Half a solar rotation later, on June 18, 0624 — 05 exhibited a 200% increase in its index. This increase was then observed to move sequentially through the sources whose lines of sight lay to the east of the Sun; 0802 + 10 on June 17, 0933 + 04 and 1005 + 07 on June 21, 1226 + 02 on June 23 and 1309 — 22 and 1328 + 25 on June 24-25. The relatively small changes in scintillation index on these sources emphasizes the weakness of the disturbance, and consequently no geophysical events were apparent when the stream met the Earth again.

CONCLUSIONS

A recent paper by Wilcox and Colburn[11] presenting the positions of the quiet Sun magnetic field sector boundaries for 1969 lends strong support to the interpretation of our scintillation results. Figure 3 is a reproduction of the sector boundary crossings during 1969. A reversal of the dominant field polarity from June 7-8 coincided exactly with the position of the blast wave which we have deduced from scintillation observations. The width of the field reversal at the Earth (1 day) also agrees well with our estimate of the width of the blast in the ecliptic plane. When the associated plasma stream corotated past the Earth on June 15-16, it was preceded by a reversal in the polarity of the solar magnetic field on June 14. Thus the stream which we have analysed corresponded to the turbulent region of plasma which is known to accompany magnetic field sector boundaries. Both of the abovementioned events were associated with sudden-commencement geomagnetic storms on June 8 and June 16.

The weaker stream from region B on the Sun can be seen (Figure 3) to be associated with a sector boundary crossing on June 23 when the dominant field polarity was again reversed.

Thus it is evident that the IPS of a grid of radio sources is a particularly useful method for tracing the development of interplanetary streams, plasma blasts and magnetic field sector boundaries in the solar wind. We have shown that both streams and plasma blasts are primary agents in the onset of sudden commencement geomagnetic storms, and that corotating streams are often associated with the sector boundaries in the solar magnetic field.

It is a pleasure to thank Dr J. P. Wild and the staff of CSIRO for making the radioheliograph available for the observations. One of us (M.W.) acknowledges the support of a Commonwealth Postgraduate Award.

Note in proof: Consideration of the power spectra of the scintillations has revealed a more detailed structure of the streams which will be described in a later paper.

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Bessellian Spectral Analysis of Interplanetary Scintillation

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It is now well established that observations of interplanetary scintillation from a single station can yield useful information on the angular structure of radio sources,[1] and on the propagation of large-scale disturbances through the interplanetary medium.[2, 3] However, when it is required to obtain detailed information on the plasma properties single station observations suffer from the disadvantage that, in general, it is not possible to measure the velocity and scale of the irregularities independently. For example, a change in the width of the observed temporal power spectrum of the scintillations might be caused by either a change in velocity, or a change in scale, or a combination of both.

Lovelace *et al.*,[4] recently pointed out that under certain conditions the observed power spectrum might develop a modulation from which the velocity of the drifting diffraction pattern (and hence the solar wind) could be determined. More recently[5] the technique has been applied to ionospheric scintillations and to some interplanetary scintillation data.

It is the purpose of this paper to examine the dependence of the modulation on various solar wind parameters, in particular the distance of the scattering region from the observer, the thickness of the scattering layer, and the presence of other than a single well-defined velocity. In addition we discuss some observations of scintillation at 80 MHz which we have analysed using these techniques.

For the case of a thin, weakly scattering layer (rms phase deviation $\phi_0 < 1$), the two dimensional intensity power spectrum at a distance Z from the layer can be approximated by,[6]

$$P_I(q_x, q_y) = P_\phi(q_x, q_y) \sin^2 \left(\frac{\lambda Z}{4\pi} q^2 \right), \tag{1}$$

where q_x and q_y are spatial frequencies, $q^2 = q_x^2 + q_y^2$, and P_ϕ is the power spectrum of the phase fluctuations imposed on emergence from the layer. The spectrum is modulated by the $\sin^2$ term and in this ideal case the modulation minima extend to zero. By applying a two-dimensional Fourier transform to the two-dimensional autocorrelation function, $\rho_I(r_x, r_y)$, of the diffraction pattern on the ground, $P_I(q_x, q_y)$ could be found. However, a single station can yield only a cross-section, $\rho_I(r_x, 0)$, of the autocorrelation function. Normal procedure is to obtain the power spectrum from this observed function via a one-dimensional Fourier transform, but in so doing the modulation is smeared since this function is actually the projection of the two-dimensional power spectrum onto one-dimension. If circular symmetry is assumed (which corresponds to isotropic scattering irregularities), the Bessel transform of $\rho_I(r_x, 0)$ may be formed to yield the two-dimensional Fourier transform,

$$P_I(q) = \int_0^\infty \rho_I(r)\, r J_0(2\pi q r)\, dr ,$$

where $r^2 = r_x^2 + r_y^2$. Thus the modulation is retained, and it is in principle possible to determine the velocity from the positions of the zeros which in equation (1) occur when

