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OBSERVATIONS OF FINE STRUCTURE IN THE INTERPLANETARY MEDIUM

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Abstract—Observations of the interplanetary scintillation of radio sources using spaced receivers enable the size and motion of plasma irregularities in the solar wind to be studied. It has been noted previously that the scale of these irregularities is of the order of the ion gyroradius in the medium, and in this paper it is shown that the scale increases with distance from the Sun.

1. INTRODUCTION

Interplanetary scintillation is now recognised to be a useful technique for investigating the solar wind[1–3] and the angular structure of radio sources.[4–6] In a previous paper[2] (hereafter referred to as paper 1) observations of the magnitude and direction of the solar wind over a wide range of heliocentric latitude and radial distance were presented. This investigation was based upon the interplanetary scintillation of the radio source 3C48 and the compact component of the Crab Nebula observed at 81·5 MHz during February–July 1966. The results apply to the interplanetary medium near the minimum of the present sunspot cycle. In this note the same observational data are used to obtain information about the scale of the fluctuations in plasma density, and the variation of this quantity with distance from the Sun.

2. ANALYSIS OF THE OBSERVATIONS

The observational system, which comprised a triangular arrangement of receiving sites, was fully described in paper 1. Following the method of analysis described by Phillips and Spencer[7] the scale ξ_0' of the diffraction pattern was calculated using auto and cross-correlograms and the results are shown in Fig. 1a where the values plotted represent the mean radius of the 'characteristic ellipse'. The diffraction pattern was often found to exhibit significant elongation along the direction of motion, the characteristic ellipse having a mean axial ratio of 1·8:1. On theoretical grounds an elongation of the plasma density fluctuations along the corotating field direction might be anticipated, rather than along the radial wind direction. There are indications in the present data that this may have been the case but since for the bulk of the data the projected 'hose-pipe' direction did not differ greatly from the radial direction the result is barely significant.

Also plotted in Fig. 1a is a broken line showing the value of ξ_0' obtained by a different method. For a drifting diffraction pattern which is time-stationary it is possible to derive ξ_0' from the temporal variations observed at a single site, provided the drift velocity of the pattern is known. This method affords a valuable check when, as in the present case, the diffraction pattern is highly correlated at the observing sites. The values of the velocity u and correlation time τ_0 presented in paper 1 were used to calculate $\xi_0' = u\tau_0$, allowance being made for the mean elongation mentioned above; it may be seen from Fig. 1a that the two methods are in good agreement. In paper 1 it was stated that this agreement indicates that the lifetime of the diffraction pattern must exceed 0·6 sec, the mean correlation

