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ANISOTROPIC STRUCTURE OF THE SOLAR WIND IN ITS REGION OF ACCELERATION

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ABSTRACT

Radio remote-sensing techniques have shown that the spectrum of irregularities of both the electron density and magnetic field are spatially anisotropic. New experimental data on the electron density irregularities have been obtained from simultaneous recordings of spacecraft signals at several widely-spaced ground stations. A cross-correlation analysis using phase and/or frequency fluctuations yields the outward flow speed of the irregularities. In contrast to earlier amplitude fluctuation measurements, correlation time lags across an intercontinental baseline may reach several tens of seconds. Temporal spectra of the amplitude fluctuations, on the other hand, are sensitive to both the velocity of the irregularities and the anisotropy coefficient. This technique was applied to experimental data recorded during the solar occultations of the Venera spacecraft. Typical values of the anisotropy coefficient are determined to be less than 2 at solar distances outside 15 $R_\odot$ and greater than 2 inside this distance. It is suggested that the radial dependence of the anisotropy is governed primarily by the coronal magnetic field strength.

INTRODUCTION

On the basis of angular broadening observations of radio sources with multiple antennas at the Very Large Array (VLA), Armstrong *et al.* (1990) suggested that the density structure of the solar wind near the Sun was anisotropic. Furthermore, the anisotropy coefficient (axial ratio of the density fluctuation spatial scales) appeared to depend strongly on the scale of the irregularities. The density microstructure at scales smaller than about 35 km was radially-aligned and became increasingly anisotropic at smaller solar distances. Follow-up observations implied that the small-scale anisotropy changed quite abruptly at about 6 $R_\odot$ (Grall *et al.*, 1997). Typical values of the anisotropy coefficient ξ for heliocentric distances greater than 6 $R_\odot$ varied over the range $1.5 < \xi < 4$. At distances less than 6 $R_\odot$ this quantity reached values $\xi > 10$. Only a slight increase in anisotropy toward smaller solar distance ($\xi = 1.4$ at the minimum offset $R = 8$ $R_\odot$) was detected during the more recent observations of Yamauchi *et al.* (1998). Grall *et al.* (1997), conducting simultaneous VLA measurements to investigate smaller scales (< 30 km) and Very Long Baseline Array (VLBA) measurements for larger scales (200–3000 km), concluded that the anisotropy is basically confined to the smaller scales.

Other experimental data obtained with spacecraft signals during solar conjunction may provide further insight into this problem. A review of the various radio sounding techniques available for investigating the spatial spectrum of the coronal plasma fluctuations has been published by Bird and Edenhofer (1990).

We report here simultaneous observations of amplitude and frequency fluctuations at two widely-spaced ground stations. An analysis of earlier data (Efimov *et al.*, 1990) revealed a surprising minimum for the velocities derived from the amplitude fluctuations at heliocentric distances near 10–15 $R_{\odot}$. This feature can be explained by magnetosonic waves propagating toward the Sun, which contribute more strongly to the scintillations than the outward propagating waves. The measured speed of the diffraction pattern at Earth-based receiving stations is thus the difference of the solar wind velocity and the speed of the magnetosonic waves. The apparent velocity of the diffraction pattern will thus have a minimum in the region near 10–15 $R_{\odot}$, where these velocities are nearly the same.

THEORY

Temporal spectra of the amplitude fluctuations usually have a specific form: approximately flat at low frequencies and power law at high frequencies. The intersection of the low- and high-frequency asymptotes occurs at the so-called break frequency ν_0, which depends on the following quantities:

r_F = radius of the Fresnel zone
v = velocity of the irregularities
v_w = speed of magnetosonic waves
ξ = anisotropy coefficient (axial ratio of irregularities)

Generally speaking, we can represent the dependence of the break frequency ν_0 on these quantities as

$$\nu_0 = \frac{g_1(p) \cdot v_{app}}{r_F} \tag{1}$$

$$v_{app} \pm u = g_2(\xi) \cdot (v_{eff} \pm u) \tag{2}$$

with u the radial velocity of the radio ray path with respect to the Sun ($\pm$ for egress and ingress, respectively). The coefficient $g_1(p)$ depends on the spectral index p of the spatial spectrum of the irregularities (Efimov *et al.*, 1990), $g_2(\xi)$ is a function of the anisotropy coefficient, and v_{eff} is a superposition of the two velocities v and v_w. To a first approximation, $g_2 = 1$ if the irregularities are isotropic and $g_2 = \xi^{-1}$ if the irregularities are elongated radially along the coronal magnetic field. As a result, the temporal spectra of the amplitude fluctuations can be used to infer an effective velocity of the motion of the diffraction pattern to within a factor $g_2(\xi)$ which depends on the mean weighted elongation of the irregularities.

