DOPPLER SCINTILLATION MEASUREMENTS OF THE HELIOSPHERIC CURRENT SHEET AND CORONAL STREAMERS CLOSE TO THE SUN

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Abstract. Prominent enhancements in Doppler scintillation lasting a fraction of a day (solar source several degrees wide) and overlying the neutral line represent the signature of the heliospheric current sheet and the apparent interplanetary manifestation of coronal streamers near the Sun. This first detection of coronal streamers in radio scintillation measurements provides the link between *in situ* measurements of the spatial wavenumber spectrum of electron density fluctuations beyond 0.3 AU and earlier measurements deduced from radio scintillation and scattering observations inside 0.3 AU. Significant differences between the density spectra of fast streams and slow solar wind associated with the heliospheric current sheet near the Sun reinforce the emerging picture that high- and low-speed flows are organized by the large-scale solar magnetic field, and that while the contrast between solar wind properties of the two flows is highest near the Sun, it undergoes substantial erosion in the ecliptic plane as the solar wind expands.

1. Introduction

Compressive structures and fluctuations spanning an extensive range of scale sizes are ubiquitous in the solar wind. Investigations of these fluctuations have been based on *in situ* plasma measurements (Intriligator and Wolfe, 1970; Goldstein and Siscoe, 1972; Neugebauer et al., 1978; Marsch and Tu, 1990) as well as remote sensing radio scintillation measurements using both natural and spacecraft radio sources (Hewish, 1971; Coles, 1978; Woo and Armstrong, 1979). The latter represent essentially our only means for studying electron density fluctuations inside 0.3 AU. Amongst the wide range of scintillation phenomena (Coles, 1978; Woo, 1993), Doppler or equivalently phase scintillation measurements have been especially useful, because they not only probe the fullest range of spatial wavenumbers, but also a heliocentric distance range that starts near the Sun and extends to near Earth orbit. In spite of some progress (Montgomery et al., 1987; Marsch and Tu, 1990), the nature of compressive fluctuations is still not yet fully understood.

Variations in compressive fluctuations, reflecting solar wind changes, produce enhancements [also referred to as transients, see Woo (1993)] in Doppler scintillation. While many of these enhancements are caused by propagating interplanetary disturbances, some of which drive interplanetary shocks (Woo and Armstrong, 1981), others are due to quasi-stationary structure such as coronal streamers, and still others arise from dynamic interaction in the solar wind with increasing heliocentric distance, such as the formation of compressed plasma in interaction regions ahead of fast streams (Houminer and Hewish, 1972). One of the advantages of observing the solar wind near

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the Sun is that variations of solar origin can readily be distinguished from those that evolve as a result of dynamic interaction.

With the availability of high time resolution Doppler scintillation observations for comparisons with both solar and *in situ* plasma measurements, there is growing evidence that the morphology of Doppler scintillation is organized by the large-scale solar magnetic field (Woo and Gazis, 1993). In this paper, we provide further evidence for this morphology, including the first apparent signature of the heliospheric current sheet, and differences between the spatial wavenumber spectrum of electron density fluctuations for fast and slow solar wind. Finally, we summarize the emerging global picture of large scale solar wind structure in the vicinity of the Sun based on recent radio scintillation and scattering results.

2. Doppler Scintillation Measurements

Doppler scintillation is a path-integrated measurement that responds to electron density fluctuations and solar wind speed transverse to the radio path (Woo and Schwenn, 1991). Correlation of Doppler scintillation measurements with solar source surface magnetic field maps (Hoeksema and Scherrer, 1986) reveal that scintillation enhancements are generally observed in the vicinity of the neutral line near the Sun. In the case of the 1984 Pioneer Venus measurements investigated in Woo and Gazis (1993), these enhancements extended over a longitude range of 90-140°. However, enhancements lasting only a fraction of a day (corresponding to an extent of several degrees), probably reflecting those occasions on which coronal mass ejection (CME) activity is either absent or low, also appear frequently. Two examples of these transients observed by Pioneer Venus in 1987 are shown in Fig. 1, along with the contour map of the source surface magnetic field strength produced by the Wilcox Solar Observatory (see e.g., Hoeksema and Scherrer, 1986) and corresponding to the relevant Carrington Rotation CR 1772. The corresponding closest approach distances of the Pioneer Venus radio path in solar radii and AU, shown at the top of the time series panel, indicate that the S-band (13 cm wavelength) measurements probed the solar wind around 35 R_O.

