Coronal occultation of *Voyager 2*, 1979 August

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**Summary.** Simultaneous observations of the angular and spectral broadening of *Voyager 2* radio signals at $\lambda\ 13.1$ cm have been performed during superior conjunction, when the line of sight to the spacecraft passed within $2.1R_\odot$ of the Sun’s north pole, and have been used to derive solar wind speeds. The measured angular broadening $\phi$ follows the trend established by other workers from observations of natural radio sources at solar maximum and at larger separations from the photosphere, as well as from observations of a single spacecraft at smaller separation. Representatively, $\phi$ was 0.26 arcmin at a separation of $2.9R_\odot$. It is suggested that the scattering observed is sufficient at solar maximum to account for the fact that solar `plasma-frequency' radio bursts in ground-based observations appear to occur well above the plasma-frequency level.

**1 Introduction**

Coronal density inhomogeneities close to the Sun can be investigated by measuring the angular and spectral broadening of spacecraft radio signals during coronal occultation. Previous measurements of the angular broadening of natural radio sources have been limited to apparent separations $h$ from the solar limb greater than $4R_\odot$. Woo (1978) inferred the angular broadening of *Helios 1* at $h = 0.7R_\odot$ from the loss of signal received by the 64-m tracking antenna at Goldstone. This measurement demonstrated that the scattering of spacecraft signals could be measured very close to the Sun, because the signals are strong ($\sim 10^5$ Jy in a 1-Hz band), and a large reduction in solar interference can be obtained by comparing the signal levels on and off the satellite frequency.

In this paper we report the first of what is intended to be a series of such measurements spanning the present maximum and next minimum of the solar cycle. These measurements yield the variation of angular broadening and spectral broadening with distance from the Sun at a variety of heliographic latitudes. Combining simultaneous spectral and angular broadening measurements by Woo’s method yields the associated range of solar wind speeds.
Angular broadening measurements close to the Sun can be used to assess the effects of coronal scattering on ground-based observations of solar ‘plasma-frequency’ radio bursts. Such observations, which are confined to $h \leq 2R_\odot$ by the low-frequency cut-off of the ionosphere, imply that the bursts are generated well above the average plasma-frequency level in the corona (Stewart 1976). This discrepancy could be attributed to coronal scattering, if the scattering were as strong as is indicated by extrapolating toward the Sun the angular broadening of natural radio sources observed near solar maximum (Bradford 1979). One objective of the proposed series of measurements is to determine whether scattering close to the Sun is indeed this strong, and whether it remains so throughout the solar cycle.

This paper describes measurements of coronal angular broadening and spectral broadening of the 2296-MHz carrier signal of Voyager 2 during superior conjunction in 1979 August, when the line of sight to the spacecraft passed over the north pole of the Sun. The minimum separation of the line of sight from the limb was 2.1 $R_\odot$ (Fig. 1).

![Figure 1. Apparent trajectory of Voyager 2.](image)

2 Equipment

Measurements were made with the Owens Valley Radio Observatory interferometer, which consists of two 27-m paraboloids on an east–west baseline. Right circular polarization was received, and the antenna spacing was varied as shown in Table 1.

A Spectral Dynamics 360 digital cross-power spectrometer was used to compute 512-point spectra with 10-Hz channel spacing. The instrumental bandwidth was 14.34 Hz between $e^{-1/2}$ power points. The integration time was 23.9 s and the spectrometer provided 11-bit full-scale resolution.

