STRUCTURE IN THE SOLAR CORONA FROM RADIO SCINTILLATION MEASUREMENTS

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Abstract. Since the 1950s, a wide variety of radio observations based on scattering by electron density fluctuations in the solar wind has provided much of our information on density fluctuations and solar wind speed near the source region of the solar wind. This paper reviews recent progress in the understanding of the nature of these density fluctuations and their relationship to features on the Sun. The results include the first measurements of fine-scale structure within coronal streamers and evidence for structure in solar wind speed in the inner corona.

1. Introduction

In the absence of direct measurements, radio propagation measurements using both natural radio sources and spacecraft radio signals remain our only means for probing electron density fluctuations and solar wind speed in the vicinity of the Sun. Starting with angular broadening measurements in the 1950s [*Hewish*, 1958; *Vitkevitch*, 1958], a wide variety of observations based on radio scattering by the solar corona has yielded many details of the density fluctuations and provided general evidence for acceleration of the solar wind [see e.g. *Coles*, 1993]. However, little is known about the nature of the density fluctuations and their relationship to features on the Sun, and the causes of the large variations observed in solar wind speed [*Armstrong et al.*, 1986].

In situ measurements beyond 0.3 AU have given many indications that solar wind properties seem to be organized around the large-scale solar magnetic field [*Schwenn*, 1990], but nowhere is this organization more conspicuous than in the vicinity of the Sun before the solar wind has had a chance to evolve. The recent demonstration that scintillation measurements reflect this organization [*Woo and Gazis*, 1993; *Woo et al.*, 1994], often in a dramatic way, significantly aids in separating spatial and temporal variations and distinguishing high and low speed wind when speed measurements are not available. As a result, advances have been made not only in the global picture of the inner solar wind based on centimeter wavelength measurements, but also in its relationship to white-light coronagraph results and in situ plasma measurements beyond 0.3 AU. This paper summarizes progress since that reported by *Woo* [1994], and includes the first measurements of fine-scale filamentary structure within coronal streamers [*Woo et al.*, 1995a] and evidence in the inner corona for structure in solar wind speed [*Woo*, 1995].

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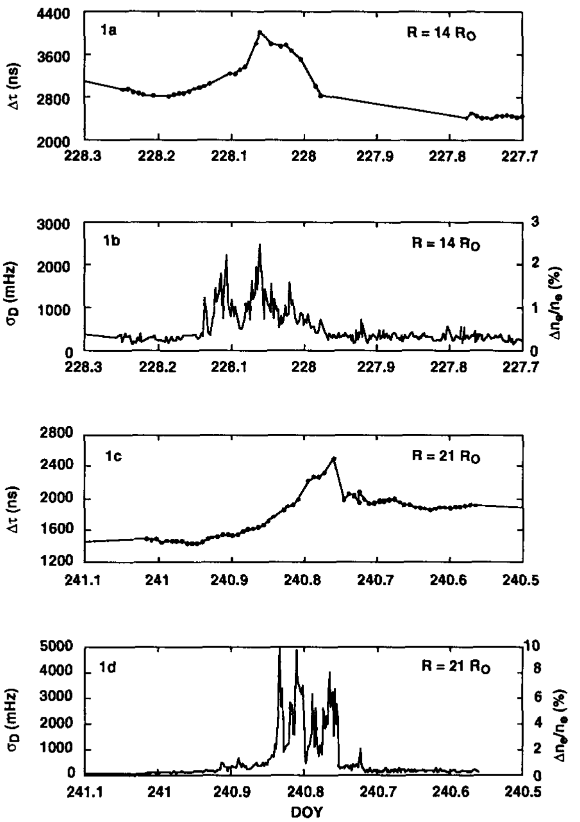

Fig. 1. Profiles of $\Delta\tau$ ($\sim n$) and σ_D ($\sim \Delta n$) of coronal streamer near Carrington longitude 350° vs day of year DOY

2. Coronal Streamers

Ranging or time delay $\Delta\tau$ observes path integrated electron density n

$$\Delta\tau \sim \int n \, ds \tag{1}$$

and Doppler frequency f_D the time derivative of path integrated density

$$f_D \sim \frac{d}{dt} \int n \, ds \tag{2}$$

where s is distance along the ray path. Doppler scintillation σ_D is the rms of Doppler frequency fluctuations estimated for some time scale. For a spherically symmetric solar wind, ranging essentially probes density n [*Bird et al.*, 1994], and Doppler scintillation density fluctuations Δn [*Woo*, 1978] near the closest approach of the radio path.

