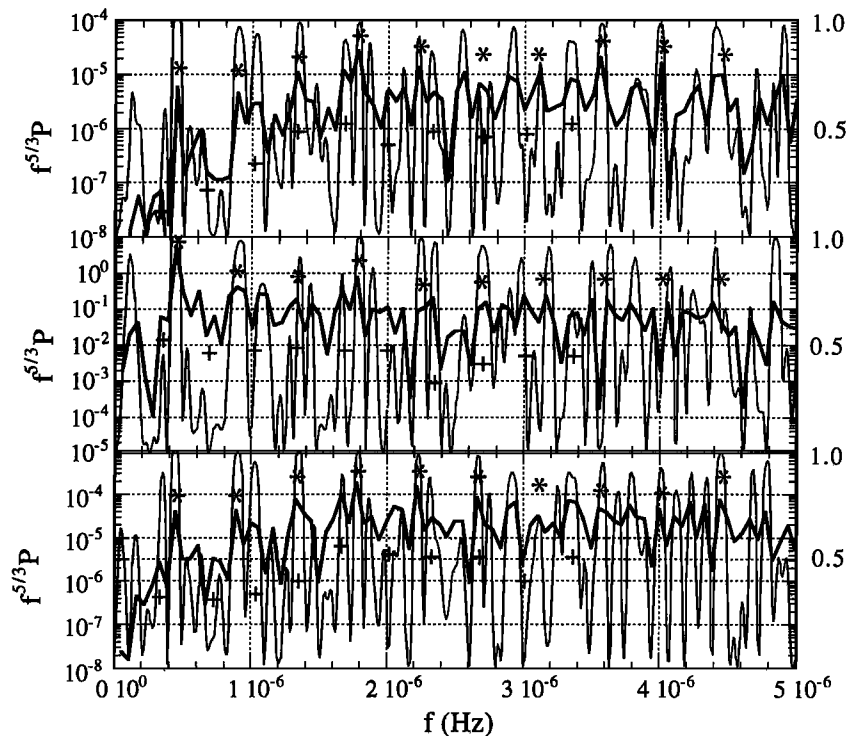


Fig. 3. Power spectra of the time series in Fig. 2 (thick lines), multiplied by  $f^{5/3}$ . (Top) Spectrum of the density. (Middle) Spectrum of the speed. (Bottom) Spectrum of the magnitude of the magnetic field. The symbols are centered on the harmonic series for 26.0 (\*) and 34.3 (+) day fundamental periods, and the width of the symbols is roughly the width of the individual peaks. The thin lines (with the scale on the right) give the significance of the density modes as found from a multi-taper spectral analysis.

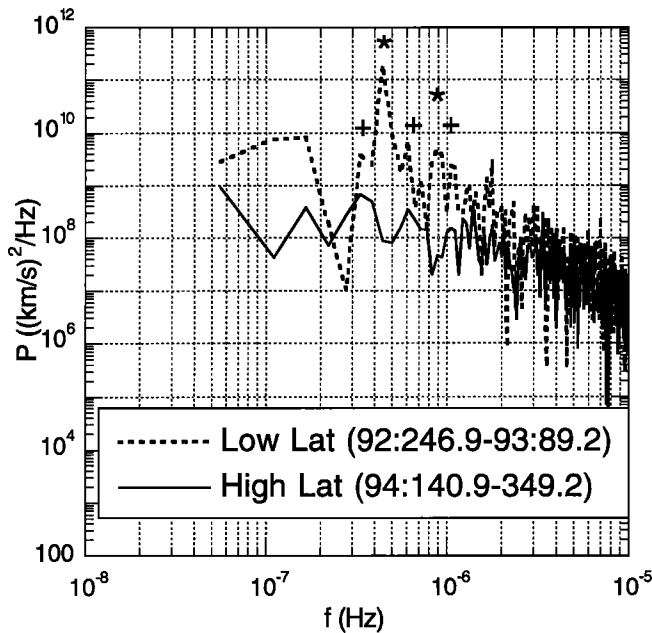


Fig. 4. Power spectra of the speed from the time series in Fig. 2 (dotted line) and of a polar time series (solid line), presented unweighted.

is probably due to the time variability and thus the nonrepeatability in detail of the source region.

