VLBI OBSERVATIONS OF TURBULENCE IN THE INNER SOLAR WIND

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Abstract. I discuss the use of Very Long Baseline Interferometer (VLBI) phase scintillations to probe the conditions of plasma turbulence in the solar wind. Specific results from 5.0 and 8.4 GHz observations with the Very Long Baseline Array (VLBA) are shown. There are several advantages of phase scintillation measurements. They are sensitive to fluctuations on scales of hundreds to thousands of kilometers, much larger than those probed by IPS intensity scintillations. In addition, with the frequency versatility of the VLBA one can measure turbulence from the outer corona $\sim 5-10\ R_{\odot}$ to well past the perihelion approach of the Helios spacecraft. This permits tests of the consistency of radio propagation and direct in-situ measurements of turbulence. Such a comparison is made in the present paper. Special attention is dedicated to measuring the dependence of the normalization coefficient of the density power spectrum, C_N^2 on distance from the sun. Our results are consistent with the contention published several years ago by Aaron Roberts, that there is insufficient turbulence close to the sun to account for the heating and acceleration of the solar wind. In addition, an accurate determination of the $C_N^2(R)$ relationship could aid the detection of transients in the solar wind.

1. Introduction

This paper will deal with the information provided by radioastronomical Very Long Baseline Interferometry for studies of the Solar Wind. I wish to particularly emphasize the potential of the recently completed Very Long Baseline Array (VLBA) of the National Radio Astronomy Observatory (NRAO*) for such observations. A fuller description of the material I will be presenting here is to be found in Spangler and Sakurai (1995).

There are a number of reasons for interest in solar wind turbulence. A primary one is the suggestion that such turbulence, through damping or wave pressure effects, can accelerate the solar wind. Unfortunately, a direct experimental test of this suggestion is not possible because the important physical processes are occurring in a part of space where no direct observations are available. This may be demonstrated by reference to representative solar wind models (Coles *et al.* 1991). Shown in Figure 4 of that paper are theoretical models of the solar wind speed as a function of heliocentric distance for a coronal hole, slow speed solar wind (but with wave driving) and a purely thermal solar wind without the agency of wave acceleration. This

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figure shows that by the distance of closest approach of the Helios spacecraft at about 60 $R_\odot$, the solar wind has reached its asymptotic speed. Clearly, the region of solar wind acceleration, which corresponds to the most interesting wave and turbulence dynamics, lies in a region of space for which we have no direct measurements. However, we can easily observe radio sources whose lines of sight traverse this part of space, and deduce properties of the turbulence from these observations. Such an undertaking is the basis of the generic field of interplanetary scintillations, which is reviewed by Coles (1978) and Bourgois (1993).

The physical basis of radio wave scintillations has been discussed amply in many previous papers, but a few comments are in order here for the sake of continuity. The refractive index for radio waves propagating in a plasma is directly proportional to the plasma density. Wave and turbulence induced density fluctuations thus cause spatial and temporal fluctuations in the radio refractive index, and a wave propagating through such a medium will experience phase and amplitude fluctuations. The phase change $\delta\phi$ experienced by a wave propagating through such a medium (relative to a wave propagating through a uniform, nonturbulent medium) is given by

$$\delta\phi = r_e \lambda \int_0^L \delta n_e ds \qquad (1)$$

where L is the path length through the medium, δn_e is the density fluctuation, r_e is the classical electron radius, and λ is the wavelength of observation. Obviously the expectation value $\langle(\delta\phi)\rangle = 0$ but $\langle(\delta\phi)^2\rangle \neq 0$. These phase and corresponding amplitude variations produce the phenomenon of radio wave scintillations.