On the other hand, when we have simultaneous observations of frequency fluctuations at two widely-spaced ground stations, it is also possible to determine the real effective velocity of the irregularities

$$v_{eff} = \frac{\Delta R}{\tau_{max}} \tag{3}$$

where ΔR is the projection of the coronal separation of the ray paths onto the radial direction and τ_{max} is the time lag of maximum correlation. Typical values of τ_{max} are a few seconds to tens of seconds for the large spatial separations of the ground stations ($\Delta R > 2500$ km). Frequency fluctuations, in contrast to signal level fluctuations, are correlated at ray path separations greater than the Fresnel zone size. A more accurate estimate for v_{eff} results from the smaller relative error in the determination of τ_{max}.

Combining (1)–(3) and knowing the form of $g_1(p)$ from the spectral index of the amplitude spectrum, one may derive the function $g_2(\xi)$, which is essentially the reciprocal of the anisotropy coefficient (axial ratio).

OBSERVATION AND DATA ANALYSIS

Simultaneous observations of signal amplitude and frequency fluctuations were made during the solar occultations of the Venera-15 and Venera-16 spacecraft in 1984 May-June. The observing frequencies were selected such that the amplitude fluctuations were in the weak scintillation regime. In order to maintain this requirement, the sounding frequency used for analysis was increased with decreasing solar offset distance.

Three frequencies were available on the Venera spacecraft. L-band (λ_1 = 32 cm) was used at large solar distances, and C1/C2 bands (λ_2/λ_3 = 8 cm/5 cm) were employed closer to the Sun.

Figure 1 (left panels) shows examples of the temporal spectra of amplitude fluctuations obtained during a coronal sounding session on 3 June 1984 (solar offset: $R = 13.2\ R_\odot$) at the wavelengths 8 cm (panel a) and 5 cm (panel b). The scintillation index for the spectrum of Fig. 1 (left panel a), i.e., the ratio of the signal

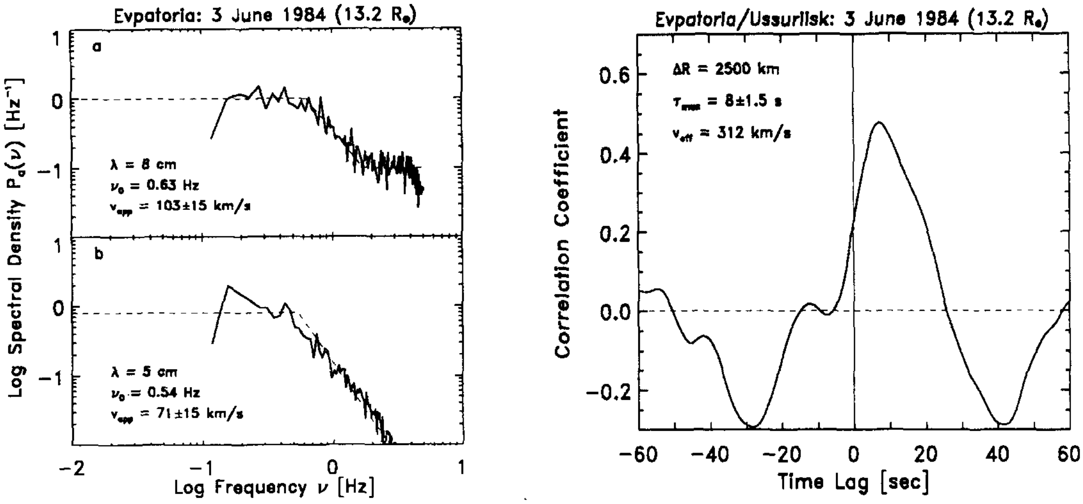

Figure 1: *Left:* Amplitude fluctuation spectra of the Venera-15 radio signals recorded at the Evpatoria ground station on 3 June 1984. Solar offset distance $R = 13.2\ R_\odot$ (panel a: λ_2 = 8 cm; panel b: λ_3 = 5 cm). *Right:* Cross-correlation function for two-station frequency fluctuations at L-band (λ_1 = 32 cm). The data were recorded at Evpatoria and Ussuriisk simultaneously with the amplitude spectra shown on the left.

level variance to its mean, was $m = \sqrt{\langle \Delta I^2 \rangle}/\langle I \rangle = 0.48$ (weak scattering). The break frequency was found with good accuracy to be ν_0 = 0.63 Hz, so that the apparent speed of the motion of diffraction pattern from Eq. (1) was v_{app} = 103 km s^{-1}. A smaller value for v_{app} was derived for the scintillation spectrum at 5 cm (left panel b). A possible explanation for this difference is the relatively large scintillation index at λ_2 = 8 cm, where the fluctuations are barely in the weak regime.

