OBSERVATIONS OF THE SOLAR PLASMA USING RADIO SCATTERING AND SCINTILLATION METHODS

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An invited review

ABSTRACT

Observations of the solar plasma using the interplanetary scintillation technique have been made at radial distances of 0.03 to 1.2 AU. The solar wind is found to be independent of ecliptic latitude and radial distance, except close to the sun where acceleration is observed. Plasma density irregularities on a scale near the proton gyro radius, which modulate the mean density by about 1 percent, are present throughout the observed range of radial distance.

INTRODUCTION

Radio waves traversing the solar plasma are scattered by irregularities of plasma density. Measurements of the angular spectrum of the scattered radiation now exist in the range 0.025 AU to nearly 0.5 AU. Alternatively, for compact radio sources that illuminate the plasma with sufficient coherence the interference of the scattered waves produces a diffraction pattern at the earth. This is the phenomenon of *interplanetary scintillation.*

Studies of the motion and correlation of the diffraction pattern observed at spaced sites give information about the solar wind and the plasma irregularity wave number spectrum. The temporal variations observed at a single site give corresponding, but less complete, information about the wave number spectrum if a drift velocity is assumed. In addition, measurement of the fraction of the incident radiation scattered gives information about the density modulation caused by the irregularities. The importance of these techniques is that they permit study of the solar wind at radial distances and ecliptic latitudes not yet accessible to spacecraft. They also provide evidence of structure on a smaller scale than has been revealed by space probes in interplanetary space.

This paper is a survey of the current observational situation using radio scattering methods. Other methods for studying the solar plasma include Faraday rotation, time delays in pulses from pulsars, and differential group and phase path measurements from spacecraft. Such techniques give data on the mean plasma density and large-scale irregularities. These latter methods will not be considered.

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SCINTILLATION PARAMETERS AND THE SOLAR PLASMA

The relation between observed scintillation parameters and the plasma irregularities is illustrated in figure 1. We assume the density variations to be time stationary and described by a wave number power spectrum $G(k_1, k_2, k_3)$. If the medium is convected past a space probe at velocity V (along k_1) then the wave number components giving rise to temporal fluctuations of angular frequency $\omega = k_1 V$ lie in the sheet $\mathbf{k} \cdot \mathbf{V} = \omega$. Hence the temporal power spectrum $H(\omega)$ of the density fluctuations seen by a spacecraft is a two-dimensional strip scan of $G(k_1, k_2, k_3)$. For a power law irregularity spectrum, as discussed by *Cronyn* [1970], $H(\omega)$, will consequently be flatter than $G(k)$.

Consider next the phase modulation imposed on a plane radio wave incident along k_3. The phase variations will have a two-dimensional spectrum proportional to $G(k_1, k_2)$. This will also define the angular spectrum of the scattered radiation when the scattering is weak. In what follows we consider only the weak scattering case; in practice, this condition may be realized by observing at a sufficiently short wavelength.