The Doppler scintillation time series in Fig. 1 has been scaled to 1 AU by multiplying the observed rms Doppler scintillation (3-min values based on 1 per 10 sec Doppler measurements) by $R^{1.5}$, representing a R^{-2} fall-off in electron density fluctuation with heliocentric distance R. The dots on the magnetic field map represent the points of closest approach of the Pioneer Venus radio path on the indicated days of year (DOY) at 0000 UT mapped back to the surface of the Sun assuming a constant radial solar wind speed of 450 km/s. For convenience of comparison, the time axis of the normalized Doppler scintillation has been reversed and displayed in such a manner that DOY lines up approximately with the corresponding dots on the magnetic field map. The scintillation enhancements occur during crossings of (or when the measurements are very close to) the neutral line, and in agreement with previous results (Woo and Gazis, 1993, 1994), Doppler scintillation levels away from neutral line

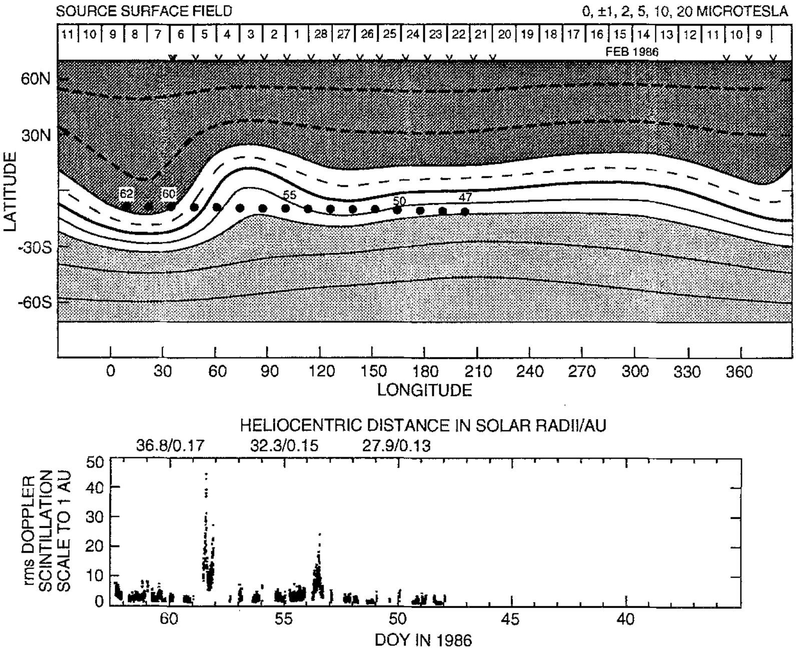

Fig. 1 Contour map of the source surface magnetic field strength produced by Wilcox Solar Observatory corresponding to Carrington Rotation 1772, and time series of Doppler scintillation scaled to 1 AU.

(presumably associated with the fast wind) are depressed and exhibit low variability. Recent Ulysses ranging measurements (Bird et al., 1994), show that peaks in mean density occur during enhancements like those in Fig. 1 (Woo et al., in preparation). Coincidence of Doppler scintillation enhancements like those in Fig. 1 with peak densities and the neutral line leads to the first identification in radio scintillation measurements of the signature of the heliospheric current sheet and the apparent interplanetary manifestation of coronal streamers near the Sun. *In situ* fields and particles measurements beyond 0.3 AU have shown that minimums in helium abundance, solar wind flow speed and proton temperature, coincide with the peak density observed at the sector boundary (Gosling et al., 1981).

3. Spatial Wavenumber Spectrum of Electron Density Fluctuations

In situ measurements of proton density fluctuations (limited to frequencies lower than 6 x 10^{-3} Hz) in the heliocentric distance range of 0.3-1.0 AU by Helios have shown that they are significantly different between high and low-speed solar wind flows especially near 0.3 AU (Marsch and Tu, 1990). In the slow wind near the sector boundary, the compressive fluctuations are more fully developed and intense, and exhibit a spatial wavenumber spectrum that is radially invariant and approximately Kolmogorov. In contrast, fast stream turbulence is significantly less compressive in terms of relative density fluctuations, but becomes increasingly compressive as the solar wind expands, with its density spectrum showing a flatter high-frequency part that evolves with heliocentric distance.

Radio scintillation and scattering observations complement these *in situ* plasma measurements, because they not only provide the only measurements of the spatial wavenumber spectrum of electron density fluctuations inside 0.3 AU, but over an extensive range of spatial scales as well, including scales smaller than those observed by *in situ* measurements. Yet, the lack of simultaneous measurements of solar wind speed has so far precluded discriminating high and low-speed flows (Woo and Armstrong, 1979; Coles et al., 1991).

That enhancements like those in Fig. 1 coincide with sector boundary crossings, where *in situ* measurements beyond 0.3 AU have shown that the solar wind is slow and highly compressive, strongly suggests that at least some of the enhancements identified as 'transients' in Coles et al. (1991) represent similar slow solar wind, while the 'transient'-free solar wind more likely represents the fast streams. Evidently, although many Doppler scintillation enhancements, especially those during the high activity phase of the solar cycle, represent interplanetary disturbances characterized by fast moving solar wind (speeds exceeding about 500 km/s) (Woo and Schwenn, 1991), the enhancements in Fig. 1 are associated with slow solar wind. While correlations between Doppler scintillation near the Sun and *in situ* solar wind speed measurements near 1 AU (but 90° apart in longitude) conducted in 1984 show a close association between scintillation enhancements in the vicinity of the neutral line and the slow solar wind (Woo and Gazis, 1993), more direct evidence has recently been obtained (Woo and Martin, in preparation) with solar wind speeds deduced from Voyager 1 and 2 intensity scintillation measurements of the near-Sun solar wind during 1979-1982 (Martin, 1985).