2. Interferometer Phase Scintillations

Radio interferometers are excellent devices for measuring turbulence because they more or less directly measure the turbulence induced phase shifts. The radio frequency signals from two antennas are brought together and correlated. The correlation coefficient is a complex number with phase and amplitude. The phase is proportional to the electrical path difference between the two antennas. If a plasma density irregularity moves across the line of sight to one of the antennas, there will be a change in the electrical path length, and thus a phase change will be observed. More generally, and in the case of interest here, if both antennas are observing through turbulence, the interferometer phase will be a randomly varying quantity.

An illustration of this phenomenon is shown in Figure 1 (Spangler and Sakurai 1995). The panel at left shows phase measurements of a source far from the sun, when the VLBA phase measurements were affected only by

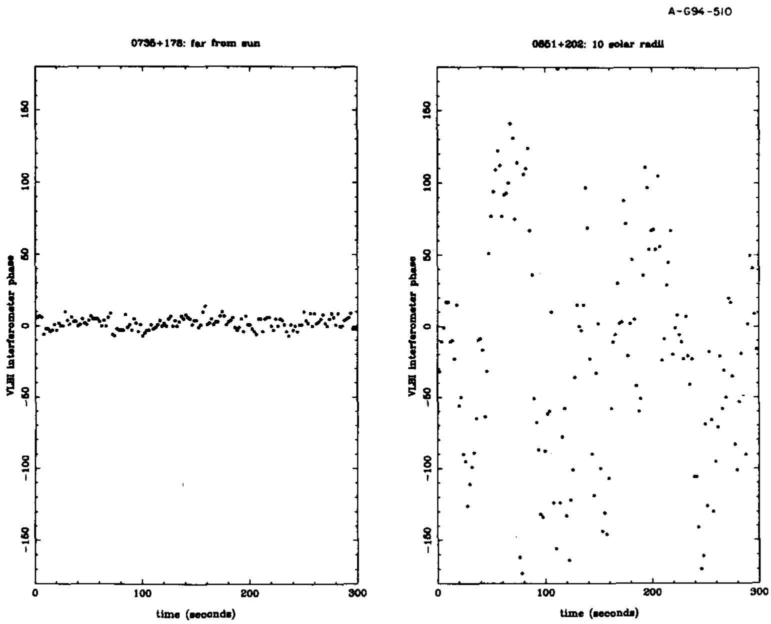

Fig. 1. Interferometer phase on the Fort Davis - Los Alamos baseline of the VLBA, at a frequency of 5 GHz. The left panel shows interferometer phase measurements of a source far from the sun, where only radiometer noise and tropospheric variations cause phase variations. The observations in the right hand panel are from the source 0851+202 when its line of sight passed 10 $R_{\odot}$ from the sun. The large phase fluctuations are caused by coronal turbulence (from Spangler and Sakurai (1995).

radiometer noise and tropospheric effects. The panel at right shows measurements on the same baseline and frequency, but of a source viewed through the corona at a solar elongation of 10 $R_{\odot}$. Large fluctuations are observed due to plasma turbulence in the corona and solar wind. From such a time series, we can make measurements such as the phase variance and phase power spectrum.

The VLBA has a number of advantages for this type of work. The ten antennas provide a large range of baseline length and orientation. Since phase fluctuations on a given baseline are primarily determined by irregularities with a size equal to the baseline, a wide range of baseline lengths and orientations allow a more complete determination of the spatial spectrum of the density irregularities. The frequency versatility of the VLBA is also very important. The magnitude of scintillation observables are strongly dependent on the observing wavelength; in the case of phase scintillations the phase variance is proportional to the square of the observing wavelength.

The ability to rapidly switch observing wavelength allows one to reliably distinguish scintillations from other types of phase variations. In addition, one can optimize the observing wavelength for the source being observed.