The intensity diffraction pattern at the earth is again

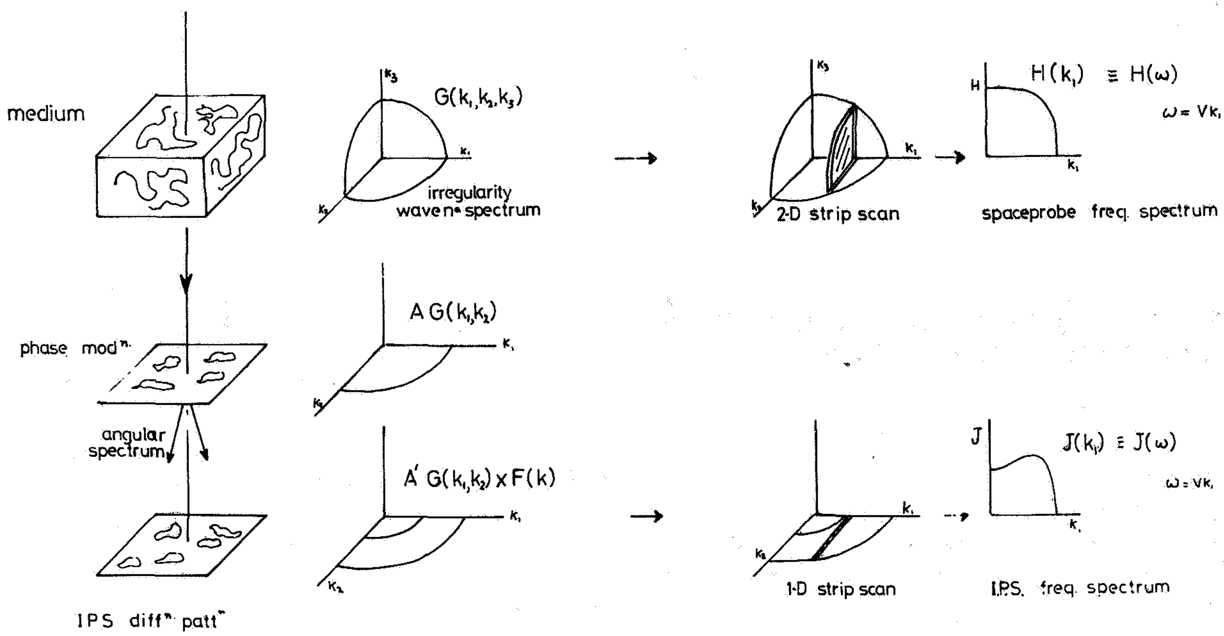

Figure 1. *Relation between the wave number spectrum of plasma density irregularities and power spectra as measured by space-probe and scintillation techniques.*

proportional to $G(k_1, k_2)$ but it is multiplied by a factor $F(k) = \sin^2 (k^2 z\lambda/4)$, where λ is the radio wavelength and z the distance of the medium from the earth. $F(k)$ arises from Fresnel "filtering" which removes low wave number components from the diffraction pattern. Measurements at spaced sites permit determination of the autocorrelation function and drift velocity of the medium, while the temporal power spectrum $J(\omega)$ at a single site is given by a one-dimensional strip scan of $G(k_1, k_2)F(k)$.

Another important observational parameter is the scintillation index m, defined as the rms variation of intensity in the diffraction pattern divided by the mean intensity. Since $m^2 \propto \lambda^2 F(k) G(k_1, k_2) dk_1, dk_2$ [*Salpeter,* 1967], it is clear that the scintillation index gives information about the magnitude of the plasma density variations.

When considering effects due to integration along an extended line of sight it is useful to define the scattering power S of the medium. We put $d(m^2) = S^2(z)dz$ where dz is an element of the line of sight. It is assumed that the distance z from the earth to this element is so great that, the diffraction pattern is unaffected by Fresnel filtering. Thus S depends on the medium alone and we have $S^2 \propto \lambda^2 G(k_1, k_2) dk_1\, dk_2$; of course, S will vary with radial distance from the sun.

THE WAVE NUMBER SPECTRUM OF THE IRREGULARITIES

Observations of interplanetary scintillation were originally interpreted in terms of irregularities having a size of the order of 100 km at a distance of 0.5 to 1.0 AU [*Dennison and Hewish,* 1967; *Cohen et al.,* 1967]. This conclusion has recently been questioned by authors who have suggested that a power law spectrum $G(k) \propto k^{-n}$ may be more appropriate [*Jokipii and Hollweg,* 1970; *Lovelace et al.,* 1970; *Cronyn,* 1970]. A detailed comparison of observation and theory shows that a power law spectrum cannot, in fact, describe the irregularities [*Hewish,* 1971; *Little,* 1971; *Lotova and Chashey,* 1971]. Since this point is important, the evidence refuting a power law spectrum will be summarized.

Measurements now exist at frequencies ranging from 26 to 2700 MHz, and it is interesting to see how the observed parameters should behave under different assumptions about the irregularity spectrum. In figure 2 we show the general behavior of the Fresnel filter $F(k)$ at 81 MHz and 2695 MHz, where the approximation

$$F(k) = \sin^2\left(\frac{k^2 z\lambda}{4}\right) \qquad k < \sqrt{\frac{2\pi}{z\lambda}}$$
$$= \frac{1}{2} \qquad k > \sqrt{\frac{2\pi}{z\lambda}}$$

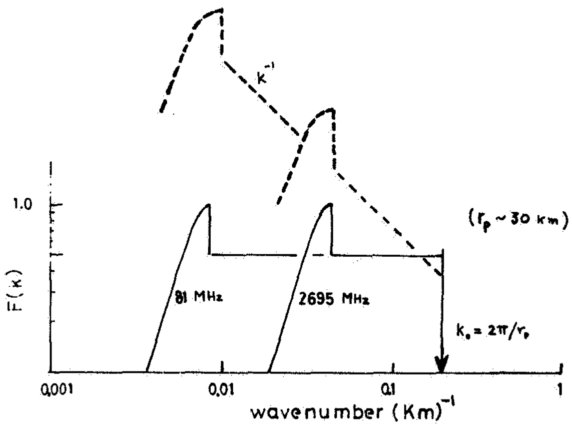

Figure 2. *Approximate form of the Fresnel filter for a one-dimensional spectrum. k_o is an assumed upper limit to the spectrum set by the proton gyroradius. The dashed curve shows the effect of filtering on a k^{-1} spectrum.*