3 Measurements

Using the area $P_{AB}$ under the cross-power spectrum, and areas $P_A$ and $P_B$ under each of the auto-power spectra, normalized fringe visibilities

$$\rho = P_{AB}(P_A P_B)^{-1/2}$$

were calculated, in which each area involved was measured above the broadband background level. Measurements of signals from Voyager 1, at $h > 19R_\odot$, were made to check the system at 100 per cent fringe visibility.
Coronal occultation of Voyager 2, 1979 August

Table 1. Observations of Voyager 2 during coronal occultation. The errors are one standard deviation of the mean.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Date (1979 August)</th>
<th>$h$ (R$_\odot$)</th>
<th>Baseline (m)</th>
<th>$\phi$ (arcmin)</th>
<th>$B$ (Hz)</th>
<th>$v$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 13</td>
<td>1730–1746</td>
<td>3.60</td>
<td>670</td>
<td>0 ± 0.07</td>
<td>10.5 ± 0.5</td>
<td>42 ± 11</td>
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<tr>
<td>B 13</td>
<td>1856–2025</td>
<td>3.50</td>
<td>670</td>
<td>0.20 ± 0.04</td>
<td>10.0 ± 0.6</td>
<td>62 ± 16</td>
</tr>
<tr>
<td>C 13</td>
<td>2226–2355</td>
<td>3.20</td>
<td>670</td>
<td>0.18 ± 0.04</td>
<td>12.7 ± 0.5</td>
<td>62 ± 16</td>
</tr>
<tr>
<td>D 14</td>
<td>1730–1850</td>
<td>2.20</td>
<td>670</td>
<td>0.20 ± 0.03</td>
<td>23.9 ± 0.9</td>
<td>102 ± 18</td>
</tr>
<tr>
<td>E 14</td>
<td>1938–2037</td>
<td>2.15</td>
<td>670</td>
<td>0.18 ± 0.04</td>
<td>21.0 ± 0.7</td>
<td>99 ± 24</td>
</tr>
<tr>
<td>F 14</td>
<td>2110–2350</td>
<td>2.15</td>
<td>670</td>
<td>0.22 ± 0.03</td>
<td>21.9 ± 0.7</td>
<td>84 ± 15</td>
</tr>
<tr>
<td>G 15</td>
<td>1800–1819</td>
<td>2.70</td>
<td>427</td>
<td>0.25 ± 0.08</td>
<td>30.6 ± 0.3</td>
<td>105 ± 37</td>
</tr>
<tr>
<td>H 15</td>
<td>1855–1919</td>
<td>2.75</td>
<td>427</td>
<td>0.27 ± 0.04</td>
<td>28.4 ± 0.3</td>
<td>91 ± 25</td>
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<tr>
<td>I 15</td>
<td>2009–2123</td>
<td>2.85</td>
<td>427</td>
<td>0.23 ± 0.01</td>
<td>19.2 ± 0.6</td>
<td>71 ± 6</td>
</tr>
<tr>
<td>J 15</td>
<td>2141–2250</td>
<td>2.90</td>
<td>427</td>
<td>0.29 ± 0.01</td>
<td>22.9 ± 0.9</td>
<td>68 ± 4</td>
</tr>
<tr>
<td>K 15</td>
<td>2345–2355</td>
<td>3.05</td>
<td>427</td>
<td>0.22 ± 0.04</td>
<td>20.6 ± 0.4</td>
<td>81 ± 17</td>
</tr>
<tr>
<td>L 16</td>
<td>1720–1738</td>
<td>4.60</td>
<td>670</td>
<td>0.05 ± 0.03</td>
<td>8.2 ± 0.3</td>
<td>140 ± 75</td>
</tr>
<tr>
<td>M 16</td>
<td>1943–2038</td>
<td>4.85</td>
<td>670</td>
<td>0.06 ± 0.07</td>
<td>7.6 ± 0.2</td>
<td>105 ± 120</td>
</tr>
<tr>
<td>N 16</td>
<td>2232–2255</td>
<td>5.10</td>
<td>670</td>
<td>0 ± 0.05</td>
<td>6.6 ± 0.2</td>
<td>81 ± 17</td>
</tr>
</tbody>
</table>

From the measured visibility $\rho$ and the projected interferometer baseline, the apparent angular size $\phi$ of the source was calculated, assuming a circular Gaussian brightness distribution. The semimajor axis $\phi_a$ of an elliptical Gaussian brightness distribution of axial ratio 2 and with its minor axis aligned radially was also calculated. (Both $\phi$ and $\phi_a$ are e$^{-1}$ half-widths.) To allow comparison with published data, $\phi$ and $\phi_a$ were adjusted to represent the angular broadening of a point source at infinity by multiplying them by 1.19, the ratio of the distance from the spacecraft to the Earth to the distance from the spacecraft to the Sun.