Shown in Fig. 1 are S-band time delay and Doppler scintillation measurements of a coronal streamer observed by Ulysses near Carrington longitude 350°, first on the east limb on day of year DOY 228 and then a half a solar rotation later on DOY 240 when the Ulysses radio path had crossed over to the west limb [*Woo et al.*, 1995b]. Time delay $\Delta\tau$ is sampled once every 10-min [*Bird et al.*, 1994], while the 3-min Doppler scintillation measurement σ_D is based on 10-sec Doppler data [*Woo et al.*, 1985]. The time axes are shown in reverse to coincide with solar synoptic maps, for which increasing Carrington longitude usually runs from left to right, and the period covers 0.6 day or 14.4 hrs. Fractional density fluctuation Δn/n is estimated once every 3 mins.

The results in Fig. 1 illustrate that while enhancements in density n ($\Delta\tau$), density fluctuation Δn (σ_D) and relative fluctuations $\Delta n/n$ are the manifestation of the streamer or heliospheric current sheet crossing, those of Δn and $\Delta n/n$ are strikingly higher than that of the mean or large-scale density [*Woo et al.*, 1994, 1995b]. The region of enhanced density fluctuations represents a flow tube (or edge-on view of a sheet) of angular extent 1.8° in heliographic longitude, and appears to correspond to the stalks of coronal streamers of similar size and observed in eclipse pictures processed to reveal spatial gradients [*Koutchmy and Livshits*, 1992]. As evident from eqn. (2), Doppler scintillation measures the spatial gradient of the corotating quasi-stationary structure.

The density fluctuations within the stalk of the coronal streamer represent filamentary structure, which is demonstrated by the similarity in scintillation time series during successive solar rotations as highlighted by the alternating shaded regions in Figs. 2b and 2c. Clustering of filamentary structure within this flow tube is evident, as there appears to be as many as three smaller flow tubes that are not only long-lived but extend from 14 to 77 R_o. The 3-min sampling rate of the Doppler scintillation data indicates that the filamentary structure extends to sizes as small as 340 km at the Sun (0.5 arcsec). Although not as small, fine-scale structure has been observed in images of the corona [*Koutchmy et al.*, 1994; *Habbal*, 1992; *Fisher and Guhathakurta*, 1995; *Guhathakurta and Fisher*, 1995]. The flow tube's angular size as measured by the duration of the enhanced scintillation changes little over this heliocentric distance range, indicating approximate radial expansion. When extrapolated back to the Sun, the size of the largest flow tube is 2×10^4 km (30 arcsec) and that of the smaller ones is 7300 km (10 arcsec). The three inner tubes suggest three current sheets that are associated with twin- or three-arch helmet streamers [*Crooker et al.*, 1993].

The evolution of the coronal streamer at Carrington longitude 350° with heliocentric distance beyond 77 R_o can be seen in the X-band measurements shown in Figs. 2a and 2e. Multiplication of the X-band measurements σ_D by the factor $(3/11)\times\sqrt{2}$ converts them to an approximate correspondence

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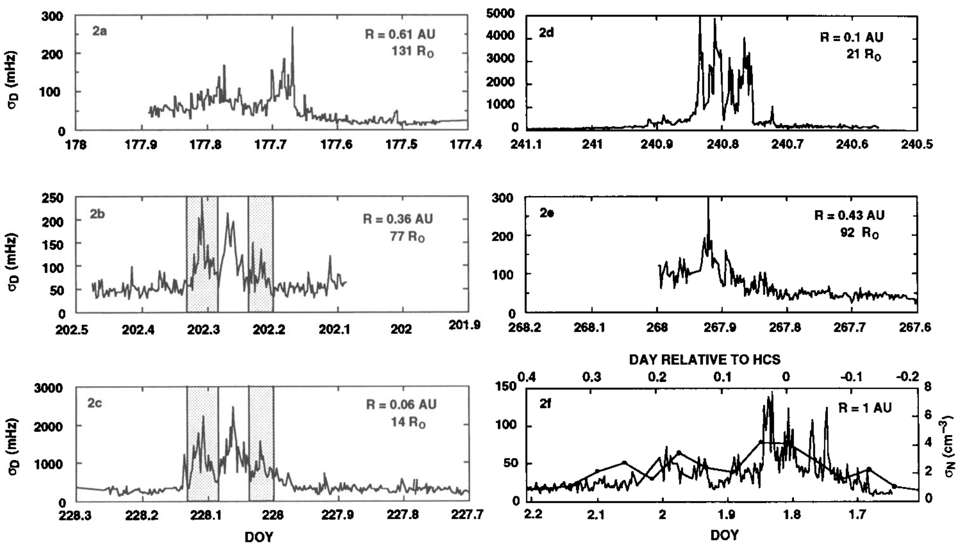