$$\frac{\lambda Z}{4\pi} q^2 = n\pi \,, \qquad (n = 0, 1, 2, \ldots\ldots).$$

For a single, well-defined velocity u, the temporal frequencies at which the dips occur are then given by,

$$= \frac{\sqrt{n}\,u}{\sqrt{\lambda Z}}. \qquad (2)$$

So far we have assumed a thin scattering screen. Salpeter[7] derived an expression for the two-dimensional power spectrum arising from an extended scattering region of thickness L,

$$P_I(q_x, q_y) = P_\phi(q_x, q_y) \left[1 - \frac{4\pi}{L\lambda q^2} \sin\left(\frac{L\lambda}{4\pi} q^2\right) \cos\left(\frac{2Z\lambda}{4\pi} q^2\right)\right],$$

from which it is clear that for an extended layer the minima no longer reach zero. In most cases we expect this extended screen to be a more realistic model than the thin screen. To illustrate the effect of varying the distance Z and thickness L of the screen, spectra at 80 MHz have been computed and are shown in Figure 1. As the screen is approached the minima move to higher frequencies and therefore become more difficult to observe. As the thickness of the screen is increased the minima become smeared as expected from the expression for $P_I(q_x, q_y)$. The assumed form of the phase function P_ϕ affects the slope of the power spectrum but not the position of the minima. It can be seen from Figure 1 that the reduced slope of the spectrum computed using a power-law phase function allows minima to be observed out to higher frequencies than for the case of a Gaussian phase function. In both cases an irregularity scale of 200 km was used.

In addition to the above effects, further smearing of the modulation pattern is expected due to the variation of the

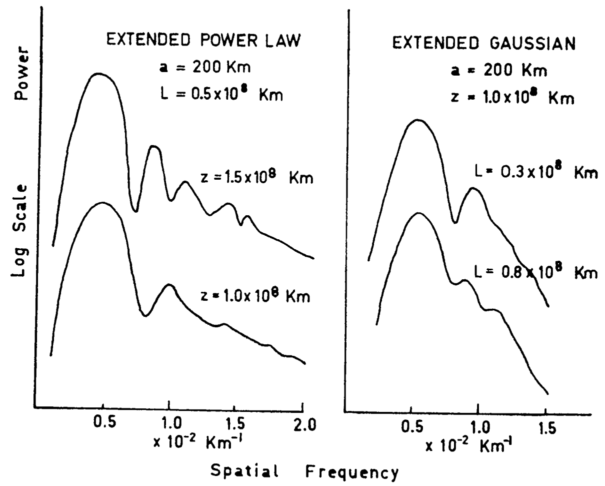

Figure 1. Computed power spectra showing the effects of varying the distance Z or the thickness L of the scattering layer.

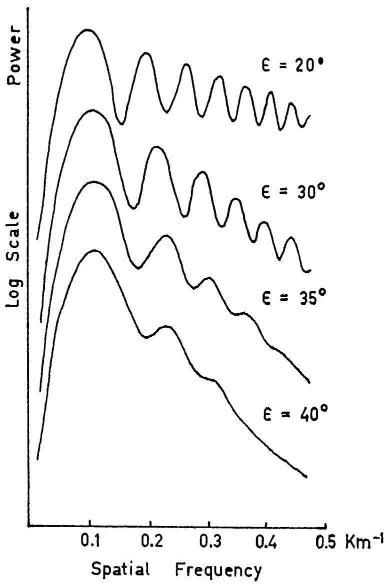

Figure 2. The effects of integration along an extended line of sight, for various elongations ϵ of the source relative to the Sun. The spectra were computed for an observing wavelength of 1 cm.

projected velocity of the plasma at different points along the line-of-sight. To assess this purely geometrical effect, power spectra have been computed for several elongations by dividing the medium into a series of thin screens along the line-of-sight, and adding the contributions from each with a weighting factor proportional to the scattering power of the medium (r^{-4}, where r is the distance from the Sun). A Gaussian phase spectrum was used with a width dependent on the scale of the irregularities, a. Values for the scale were taken from Readhead,[8] and vary from 20 km at $r = 0.1$ A.U. to 220 km at $r = 1$ A.U. The results are shown in Figure 2, from which it is apparent that the modulation is blurred rapidly for elongations $\gtrsim 35°$. This rapid onset of blurring is the result of both the geometrical velocity effect and also the increase in scale, a, which steepens the spectra. It is also clear from Figure 2 that as the geometrical effect increases at larger elongations, the reduction of the apparent ('integrated') velocity causes the minima to move to higher spatial frequencies. The spatial frequencies indicated on the axis of Figure 2 correspond to an observing wavelength of 1 cm.

Apart from the above-mentioned geometrical effect, a range of velocities might exist even at a fixed distance Z. The effect of such a random velocity field is shown in Figure 3, where the spectrum was computed for a thin screen at a fixed distance, with the velocity varying $\pm$ 25 km/s about its mean value, and for an observing frequency of 80 MHz.