Given a measurement of the variance or some other statistical property of the phase variations, how does one infer the statistical properties of the density fluctuations? The observable quantity of interest here is the *phase structure function*, defined as the mean square phase difference between two points separated by s (in general a vector),

$$D_\phi(s) = \langle (\phi(x) - \phi(x+s))^2 \rangle \tag{2}$$

where x is an arbitrary reference position. The phase structure function is readily related to the conventional interferometric visibility as

$$V(s) = e^{-\frac{1}{2}D_\phi(s)} \,. \tag{3}$$

Equation (3) accounts for the common scintillation phenomenon of angular broadening or blurring of an object viewed through a turbulent medium.

The structure function is determined by the statistical properties of the density turbulence, most simply expressible through the spatial power spectrum. Following usual practice, one can adopt a power law model for this spectrum,

$$P_{\delta n} = C_N^2 q^{-\alpha} \tag{4}$$

characterized by a turbulent intensity C_N^2 and a spectral index α. The spatial wavenumber is given by q. The theory of wave propagation in a random medium gives the following expression for the phase structure function (Sakurai *et al.* 1992)

$$D_\phi(s) = 4\pi^2 r_e^2 \lambda^2 f(\alpha) s^{\alpha-2} \int_0^L C_N^2 ds \tag{5}$$

where $f(\alpha)$ is a dimensionless function of α, with value of order unity, and ds is an incremental path along the line of sight.

Equation (4) shows that measurement of the phase structure function D_ϕ, either via direct calculation from the phase time series or via measurements of angular broadening, allow one to measure both the spectrum of the turbulence (α via the baseline scaling) and its intensity (through the path integral of C_N^2).

3. Recent VLBI Phase Scintillation Observations

In this section, I will discuss some recent results from measurements of phase scintillations, mainly from observations made in 1991 using the VLBA

(Spangler and Sakurai 1995), but also including observations made two years previously with the VLBI network (Sakurai, Spangler, and Armstrong 1995; Sakurai 1993). The VLBA observations were at wavelengths of 3.6 and 6 cm. Observations of two sources, 0735+178 and 0851+202, were made on three days in July and August 1991. The solar elongations of closest approach, or "impact parameters" ranged from 10 to 50 $R_\odot$. These observations were complemented by two observations from Sakurai (1993) made at a wavelength of 6 cm of sources with impact parameters of 18 and 35 $R_\odot$. Thus a total of six lines of sight were probed.

There has been a great deal of prior investigation of the radio scattering properties of the corona and interplanetary medium, extending back to the pioneering work of Professor Hewish (Hewish 1955). Most of these prior observations constrained variations on different spatial scales than those probed by VLBI, or in the case of spectral broadening of spacecraft signals, involved dependence on the solar wind speed (Woo and Armstrong 1982). This large amount of information was organized and significantly expanded in the work by Coles and Harmon (1989), and I will refer below to the Coles and Harmon model as a description of the scattering properties of the interplanetary medium as a function of solar elongation and scale size of the irregularities. A typical observation is shown in Figure 2, taken from Sakurai (1993). The Coles and Harmon model for the level and spectral properties of the scattering is seen to be in quite good agreement with the observations, and suggests that it is a good fiducial model for estimating the strength of scattering, at least in the ecliptic plane and for the "nominal" solar wind. The results of Figure 2 and similar plots in Spangler and Sakurai (1995) indicate that the Coles Harmon model can be used to indicate if anomalous scattering due to solar wind transients such as coronal mass ejections can be detected.

Data such as those shown in Figure 2 may be used, with the intercession of equation (5), to deduce characteristics of turbulence in the solar wind. First, the baseline dependences of D_ϕ are in entirely satisfactory agreement with a Kolmogorov spectrum with $\alpha = 11/3$. We can therefore conclude, consistent with previous investigations, that the density power spectrum in the interplanetary medium on spatial scales of 200–2000 kilometers is Kolmogorov, with perhaps an indication of enhancement of spectral power on the shortest spatial scales.

Second, we can use the level of the phase scintillations to deduce the path integral of C_N^2; if we assume azimuthal symmetry and recognize that the dominant contribution to the integral comes from the point closest to the sun, we can determine the function $C_N^2(R)$. The results of these calculations are shown in Figure 3.