The right side of Figure 1 presents the cross-correlation function of L-band frequency fluctuations recorded at the ground stations Evpatoria and Ussuriisk during the same time interval. The geometrical distance between the ground stations is about 7700 km, which projects to a coronal separation of the ray paths of $\Delta R \simeq 2500$ km. For this example, the effective velocity of the irregularities inferred from the measurement τ_{max} =8±1.5 s is $v_{eff} \simeq 312\pm60$ km s^{-1}. Combining this two-station result and the mean value of the amplitude spectrum determination of velocity ($\langle v_{app} \rangle$ = 87 km s^{-1}), we arrive at the ratio

$$\xi = \frac{v_{eff} - u}{\langle v_{app} \rangle - u} = 4.01 \pm 0.76 \qquad (4)$$

where u = 7.9 km s^{-1} is the radial ray path velocity in this example.

Measurements of the anisotropy coefficient (Venera data: 1984) using the combined velocity determination techniques are displayed in Figure 2. The results of ongoing studies using Ulysses data from 1991 will be reported in a subsequent paper. The Venera data alone are insufficient to provide a definite conclusion regarding the dependence of the axial ratio on solar distance. Nevertheless, there is a tendency for the anisotropy coefficient to increase toward smaller solar distances. This trend runs counter to the result of (Grall *et al.*, 1997) that electron density irregularities on scales of 200 to 3000 km are nearly isotropic ($\xi \simeq 1.5$) at 9 $R_\odot$. Spectral analysis of Helios Faraday rotation measurements (Andreev et al., 1997) provides evidence for strong anisotropy ($\xi \simeq 1.5$) of the magnetic field irregularities at even larger scales.

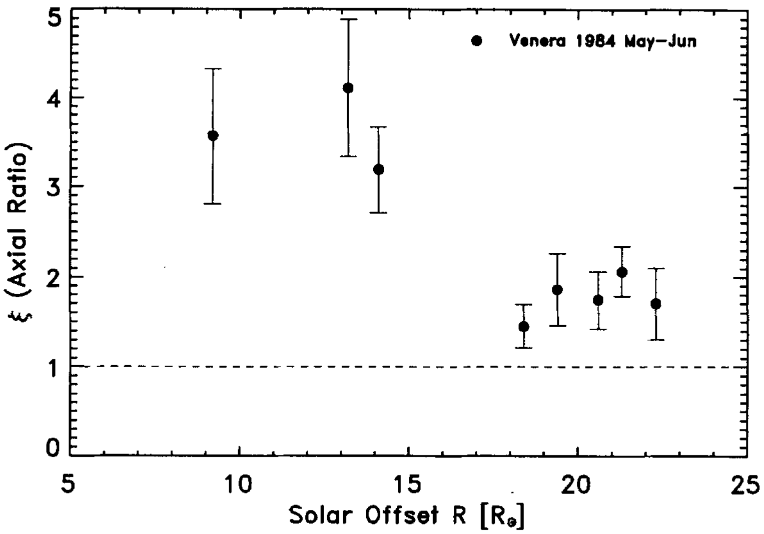

Figure 2: *Anisotropy coefficient ξ (axial ratio: Eq. 2, with $g_2 = \xi^{-1}$) as a function of solar offset distance from Venera (1984) measurements. The trend to larger anisotropy at smaller solar offset is apparent.*

CONCLUSIONS

Simultaneous measurements of coronal velocities from amplitude fluctuation spectra and cross correlations of frequency variations recorded at two widely spaced ground stations display a systematic difference between the two different techniques. Values of the "effective velocity" v_{eff} from the cross correlations of spaced frequency fluctuation observations are found to exceed the values of the apparent velocity v_{app} determined from temporal spectra of amplitude scintillations. Typical values of the anisotropy coefficient are $\xi = v_{eff}/v_{app} < 2$ for solar distances $R \gtrsim$ 15 $R_\odot$ and $\xi > 2$ for $R \lesssim$ 15 $R_\odot$. The difference in the derived values for v_{eff} and v_{app} can be attributed to elongation of the electron density irregularities up to scales of a few thousand km along the radial direction, implying that they are controlled by the coronal magnetic field for solar distances out to 15 $R_\odot$. This phenomenon may well be another manifestation of the same process(es) responsible for heating the corona and accelerating the solar wind.

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