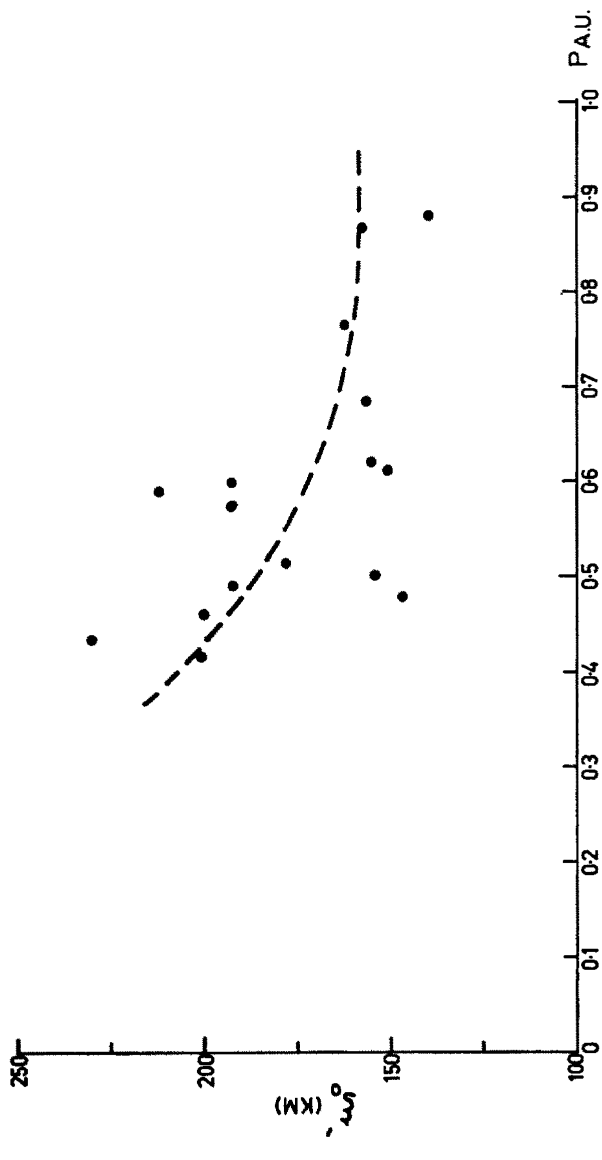

FIG. 1a. THE SCALE OF THE DIFFRACTION PATTERN DERIVED FROM CORRELATION ANALYSIS.
The broken curve represents the scale derived from the temporal fluctuations at the separate sites.

time. Following the analysis of Phillips and Spencer a value $V_c = 100 \pm 50$ km/sec is obtained for the random velocity component which, for $\xi_0' \sim 150$ km, leads to a lifetime in the range 1–3 sec. The apparent value of V_c is, however, probably determined by the fact that the actual pattern is a super-position of many patterns moving with different velocities, due to the radial velocity being resolved transverse to the extended line of sight. The lifetime of the plasma irregularities themselves may, therefore, be longer than the lifetime of the irregularities in the pattern, deduced from the value of V_c.

3. DERIVATION OF THE SIZE OF THE IRREGULARITIES

For a point source ξ_0' may be immediately related to the actual scale of the plasma irregularities ξ_0, provided that the interplanetary medium acts as a 'weak' scatterer i.e. if the phase deviations imposed by the medium are smaller than one radian. In the case of 'strong' scattering where ϕ_0, the total r.m.s. phase deviation imposed by the medium, is greater than one radian, ξ_0' becomes smaller than ξ_0 by a factor of $\sqrt{(2)}\phi_0$.[8] We shall consider the scattering regime in more detail later and for the moment consider that the weak scattering theory applies, in which case the actual scale ξ_0 may be obtained directly. It is still necessary, however, to take into account the finite angular diameter of 3C48 since this blurs fine detail in the diffraction pattern and causes ξ_0' to exceed the true scale of the irregularities ξ_0. A detailed analysis of this effect[4] has shown that for a circularly symmetrical Gaussian source the true scale is given by $\xi_0 = V\xi_0'$, where the scintillation visibility V is the ratio of the scintillation index observed to that which would be given by an ideal point source.

The observed values of the scintillation index F as a function of p, the distance from the Sun, are shown in Fig. 1b, compared with corresponding values for an ideal point source. The latter were obtained from Little and Hewish,[9] after scaling in the usual way to allow for the change in wavelength. In Fig. 2a the corrected scale $\xi_0 = V\xi_0'$ is plotted and it is seen that the scale of the plasma irregularities increases with distance from the Sun. The values of ξ_0' and the corresponding values of ξ_0 have been smoothed over several days, so that no indication is given of day to day changes in the scale which may have been related to solar activity. On at least one occasion (March 14), when the scintillation index increased by more than a factor of two at a time of strong flare activity on the Sun (Paper 1), there was evidence for an increase in the scale. However, more events of this kind are needed before a definite relation may be regarded as established.