Fig. 2. Same as Fig. 1 except additional successive solar rotations. 2f is of coronal streamer at Carrington longitude 190°. For the sake of comparison, all plots cover 0.6 day. Except for 2b and 2c, no effort has been made to align the streamer enhancements. 2a-2c are east limb and 2d-2e are west limb observations. 2a 2e is in 1991 while 2f in 1992. Superimposed curve in 2f represents Δn results from superposed epoch analysis of HCS crossing by *Huddleston et al.* [1995] relative to HCS crossing indicated at top of plot.

with the S-band measurements of Figs. 2b-2d. Although the time series in Figs. 2a and 2e do not cover the full duration of streamer passage, they nevertheless hint at erosion and expansion of the enhanced region of density fluctuations with increasing heliocentric distance. A more complete and representative X-band profile near Earth orbit is that of another streamer near Carrington longitude 190° displayed in Fig. 2f, showing that the region of enhanced density fluctuations has grown to an angular width of about 8° near 1 AU. Insight into the evolution of the Doppler scintillation streamer signature is provided by results from a superposed epoch analysis of heliospheric current sheet (HCS) crossings at 1 AU based on 1-hr averages of 5-min field and particle measurements by ISEE-3 *Huddleston et al.* [1995]. The ISEE-3 Δn results are superimposed on the scintillation measurements in Fig. 2f, showing a remarkable consistency between the two. This shows that, as the fast wind runs into the slow wind, dynamic compression causes broadening of the region of density fluctuations, particularly to the east of the HCS. Thus, density fluctuation enhancements associated with corotating interaction regions formed farther from the Sun are often difficult to

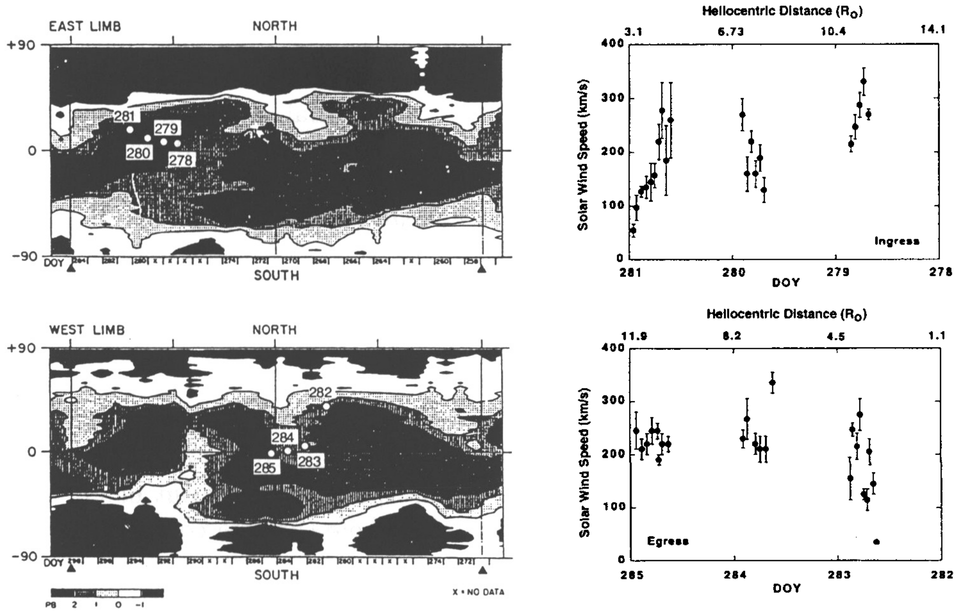

Fig. 3. Plots on the left are the HAO Mauna Loa Solar Observatory Mk III K-coronameter synoptic contour maps of polarized brightness pB at a height of 1.7 R_o. Plots on the right are VLA wind speeds.

distinguish from coronal streamers [*Ananthakrishnan et al.*, 1980; *Houminer and Gallagher*, 1993].

3. Solar Wind Speed Structure

The prevalence and organization of electron density structure by the large-scale coronal magnetic field - revealed not only by radio propagation but also white-light measurements - has led to an investigation of structure in solar wind speed [*Woo*, 1995] based on multiple-station intensity scintillation measurements conducted at the VLA in 1983 with 3C279 in the heliocentric distance range of 3-12 R_o [*Armstrong et al.*, 1986].

Shown on the left of Fig. 3 are two Mk III K-coronameter synoptic contour maps of polarized brightness pB at a height of 1.7 R_o [*Fisher et al.*, 1985] for CR 1740 constructed from data off the east (upper plot) and west (lower plot) limb. Superimposed on these synoptic maps as white circles are the closest approach points of the 3C279 radio path that have been mapped back to the surface of the Sun; the points are labelled by the corresponding DOY at 0000 UT. The time axes of the VLA measurements are reversed to facilitate comparison with the white-light synoptic maps showing Carrington longitude running positive from right to left. Although VLA measurements were made on only six days – three during ingress and three during egress – fortuitously, the ingress observations off the east limb took place over the high-density streamer belt, while the egress observations took place over the west limb which included a low-density equatorial coronal hole region.

