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 \textit{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

$$\delta \phi = r_e \lambda \int_0^L \delta n_e ds$$

where $L$ is the path length through the medium, $\delta n_e$ is the density fluctuation, $r_e$ is the classical electron radius, and $\lambda$ 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