Although the range of overlapping spatial scales is narrow, further support comes from the similarity in behavior of density spectra deduced from phase scintillation and spectral broadening measurements inside 0.3 AU (Woo and Armstrong, 1979; Coles et al., 1991) to that obtained from *in situ* Helios plasma measurements beyond 0.3 AU (Marsch and Tu, 1991). Voyager phase scintillation and spectral broadening measurements conducted in 1979-1980 (Coles et al., 1991) reveal that electron density spectra of 'transient'-free [fast wind as shown in some of cases by velocity estimates deduced from simultaneous intensity scintillation measurements (Woo and Martin, in preparation)] tend to be steep (approximately Kolmogorov) at large spatial scales (10^3-10^6 km), but which show flattening at smaller scales (10-100 km). The inflection between the steep and flatter regions is abrupt and occurs in the vicinity of 100-300 km. In the 'transient' wind [corresponding to slow wind as shown in some cases by wind speeds deduced from simultaneous intensity scintillation measurements (Woo and Martin, in preparation)], there is an overall increase of power in the density spectra at large scales and a steepening in spectra at small scales, resulting in spectra that are not only significantly higher than those of the 'transient'-free solar wind, but which are (as in the case of *in situ* measurements for slow wind) approximately Kolmogorov.

Inflections similar to those observed in the Voyager measurements were not as readily apparent (if at all) in a comprehensive study of the electron density spectrum based on 1976 Viking phase scintillation and spectral broadening measurements (Woo and Armstrong, 1979). The Viking radio measurements took place essentially in the ecliptic plane at a time when the neutral line was confined to the vicinity of the ecliptic plane (flat heliospheric current sheet) (Hoeksema and Scherrer, 1986), so that the 1976 Viking measurements essentially observed slow solar wind much of the time. On the other hand, the Voyager measurements took place in 1979-1982 when the neutral line experienced large latitudinal excursions (warped heliospheric current sheet) resulting in the probing of both slow and fast solar wind flows.

4. Global Large-Scale Solar Wind Structure

Detailed studies are still in progress, but a broad picture of global large-scale solar wind structure near the Sun can be described. Beyond 0.5 AU, we know from multiple station intensity scintillation (IPS) observations that solar wind speed is slow over the streamer belt and fast away from it (Kakinuma and Kojima, 1990; Rickett and Coles, 1991). Inside 0.3 AU, scintillation measurements conducted with coherent spacecraft radio signals have provided more details of the association of solar wind properties with large-scale solar magnetic fields. Over the streamer belt where coronal streamers and CMEs prevail, density fluctuations are enhanced and varied (Woo and Gazis, 1993), and their spatial wavenumber spectrum is close to Kolmogorov. The fast stream wind emanating from regions away from the streamer belt exhibits compressive fluctuations characterized by depressed levels and low variability, and spectra that tend to show flattening at small spatial scales. Variations in solar wind speed and mass flux are low (Woo and Gazis, 1994). *In situ* measurements have shown that the solar wind speed dividing high and low speed flows is around 450 km/s. During solar minimum conditions, when polar coronal holes serve as sources of polar fast streams, and slow wind is confined mainly to the equatorial region, the differences between fast and slow winds are manifested as latitudinal variation showing pole-to-equator increases in mass flux and pole-to-equator decreases in solar wind speed (Woo and Goldstein, 1994).

Because their sources are physically separate at the Sun, contrast in properties of the high- and low-speed solar winds is highest near the Sun and tends to be abrupt. With solar wind expansion, dynamic interaction, which is greatest in the ecliptic plane, leads to erosion of this contrast, and is manifested by: (1) an increase in compressive fluctuations with heliocentric distance within fast streams (Marsch and Tu, 1991), (2) a trend showing decreasing differences with heliocentric distance between the intensity (magnitude) and spatial wavenumber spectrum of density fluctuations of both flows (Marsch and Tu, 1991; Woo and Gazis, 1993, 1994), (3) a slight increase in mass flux with heliocentric distance in fast streams (Schwenn, 1990; Woo and Gazis, 1994), and (4) a corresponding decrease in mass flux with heliocentric distance in the slow solar wind (Schwenn, 1990). Due to reduced interaction with slow wind, density fluctuations in the polar fast wind currently being encountered by Ulysses at high latitude but beyond 1 AU might be expected to possess a spatial wavenumber spectrum that more closely resembles that of the fast wind observed by radio scintillation measurements in the vicinity of the Sun (showing flattening at small scales).

Although contrasting high- and low-speed solar wind in the vicinity of the Sun is most evident near solar minimum conditions when the large-scale solar magnetic field configuration is more stable and coronal mass ejections less frequent (Howard et al., 1986; Hundhausen, 1993), results obtained to date indicate that it is discernible at other times of the solar cycle, both in and out of the ecliptic plane.

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