The values of the scintillation index shown in Fig. 1b also enable the angular diameter of 3C48 to be estimated following the method of Little and Hewish.[4] Assuming an intensity distribution of the form $\exp - (\psi^2/\psi_0^2)$ we obtain $2\psi_0 = 0''{\cdot}3$, the same as the value obtained by Little and Hewish[9] from scintillation observations at 178 MHz. This result may be compared to the dimensions $0''{\cdot}3 \times \leqslant 0''{\cdot}2$ obtained from long-baseline interferometry.[10] Returning to the question of the scattering regime it has already been shown[11] from observations of scintillation at different wavelengths that the interplanetary medium behaved as a weak scatterer during 1965, for a line of sight which passed the Sun at a distance $p > 0{\cdot}5$ A.U. Although the scattering closer to the Sun is known to increase towards sunspot maximum[12] the present observations give evidence for only a small increase of scintillation during 1965–66 and it follows that the weak scattering theory should still apply for distances $p > 0{\cdot}5$ A.U. Furthermore, direct estimates of ϕ_0 have been made from the present data[13] by comparing the form of the experimental probability distributions of intensity to the curves predicted theoretically[14] for different values of

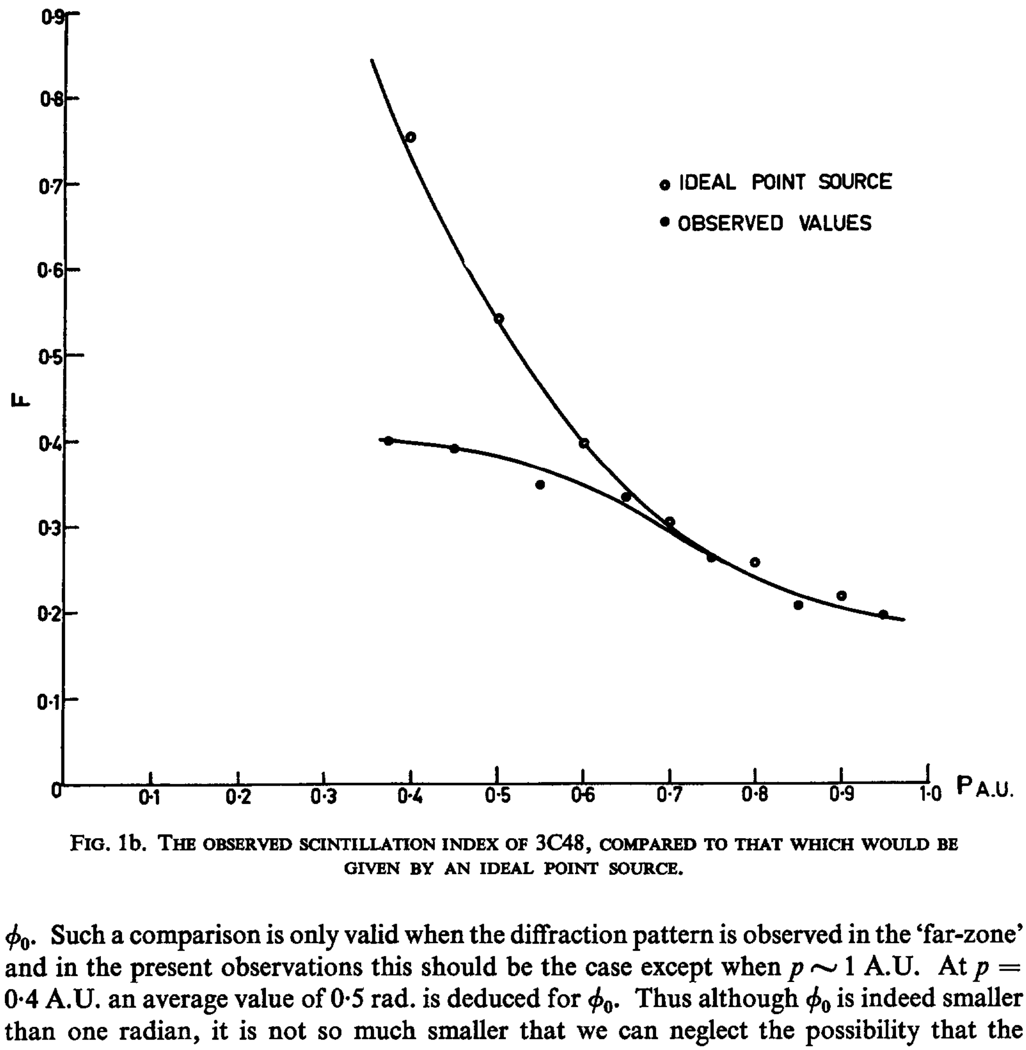

FIG. 1b. THE OBSERVED SCINTILLATION INDEX OF 3C48, COMPARED TO THAT WHICH WOULD BE GIVEN BY AN IDEAL POINT SOURCE.