The VLBI measurements are presented as filled or open circles. The triangular symbols are discussed further below. The VLBI data show a progressive

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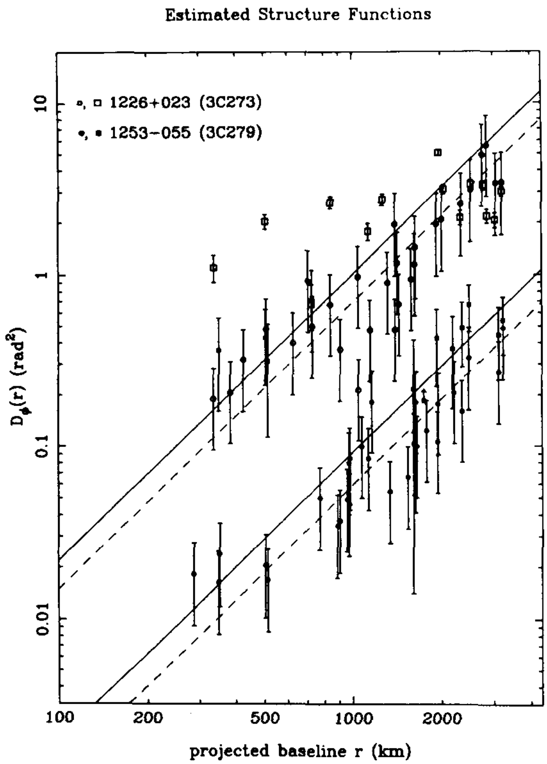

Fig. 2. Observed 5 GHz structure functions from Sakurai (1993). The observations are for 3C273, which was observed at a solar elongation of 18 $R_\odot$, and 3C279, which was observed at an impact parameter of 35 $R_\odot$. Structure function measurements from the phase time series are shown as circles, open for 3C273 and closed for 3C279. Structure function estimates from visibility measurements are indicated as squares, open for 3C273, and solid for 3C279. Least squares fit relationships are given by the dashed lines, and solid lines represent the *a priori* Coles and Harmon relationship. The data are seen to be in good agreement with this relationship.

increase in C_N^2 as the line of sight passes closer to the sun. A point to note from this figure is that VLBI measurements can detect phase scintillations even when the distance of closest approach of the line of sight is 50 to 60 $R_\odot$. This is the case even for the present observations, which were made at 6 and 3.6 cm. Observations at a longer wavelength, 18 or even 50 cm, would give a much larger signal and be detectable at much larger elongations.

These distances are comparable to the perihelion approach of the Helios spacecraft, and it is instructive to compare the measurements obtainable via the two techniques, radio wave propagation, and direct in situ measurements.

