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

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Abstract. Doppler scintillation transients overlying the neutral line and lasting a fraction of a day (solar source of several degrees) are the apparent interplanetary manifestation of coronal streamers embedded in the heliospheric current sheet. This result provides the link between measurements of the spatial wavenumber spectrum of electron density fluctuations inside 0.3 AU deduced from radio scintillation and scattering observations and those beyond 0.3 AU based on in situ proton density measurements. Significant differences in the density spectra of fast streams and slow solar wind associated with coronal streamers reinforce the emerging picture that high- and low-speed solar wind are organized by the large-scale solar magnetic field, that contrasts between the two flows are highest nearest the Sun, and that the contrasts undergo substantial erosion in the ecliptic plane as the solar wind expands.

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 radio scintillation and scattering phenomena (Coles, 1978; Bird and Edenhofer, 1990), 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 1 AU. In spite of some progress (Montgomery et al., 1987), the nature of compressive fluctuations is still not yet fully understood.

Variations in compressive fluctuations produce transients (enhancements) in Doppler scintillation measurements. While many of these transients represent propagating interplanetary disturbances, some of which drive interplanetary shocks (Woo and Armstrong, 1981), others represent quasi stationary structure such as coronal streamers, or arise from dynamic evolution with increasing heliocentric distance such as in the case of compressed plasma in interaction regions. One of the advantages of observing solar wind structure near the Sun is that structure of solar origin can be readily distinguished from that evolving from dynamic interaction.

With the availablity of more continuous (higher time resolution) Doppler scintillation observations for comparisons with both solar (e.g., white light coronagraph and solar magnetic field) 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 of this morphology, which includes the apparent signature of coronal streamers in Doppler scintillation and differences in the spatial wavenumber spectrum of electron density fluctuations between fast and slow solar wind. Finally, we summarize the emerging global picture of large scale solar wind structure based on recent radio scintillation and scattering results.

2 Doppler Scintillation Measurements of Coronal Streamers

Doppler scintillation is a path integrated measurement that responds to electron density fluctuations and solar wind speed transverse to the radio path (Woo et al., 1985). Correlation of Doppler scintillation measurements with solar source surface magnetic field maps (Hoeksema and Scherrer, 1986) reveal that scintillation transients 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), transients took place over a longitude range of 90–140°. However, transients 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 $R_\odot$. The Doppler scintillation time series in Fig. 1 has been normalized 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. As can be seen, the scintillation transients 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 (and presumably associated with the fast wind) are depressed and exhibit low variability.

Coincidence of the transients in Fig.   with the neutral line together with the similarity of their signatures with those of situ proton density measurements at the sector boundary near 1 AU (Gosling et al., 1981), indicate that the transients are the apparent interplanetary manifestation of coronal streamers. In situ fields and particles measurements near 1 AU also show 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). The transients that last a fraction of a day appear to show that the slow solar wind embedded in the heliospheric current sheet near 1 AU can be traced to a small region (several degrees wide) near the neutral line on the Sun.

3. Spatial Wavenumber Spectrum of Electron Density Fluctuations

In situ measurements of proton density fluctuations (but 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 compressive turbulence is 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, compressive turbulence is more fully developed and intense, and exhibits 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 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 including scales smaller than those observed by in situ measurements. Yet, the general lack of suitable simultaneous solar wind speed measurements has so far precluded discriminating high and low-speed flows (Woo and Armstrong, 1979; Coles et al., 1991).

That the transients 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 transients identified in earlier studies (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 transients, especially those during the high activity phase of the solar cycle, represent interplanetary disturbances characterized by fast moving solar wind (Woo and Schwenn, 1991), those in Fig. 1, are associated with the 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 have shown a close association between some scintillation transients 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) from 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 (Woo and Armstrong, 1979; Coles et al., 1991) inside 0.3 AU to those 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 reveal that electron density spectra of transient-free (consequently fast wind as shown in some of cases by velocity estimates deduced from simultaneous intensity scintillation measurements) 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 (some of which corresponds to slow wind as shown by wind speeds deduced from simultaneous intensity scintillation measurements), there is an overall increase in 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.

It is interesting to point out that inflections similar to those observed in the Voyager measurements were not 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). This can be explained by the fact that 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) so that the 1976 Viking measurements observed the 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 Picture of Large-Scale Solar Wind Structure

This paper presents the apparent interplanetary signature in Doppler scintillation of coronal streamers embedded in the heliospheric current sheet near the Sun. Manifestation takes the form of transients lasting a fraction of a day and overlying the neutral line, indicating a spatial extent of several degrees. This result provides the link between measurements of the spatial wavenumber spectrum deduced from radio sintillation and scattering observations inside 0.3 AU and those obtained from in situ proton density measurements beyond 0.3 AU. The emerging global picture of large-scale solar wind structure near the Sun can be summarized as follows.