ϕ_0. Such a comparison is only valid when the diffraction pattern is observed in the 'far-zone' and in the present observations this should be the case except when $p \sim 1$ A.U. At $p =$ 0·4 A.U. an average value of 0·5 rad. is deduced for ϕ_0. Thus although ϕ_0 is indeed smaller than one radian, it is not so much smaller that we can neglect the possibility that the observed decrease in the scale close to the Sun might be caused by the onset of strong scattering.

Bramley[15] has shown that the autocorrelation function $\rho_a(\xi)$ of the complex amplitude across the ground is related to that of the phase fluctuations $\rho_\phi(\xi)$ in the medium by

$$\rho_a(\xi) = \exp\,[-\phi_0^2(1 - \rho_\phi(\xi))].$$

It is also known[16] that in the limiting cases $\phi_0 \ll 1$ and $\phi_0 \gg 1$, the correlation functions $\rho_I(\xi)$ of the intensity fluctuations in the pattern are

$$\rho_I(\xi) = \rho_a(\xi), \qquad \rho_I(\xi) = [\rho_a(\xi)]^2$$

for the respective cases. For small phase deviations the scale ξ_0' of the intensity correlation function $\rho_I(\xi)$ is equal to that of the complex function $\rho_a(\xi)$, whereas for large phase deviations ξ_0' is smaller by a factor which is equal to $\sqrt{(2)}$ for Gaussian correlation functions. The region intermediate between strong and weak scattering has been considered by

Vsekhsvyatskaya[17] who finds that for $\phi_0 < 0{\cdot}5$ rad. ξ_0' is equal to the scale of the complex function to within 3 per cent, and for $\phi_0 < 1$ rad. to within 10 per cent. For the present observations we may therefore assume the equality with negligible loss of accuracy.