We establish the reality of the peaks as follows: First, we find clear peaks for modes 1, 2, and 4 of the 26-day series that agree to within their strict uncertainties with *Thomson et al.* [1995] values. This convinces us that we can find peaks well. Our peaks are from physically very different time series. Our tests show that these spectra are robust with respect to endpoint, spike, and sampling problems. The set of 34-day peaks appears in the physically different time series and agrees with a well-known physical period. For the density spectrum, 18 of the 20 identified harmonics are within 2% or less of significant measured spectral peaks, and our analysis accounts for nearly all the peaks in the frequency range examined. Finally, we employed the multi-taper spectral method of *Thomson et al.* (as implemented by *Paillard, et al.* [1996]) to determine a quantitative measure of the significance of the modes. The significance as determined by an *F*-test (see Fig. 3) shows that the Fourier peaks are good indicators of significant frequencies. This test, which gave peaks that were stable under changes in analysis parameters, shows a consistent although modest (except in the magnetic field) peak at the 34-day period, a broad peak at 26 days, and peaks for most of the harmonics. (None of the *F*-values is larger than one, and the broad peaks are indications of real nonstationarity of the signal.) Only a small fraction of the peaks of high significance are outside the harmonic series. Thus both physical and statistical arguments lead to the conclusion that the modes we have identified are real. We have also confirmed the existence of the peaks with other spectral methods.

Figure 1 is based on an empirically established formula for the photospheric surface rotation rate  $f_s$  as a function of latitude  $\theta$  [Howard and Harvey, 1970], namely

$$f_s = (1/26)(1 - (1/8)\sin^2\theta - (1/6)\sin^4\theta)$$

This function depends on the solar cycle, but not to a degree

that will be significant here [e.g., *Nesme-Ribes et al.*, 1993]. According to the figure, the 34-day peak corresponds to the rotation rate of the solar surface at about  $70^\circ$  latitude; with this interpretation, the range corresponding to the peak widths represents a  $\pm 5^\circ$  source region for the near-streamer belt flows. We see no other natural cause for the harmonic series based on the longer period, and thus we see no other possible interpretation. Thus these spectral results provide evidence that the coronal hole flows expand and extend downward toward the ecliptic. We note also that the photospheric rotation rate has been detected without interference from the 26-day period in moderate energy electron data taken much nearer the solar poles [Lanzerotti et al., 1995]. *Zurbuchen et al.* [1997] used autocorrelation functions to establish results similar to ours.

The 34-day peak itself appears weak in Fig. 3, although it is more significant than its neighbors and consistently observed in the *F*-test; however, this apparent weakness is an artifact of the frequency multiplier in the plots. To show this, Fig. 4 presents the traditional log-log spectrum of the speed time series from the previous figures as the dotted line. The 34-day peak, located at the first "+", would be one of the highest were it not for the peaks at 26 and 13 days ("\*", as before). As one further test of this point and of the overall significance of our results, we also present in Fig. 4 (solid line) the spectrum of the speed while Ulysses was in the pure high-speed wind over the poles. Most notable is the absence of the 26 and 13 day peaks, as well as the continuing appearance of a longer period peak and plausible harmonics of it. In this case, a fairly broad range of periods is sampled, and there is a phase change in the signal as the spacecraft passes over the polar region, and this leads to a broader peak near 34 days. However, there is very good agreement between the basic locations of the peaks in the polar and the low-latitude spectra, and the "34-day" peak is clearly the strongest in the polar spectrum. Note that the largest peaks in the polar case are lower than the corresponding nominally "weak" peaks in the other trace. Thus, Fig. 4 provides evidence for the significance of the fundamental in the low-latitude spectrum, as well as further confirmation of the reality of the 34-day peak.

## Discussion

We conclude that the differential rotation of the solar photosphere and power spectra of solar wind variables can provide evidence for the source regions of coronal hole flows. More work is needed to identify the features that give rise to the 34-day harmonic series, but the present study establishes a plausible case. The result that the wind that we see within about  $30^\circ$  of the magnetic equator actually comes from poleward of  $60^\circ$  is consistent with the pictures derived from MHD calculations and from the lack of a strong dependence of the polar magnetic field strength on latitude.

The appearance of high harmonics of basic rotation frequencies might explain the results of *Neugebauer et al.* [1995], who discovered peaks that (in retrospect) could be harmonics of a 35-day or so rotation period that would be expected in polar data above the coronal hole boundary. (Note that in Fig. 3 there is a clear peak at 3.3 days or 3.35  $\mu$ Hz.) Examination of different intervals, as with different time series, shows that while the frequencies present tend to be stable, the strength of different peaks changes in time. This corresponds to the appearance of fairly long lived structures of

a particular size, such as the approximately three-day microstreams that persisted in the interval examined by Neugebauer et al.

The observation of the differential rotation period in the solar wind spectra implies that the solar surface matters in producing the wind. This is not surprising but also not entirely obvious in that some theories rely solely on coronal structures (such as microflares) for producing the additional acceleration required for high speed streams. Thus our results provide significant support for the connection of low-latitude flows to their origin at high latitudes as well as providing hints that may be helpful in understanding the wind acceleration.

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