Over the past three years the Adelaide radio astronomy group has amassed a considerable amount of scintillation data from observations at 80 MHz using the CSIRO Radioheliograph at Culgoora, N.S.W. Consideration of the above results, however, indicates that at this frequency under ideal conditions, only two or three minima might be expected in our spectra (normally derived from $\sim$ 10 min of observation) before the power decreases to that of the noise spectrum. Integration along an extended line of sight and the possible presence of velocity dispersion[9] add

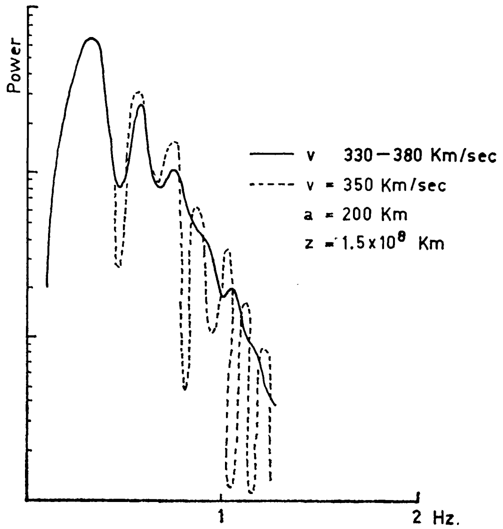

Figure 3. The effect of a random velocity field in a thin scattering layer for an observing frequency of 80 MHz. The minima in the constant velocity spectrum do not extend to zero because of the finite resolution (0.05 Hz) imposed during computation.

to the difficulties. An examination of our own data indicates that under normal conditions of the interplanetary medium, neither a Fourier nor a Bessel analysis of observations at 80 MHz is able to yield any significant modulation pattern. It appears that only under unusual circumstances might the technique be at all useful at this frequency. Such a situation arose however in May 1968, when a corotating plasma stream approached the Earth[2] and low frequency dips were seen in the scintillation power spectra of the source 0134 + 32. These were interpreted as evidence for the proximity of the scattering region, i.e. that the Earth was located within the Fresnel region, and allowed the screen to be placed at $Z \sim 0.1$ A.U. These data have

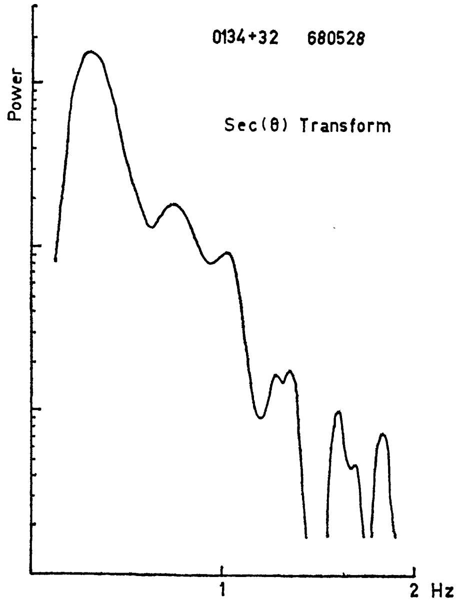

Figure 4. An experimental power spectrum computed using the sec θ transform, from observations at 80 MHz during May, 1968.

been analysed further by computing the Bessel transform, not of the autocorrelation function, but from the one-dimensional Fourier power spectrum using a sec θ transform,

$$P(f) = -\frac{d}{df}\int_0^{\pi/2} P_F(f \sec\theta)\, d\theta\,.$$

These two procedures have been shown to be exactly equivalent,[10] the sec θ transform being preferred because of its computational simplicity. The computed spectrum from these observations is shown in Figure 4. Above 1.4 Hz the spectrum becomes statistically unstable, but below this limit four minima are seen which closely fit the $\sqrt{n}$ dependence of equation (2), and which correspond to $n = 0, 1, 2$ and 3. Taking $Z = 0.1$ A.U., a velocity of 315 km/s is derived. It would appear that this was a rather rare occurrence in which the effective screen was thin due to the presence of the corotating stream and, as mentioned above, sufficiently close to the Earth that observations were within the Fresnel region.

At 80 MHz for the scattering to be weak, observations must be made at elongations $\gtrsim 30°$ so that generally the geometrical smearing effect will be important. At higher frequencies conditions are more favourable for the observation of modulation in the power spectrum. At frequencies ~ 1 GHz, observations to within 10° or less of the Sun could be made: the geometrical effect would become negligible and the smaller scale of the irregularities would allow minima to be observed out to higher spatial frequencies. On the other hand there is some evidence that within 30 $R_\odot$ turbulent velocities become important, and this may become the major cause of blurring as indicated in Figure 3.

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Coronal Broadening of the Crab Nebula 1969-71

Observations

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A description was given in a previous paper[1] of the first observations of the two-dimensional image of the Crab Nebula as it became broadened by the solar corona in June 1969. In this paper we describe further observations at 80 MHz during 1970 and 1971, again using the CSIRO