The bandwidth of the received signal was measured by first fitting a Gaussian to the top portion of the observing spectrum, calculating its full-width between e$^{-1/2}$ power points (2σ on a Gaussian profile), and correcting for the instrumental profile as follows:

$$\sigma_{\text{signal}}^2 = \sqrt{\sigma_{\text{observed}}^2 - \sigma_{\text{instrumental}}^2}.$$  

The effects of Doppler drift during the 23.9-s integration were negligible, and the intrinsic width of the carrier signal was also negligible. The bandwidth parameter $B$ (Table 1) was calculated as the full-width between the frequencies enclosing half the area under the spectrum. The solar wind speed $v$ could then be found (Woo 1978) from

$$v = 5.77B/k\phi_b,$$

where $k$ is the radio wavenumber, $\phi_b$ is the e$^{-1}$ half-width in radians along the minor axis of the elliptical Gaussian brightness distribution, and the solar wind velocity is assumed to be radial. Uncertainty in the assumed axial ratio of 2 leads to corresponding uncertainty in $v$.

4 Results

Table 1 summarizes the results of the observations. Each data set represents a more-or-less unbroken sequence of measurements in which no significant discontinuities in $\rho$ were seen. The large scatter in the resulting $\phi$'s may not be due to fluctuations in angular broadening, since $P_A$, $P_{AB}$ and $P_B$ were measured sequentially and the scatter in $P_A$ and $P_B$ was comparable to the scatter in $P_{AB}$. However, the scatter appears to be of solar origin, i.e. slow intensity-scintillation rather than receiver gain variations, because the scatter in the $P$'s was several
times larger than the scatter in the solar background power. There is too much uncertainty in the values \( v \) of solar wind speed, which were derived from \( \phi \) and \( B \), to allow detailed conclusions to be drawn, but \( v \) did appear to be significantly high on August 14 when the line of sight was over the Sun's north polar region. Fig. 2 shows that, with the exception of the August 14 data, our measurements of \( \phi_a \) follow the trend of \( \phi_a \) versus \( h \) defined by natural radio source measurements made at larger \( h \) during solar maximum, and by Woo's 1975 observation of Helios 1. The August 14 data are about a factor of 2 below this trend, suggesting that scattering over the polar region of the Sun is less than that at lower latitudes. (Note: In Fig. 2, radio source measurements have been scaled to \( \lambda = 13.1 \) cm using \( \phi_a \propto \lambda^2 \).)

According to irregular refraction models, \( \phi \propto f^{-2} \) at given \( h \) (Hewish & Wyndham 1963). A similar relation applies to solar radio bursts occurring near the limb, except that \( \phi \) is reduced by approximately \( \sqrt{2} \) because the line-of-sight distance through the corona is halved (Bradford 1971). Using these relations, and a weighted average of the August 15 \( \phi \)-observations, the frequency at which \( \phi = \pi/2 \) rad for a limb burst is found to be 13.8 MHz at \( h = 2.9 R_\odot \). Consequently, 13.8-MHz radiation from a burst originating lower in the corona would appear to come from a diffusely radiating layer at \( h = 2.9 R_\odot \). If 13.8 MHz were then interpreted as the coronal plasma-frequency on the basis of burst observations, the inferred

Figure 2. Angular broadening versus separation from photosphere.
coronal electron density would be \( \sim 10 \) times that given by the solar maximum model of Blackwell, Dewhirst & Ingham (1967). This large discrepancy is consistent with Stewart’s summary of observations (Stewart 1976). We suggest that scattering, rather than location of the source of the burst in a dense streamer, explains the discrepancy. Thus the scattering indicated by the present measurements is sufficient at solar maximum to account for the fact that ‘plasma-frequency’ radio bursts in ground-based observations appear to occur well above the plasma-frequency level.

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