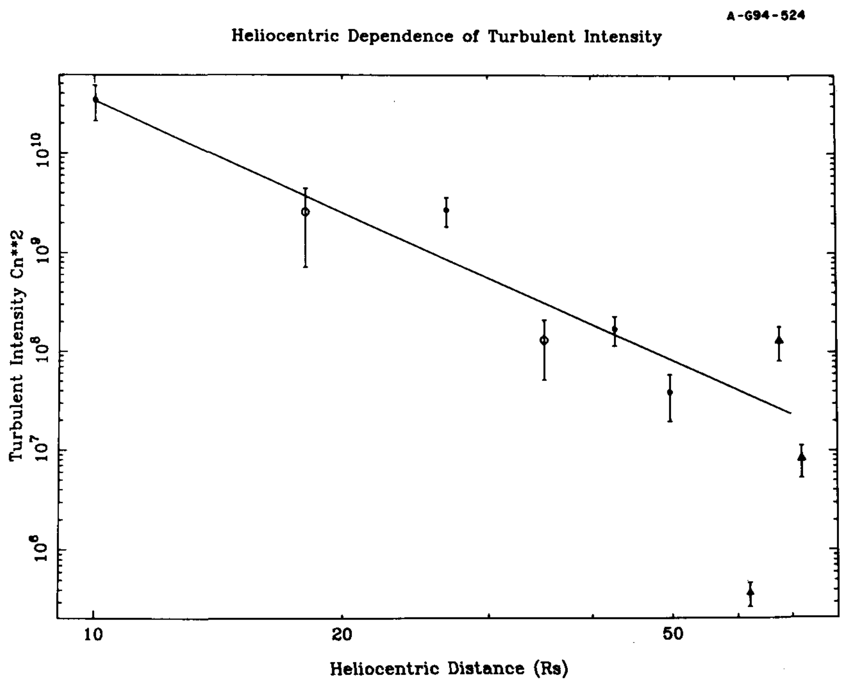

Fig. 3. Inferred values of the density spatial power spectrum normalization factor C_N^2 as a function of heliocentric distance. Circles represent VLBI remote sensing measurements. Triangles represent in situ measurements with the Helios spacecraft. From Spangler and Sakurai (1995).

Measurements of plasma density fluctuations by the Helios spacecraft were analyzed by Marsch and Tu (1990), who calculated temporal power spectra of the density times series, but provided enough information to convert their temporal power spectrum to spatial power spectra, as we measure. Details of this conversion process are given in Spangler and Sakurai (1995).

An important result of the Marsch and Tu analysis was a pronounced difference in the amplitude and spectra of density fluctuations depending on whether the spacecraft was immersed in slow speed solar wind or a high speed stream. In the slow speed solar wind, the mean density is high, and the density power spectra are Kolmogorov. In high speed streams, the mean density is lower, and the spectrum is composite. At low frequencies (temporal, as presented by Marsch and Tu (1990), but presumably spatial as well) the spectra are also Kolmogorov. At higher frequencies, Marsch and Tu (1990) report a flattening of the spectrum just short of the Nyquist frequency. In obtaining a value of C_N^2 to compare with our radio propagation measurements, we used only the Kolmogorov portion of the spectrum in both the high and low speed solar wind. The Helios measurements of Marsch and Tu (1990) are indicated in Figure 3 by the triangles. The two higher symbols show C_N^2 values from the slow speed wind. The lower of the three triangles represents a high speed wind value. The reason for this pronounced difference may be simply explained. The modulation indices of the density are similar in the high speed and low speed wind. The spectra of Marsch and Tu (1990) may, in fact, show somewhat larger fractional fluctuations in the slow speed wind. However, the mean density in the slow speed wind is much larger, so the absolute magnitude of the density fluctuations is much larger in slow speed than high speed wind.

Returning to Figure 3, we conclude that the IPS and in-situ measurements are in agreement, providing the reference medium for the in situ measurements is the slow speed solar wind. Said differently, it would appear that regions of slow speed solar wind flow, originating from closed magnetic field regions, must provide the bulk of the turbulent plasma responsible for IPS. The data in Figure 3 (excluding the in situ measurement in high speed solar wind) may be parameterized in terms of a least squares fit of the form

$$C_N^2(R) = C_{N0}^2(R/R_0)^{-\beta} \ . \tag{6}$$

We find that $\beta = 3.72 \pm 0.30$.

4. The Evolution of Turbulence in the Solar Wind

The measured heliocentric distance dependence of C_N^2 permits me to return to one of the questions posed at the beginning of this paper, which was an experimental determination of whether there is enough turbulence close to the sun to accelerate the solar wind.

A previous investigation of this point was made by Roberts (1989). The basis of Roberts' investigation was a WKB theory for the amplitude of MHD waves as they propagate out through the inhomogeneous medium of the solar wind.