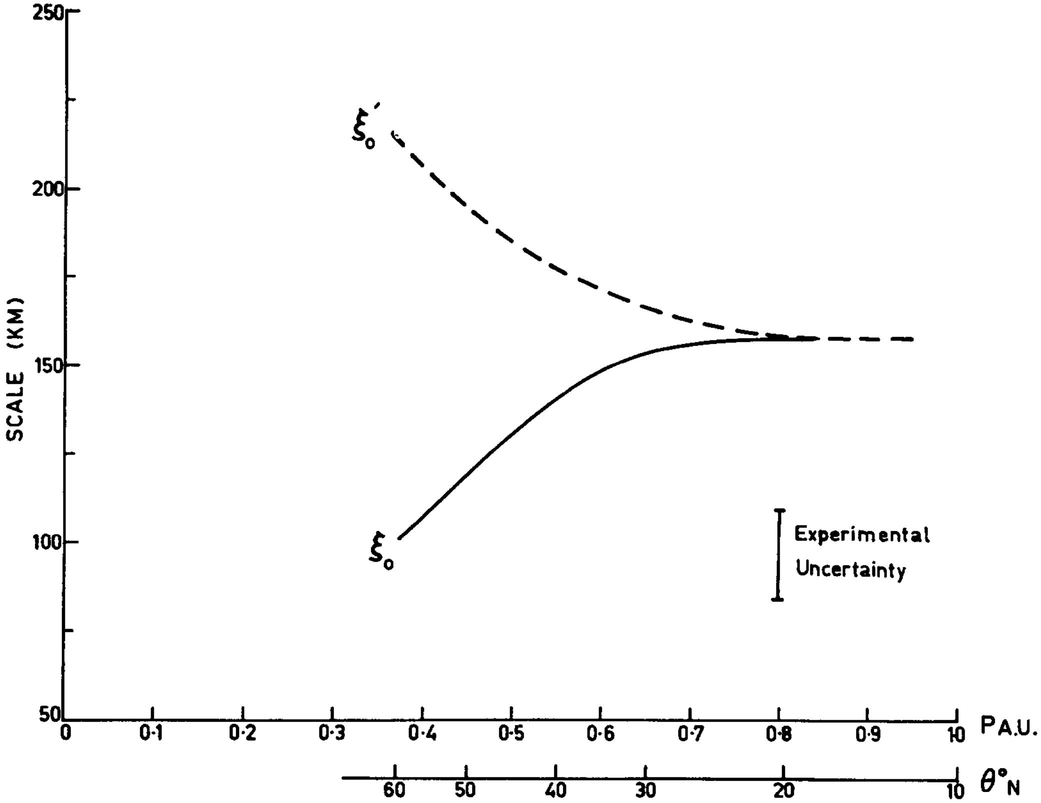

FIG. 2a. THE DERIVED SCALE ξ_0 OF THE IRREGULARITIES OF PLASMA DENSITY IN THE INTERPLANETARY MEDIUM, AS A FUNCTION OF RADIAL DISTANCE p AND HELIOCENTRIC LATITUDE θ. The observed scale ξ_0' is shown by the broken curve to illustrate the effect of blurring by the finite size of 3C48.

Assuming, as usual, that $\rho_\phi(\xi)$ takes the physically plausible form exp — (ξ^2/ξ_0^2) we may calculate, using Equation (1), the ratio ξ_0'/ξ_0 as a function of ϕ_0. In order to convert this to a variation with distance p it is necessary to know ϕ_0 as a function of p. Here we have referred to the observations of Cohen *et al.*[5] which indicate that $\phi_0 \propto p^{-1{\cdot}5}$, and have extrapolated our value $\phi_0 = 0{\cdot}5$ rad. at $p = 0{\cdot}4$ A.U. accordingly. The resulting values of ϕ_0 are shown in Fig. 2b together with the values of ξ_0' which would be observed for a constant scale $\xi_0 = 160$ km in the medium. The latter values show, as expected, that the observed scale size decreases as ϕ_0 approaches and exceeds 1 rad., but over the range of ϕ_0 relevant to the present observations this decrease amounts to less than a 10 per cent effect. It is therefore concluded that the observed decrease in the scale shown by Fig. 2a represents a genuine decrease in the scale of the fluctuations in plasma density in the interplanetary medium. It is clear that future measurements made closer to the Sun, or towards the maximum of the solar cycle, must take into account the effects of the onset of strong scattering.