Scintillation measurements reveal significantly more solar wind structure near the Sun than beyond 0.5 AU. Much of this structure can be traced to the large contrasts in solar wind properties between fast-stream and slow solar wind flows, whose boundaries tend to be abrupt. Near the Sun, slow wind flows are associated with the neutral line, and show high levels and high variability of compressive fluctuations, whose spatial wavenumber spectrum is close to Kolmogorov. The variability during solar minimum conditions appears to be closely associated with coronal mass ejection activity and related to the high variability of helium abundance characteristic of slow wind flow at 1 AU.

On the other hand, fast-stream solar wind is observed away from the neutral line (at large heliomagnetic latitudes). It exhibits conspicuously low levels and low variability of compressive fluctuations, whose spectra tend to show enhancements (or spectrum flattening) at small spatial scales. Variations in mass flux are low (Woo and Gazis, 1994). 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 in fast and slow wind 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 of physically separate sources at the Sun, the contrast between the properties of high- and low-speed solar wind is highest near the Sun. As the solar wind expands, dynamic interaction between the two flows leads to the erosion of this contrast. Evolution is greatest in the ecliptic plane, and is manifested by; (1) an increase in compressivity of fast stream turbulence with heliocentric distance (Marsch and Tu, 1991), (2) a trend showing decreasing differences with heliocentric distance between the intensity and spatial wavenumber spectra of density fluctuations of both flows (Marsch and Tu, 1991; Woo and Gazis, 1993, 1994). (3) a gradual 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).

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

It is important to emphasize that while the general morphology of scintillation is emerging, further on-going studies will elucidate the radial evolution of the interplanetary manifestation of coronal streamers, the nature and radial evolution of compressive fluctuations near the Sun, the reltationship of compressive flutuations near the Sun to those in the heliospheric current and heliospheric plasma (Winterhalter et al., 1994) sheets beyond 0.3 AU, and the interplanetary manifestation of coronal mass ejections.

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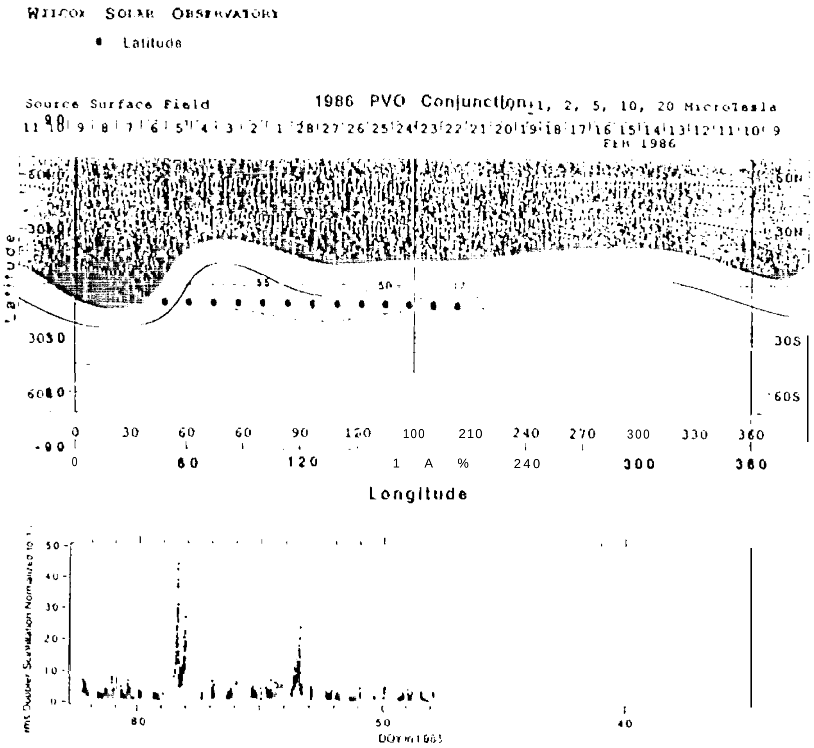
Figure Caption

Fig. 1 Contour map of the source surface magnetic field strength produced by Wilcox Solar Observatory corresponding to Carrington Rotation [illegible]. Time series of normalized Doppler scintillation obtained by multiplying the observed 3 min rms Doppler scintillation (based on 1 per 10 sec Doppler data) by $R^{1.5}$, and referring the results back to the Sun assuming a constant radial solar wind speed of 450 km/s. Corresponding heliocentric distances in solar radii and AU are indicated at top of the panel. The time axis is reversed and the time series is approximately aligned with the corresponding trace of the closest approach point of the radio path on the contour map indicated by the dots.


WILCOX SOLAR OBSERVATORY
• Latitude
Source Surface Field
1986 PVO Conjunction
1, 2, 5, 10, 20 MicroTesla
11 10 9 8 7 6 5 4 3 2 1 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9
FEB 1986
Latitude
60N
30N
30S
60S
-90
0 30 60 60 90 120 100 210 240 270 300 330 360
0 60 120 1 A % 240 300 360
Longitude
rms Doppler Scintillation Normalized to 1
0 10 20 30 40 50
80 50 40
DOY in 1985