In what follows, I briefly summarize the physical content of this evolution. A fuller discussion, including the relevant equations, is presented in Spangler and Sakurai (1995). The wave intensity, normalized by the intensity at a reference point, is determined by the plasma density, the Alfvén speed, and the solar wind flow speed at that location. If one adopts a simple solar wind model, so that the various quantities depend parametrically on the ratio of the plasma density to its value at a reference point, one can obtain a predicted dependence of the wave intensity on the plasma density.

The main point of Roberts' investigation was to show that observed magnetic field fluctuations in the heliocentric distance range 0.3 to 1.0 astronomical units obeyed this relation. He then argued that it was justifiable to extrapolate these fluxes to the sun using this WKB formula, in which case there was insufficient wave flux close to the sun to accelerate the solar wind.

I now consider what the phase scintillations measurements reported above contribute to this discussion. The most desirable goal would be for scintillations to confirm that the heliocentric distance dependence of the scaling advocated by Roberts is indeed adhered to throughout the heliocentric distance range $60R_\odot$ into 5–$10R_\odot$. In particular, we would like an observational guarantee that Roberts' analysis did not miss some highly compressive (and therefore highly dissipative) type of wave mode close to the sun which is responsible for solar wind heating and acceleration, but is dissipated by the perihelion of Helios.

Such an analysis is weakened by the obvious difficulty that Roberts dealt with measurements of wave or turbulent magnetic field, where most of the energy density is, whereas our measurements deal with the plasma density, which is a passive tracer of the turbulence, and presumably responds to fluctuations in the magnetic and kinetic energy density. To compare the result of Roberts with that of Figure 3, one must assume a $\delta n - \delta B$ relationship. I have assumed that $(\delta n)^2 \propto (\delta B)^2$ at all points. This is valid for some, though not all theoretical density compression mechanisms. A relationship of this sort has been observed by Klein *et al.* (1994) to hold in the slow speed solar wind, although not in the high speed wind. With this assumption, C_N^2 is proportional to the analogous normalization constant for the magnetic fluctuations, C_B^2, and so C_N^2 would obey the same WKB expression for dependence on heliocentric distance.

If instead the density compressions arise through ponderomotive density fluctuations in which $\delta n \propto (\delta B)^2$, the density fluctuations would show a steeper dependence on heliocentric distance than the magnetic field fluctuations.

At the time of our VLBI observations, Bird *et al.* (1994) observed coronal occultations of the Ulysses spacecraft transmitter and determined the radial dependence of the solar wind electron density. With the functional dependence found by them, we would *predict* that the heliocentric distance dependence of C_N^2 should be $\propto R^{-3.75}$. This is obviously in excellent agreement with the measured dependence, and therefore supports the conclusion of Roberts (1989).

Before leaving this section, it is necessary to append a caveat to this conclusion. As noted above, our scintillations measurements are primarily sensitive to density fluctuations in the slow speed solar wind. The flow speeds in these regions are of order to 300 to 400 km/sec, not greatly in excess of

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the flow speeds obtainable by purely thermal models of the corona and solar wind. Wave driven models of the solar wind were developed to explain the flow speeds of 700 to 800 km/sec which characterize high speed streams. Perversely, our measurements are not sensitive to fluctuations in these regions. A minimalist could then contend that our measurements show the absence of waves where they were not required, while the true wave-enhanced regions lay beyond our prospect.

5. Conclusions

I have shown that radio propagation measurements (specifically VLBI phase scintillations) yield estimates for the characteristics of solar wind density fluctuations which are in agreement with spacecraft measurements, provided that the comparison is made with regions of slow solar wind. Alternatively, it seems that plasma in slow solar wind dominates the scintillation observables.

Subject to several qualifications, the scintillation data are consistent with WKB scaling of turbulent intensity with heliocentric distance in the range 10–70$R_\odot$. There is no indication of an enhancement of scattering close to the sun as might be expected for a new genus of highly compressive turbulence. This result tends to corroborate the finding of Roberts (1989) that there is insufficient wave flux close to the sun to drive the solar wind.

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