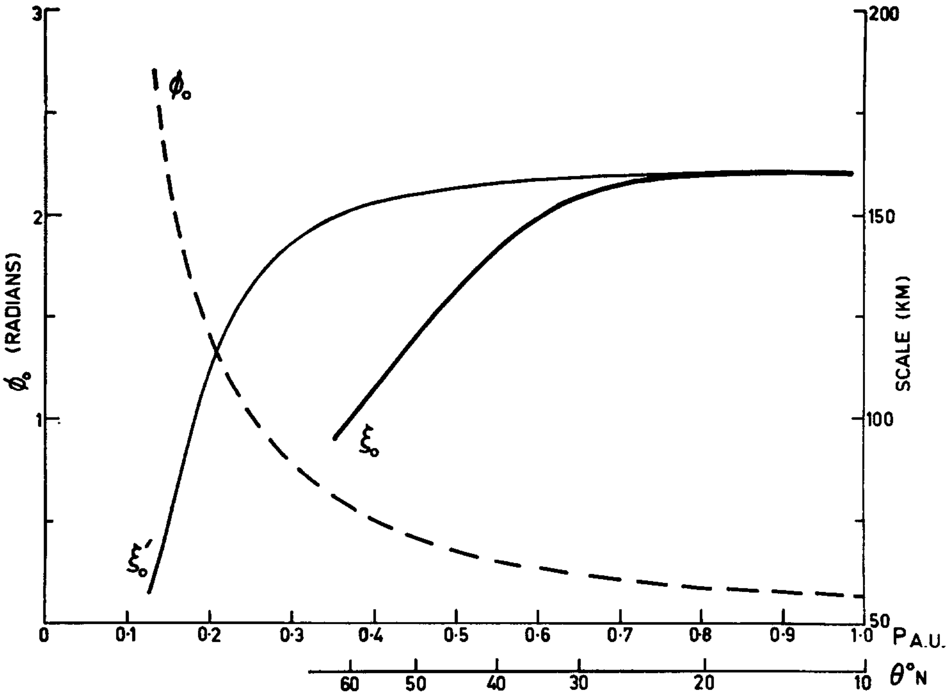

FIG. 2b. THE INFLUENCE OF THE SCATTERING REGIME ON THE SCALE ξ_0' OF THE DIFFRACTION PATTERN.
The derived values of the scale ξ_0 of the plasma irregularities are given for comparison, and values of ϕ_0 are shown by the broken curve.

4. DISCUSSION

In paper 1 it was suggested that an increase of ξ_0' with decreasing p could have arisen from a diffraction effect associated with the changing distance of the scattering irregularities from the Earth. The present calculations indicate that any such effects are probably small compared with blurring caused by the angular extent of 3C48. It was also suggested in paper 1 that the elongation of the diffraction pattern might have been caused by the ellipticity of 3C48. Recent observations by Anderson[10] have shown, however, that the major axis of 3C48 has a position angle of 62° whereas the elongation of the diffraction pattern derived from the correlation analysis had a mean position angle of 105°; in addition the measured elongation was always aligned within $\pm 25°$ of the velocity vector, which changed in direction by about 40° during the period May–June for which the correlation analysis was applied. It is therefore concluded that the elongation pattern represents a genuine extension of the irregularities.

The remarkably small scale of the irregularities and the fact that it is of the same order as the ion gyro-radius in the medium suggests that the irregularities are caused by plasma instability. If the limiting value of ξ_0 is indeed related to the gyro-radius then scintillation measurements may provide valuable information on the interplanetary magnetic field and temperature. Now the gyro-radius varies as $r \propto T^{1/2}H^{-1}$ and putting $H \propto p^{-2}$ and $T \propto p^{-1}$ as an approximation to the interplanetary magnetic field and temperature yields $r \propto p^{1.5}$. From the results shown in Fig. 2a we deduce $\xi_0 \propto p^{1.0}$ approximately, which implies that the gyro-radius varies rather more slowly with radial distance than the model would predict. It would be rash to consider the further implications of this result on the basis of the present limited data, especially as the measurements cover a rather wide range of heliocentric latitude.

In a previous communication[1] an estimate of the r.m.s. fluctuation of electron density of the irregularities was deduced from the magnitude of the scintillation index F. No allowance was then made for the decrease of the scintillation index caused by the finite angular dimensions of 3C48. Following the same analysis and making a correction for this effect yields a r.m.s. fluctuation of electron density of 0·1 electron cm^{-3} at $p = 0{\cdot}9$ A.U., and 0·72 electron cm^{-3} at $p = 0{\cdot}4$ A.U.

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