The flow speed measurements in Fig. 3 show dramatic differences between the nature of the solar wind over the streamer belt (DOY 278-280 and 282) and the equatorial coronal hole (DOY 283-284) inside 12 R_o. Over the equatorial hole, the flow speed is relatively steady and high, with peak-to-peak variations of 50 km/s and average speed of 230 km/s. The nature of the polar fast wind observed by Ulysses beyond 2 AU is similar [*Phillips et al.*, 1994], and is not surprising since the distant Ulysses fast wind undergoes less evolution due to interaction with low-speed wind by virtue of its high latitude. The relative steadiness of the wind, as characterized by velocity fluctuations divided by the mean, is also similar; Ulysses observed peak-to-peak variations of 200 km/s in its 1-hr speed averages out of an average of 750 km/s over the south polar coronal hole (private communication M. Neugebauer).

Over the streamer belt, the flow speed is not as uniformly slow as that observed beyond 0.3 AU by intensity scintillation [*Kojima and Kakinuma*, 1987; *Rickett and Coles*, 1991] and in situ plasma measurements [*Gosling et al.*, 1981; *Schwenn*, 1990], but instead exhibits regular large-scale variations in the range of 100-300 km/s, with gradients of alternating sign but similar magnitude. Hints of evolution with heliocentric distance are also apparent when synoptic maps of solar wind speed based on scintillation measurements within and beyond 0.3 AU are compared [*Kojima et al.*, 1992]. While there are gaps in the data, the flow speed variations over the streamer belt are systematic enough that at least two minima can be inferred within a longitudinal range of 40°. These minima, which represent the source regions of the slow solar wind, most likely coincide with the stalks of coronal streamers observed in white-light pictures, manifested as enhancements in Doppler scintillation, and discussed in the previous section. Speed rises with increasing distance from these minima in such a manner that the solar wind speed is at least as fast as that observed over the equatorial hole. The gradient, determined from linear fits to the four days of streamer belt measurements, is 36 km/s per degree in heliocentric coordinates, with a standard deviation of 2.4 km/s per degree. The presence of substantial wind shears over the streamer belt and near the Sun is consistent with *in situ* and scintillation measurements showing that the density spectrum has a power law form characteristic of fully developed turbulence over a much broader range of scales than in neighboring regions [*Marsch and Tu*, 1990; *Woo et al.*, 1994]. *Roberts et al.* [1991, 1992] were the first to show through simulations that shear, within as well as between streams, could lead to spectra similar to those observed via an incompressive turbulent cascade.

4. Concluding Remarks

The electron density irregularities investigated by Doppler (or phase) scintillation measurements near the Sun over the past two decades have been generally thought of as turbulent in nature. That they represent the filamentary structure of coronal streamers is somewhat surprising. This new perspective, however, elucidates the parallels between Doppler scintillation measurements and eclipse pictures that have been processed to enhance spatial gradients, reinforces the observations of ray-like structures in the enhanced eclipse pictures, explains the abrupt variations in Doppler scintillation that coincide with the stalks of coronal streamers, and improves our understanding of in situ plasma measurements of the heliospheric current sheet at 1 AU. More important, Doppler scintillation measurements offer the higher spatial resolution that has so far eluded coronal imaging [*Koutchmy et al.*, 1994]. This improved resolution has revealed that the stalks of coronal streamers, which are most likely the sources of the slow solar wind, are permeated by fine-scale filamentary structure. Although high spatial resolution is a consequence of the high time resolution, it is the high sensitivity and wide dynamic range of the Doppler measurements that have made it possible to observe the fine-scale structure within the streamer stalk. These are the same features that have enabled Doppler scintillation measurements to observe the solar wind and its variations over a heliocentric distance range that spans from the vicinity of the Sun to near Earth orbit [*Woo*, 1978].

Small-scale coronal structure has received much attention lately [see e.g., *Habbal*, 1992]. The Ulysses Doppler scintillation measurements show that small-scale structure for scale sizes in the range of 20-340 km amounts to only a few percent of the large-scale density, even within the stalk of the streamer, where it is largest. Still, the importance and need for high spatial resolution measurements is poignantly demonstrated by the fact that the range of variation of small-scale structure is far greater than that of the large-scale density. Thus, within the stalk of the streamer, the structure associated with closed magnetic fields is an order of magnitude larger than that outside the stalk associated with open fields.

The structure in solar wind speed reinforces the value of carefully conducted multiple-station intensity scintillation such as the 1983 VLA measurements. Coordinated measurements of Doppler scintillation, multiple-station intensity scintillation, and white-light coronagraph measurements should be particularly useful in providing more details on the structure of coronal streamers and its relationship to the source of the slow solar wind.

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