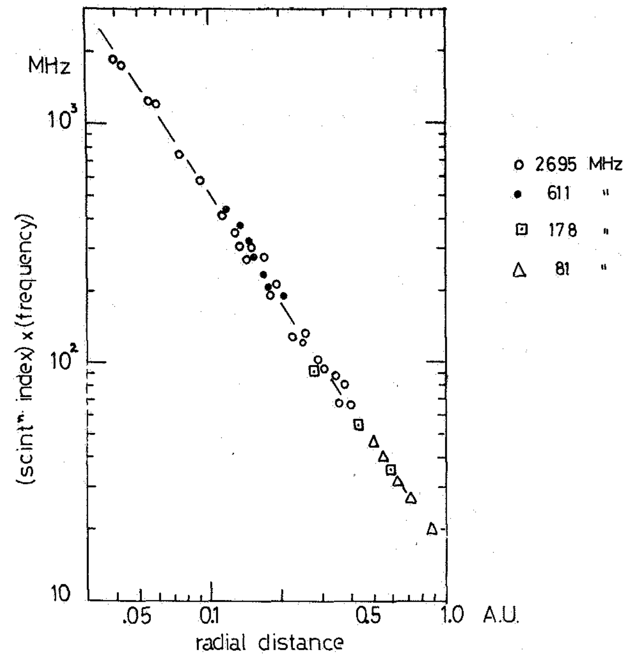

Figure 3. *Dependence of scintillation index upon distance from the sun at different radio frequencies.*

has been adopted. For the actual solar plasma it is likely that $G(k)$ has an upper bound k set by the proton gyroradius, and this is shown for a gyroradius of 30 km, appropriate to conditions at 0.5 AU. Now for a spectrum $G(k) \propto k^{-n}$ it is clear that the diffraction pattern will be dominated by wave numbers in the vicinity $k \sim \sqrt{2\pi/2\lambda}$, just greater than the Fresnel cutoff. Thus the autocorrelation function of the pattern and also $J(\omega)$ will have widths that scale approximately as $\lambda^{1/2}$ and $\lambda^{-1/2}$, respectively. In addition, for a power law spectrum, m will vary with λ and we have $m \propto \lambda^2$ for *Jokipii and Hollweg's* [1970] model, or $m \propto \lambda^{1.5}$ for the spectrum suggested by *Lovelace et al.* [1970].

Figure 3 shows observations of m taken at widely different frequencies on a number of sources by different observers; for convenience, the product $m \times$ radio frequency is plotted. These data refer to solar elongations greater than the critical value at which "turnovers" due to the finite angular size of the source become apparent [*Little and Hewish*, 1966]. The results indicate $m \propto \lambda^{1.0 \pm 0.05}$, which is not compatible with a power law spectrum. We also note that this wavelength dependence confirms the weak scattering assumption.

Further evidence may be drawn from observations of the temporal power spectrum $J(\omega)$, which approximates to a gaussian form except at distances within 0.2 AU [*Cohen et al.*, 1967]. Various measurements of the width (to e^{-1}) of $J(\omega)$ at different radio frequencies are illustrated in figure 4. The spectrum undoubtedly varies with solar distance, but the observations indicate that $J(\omega)$ is not a function of the observing frequency. Once again, this is not compatible with a power law spectrum.

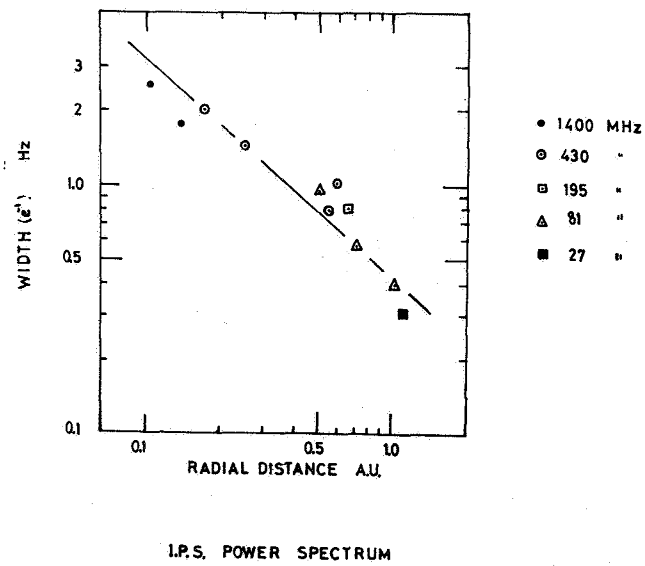

Figure 4. *Width of the scintillation temporal power spectrum. 195-, 430-, and 1400-MHz data from Cohen et al. [1967]; 81.5-MHz data from Symonds [1970] and 27-MHz data from Cronyn [1970].*

To find a spectrum that agrees with the observations we note that the relation $m \propto \lambda^{1.5}$ implies that the Fresnel factor $F(k)$ cannot modify $G(k)$ to any significant extent. This will be true only if $G(k)$ does not increase appreciably in the range of k between the Fresnel cutoffs at the extreme radio frequencies. Within the observational limits, this criterion is satisfied by $G(k) = \text{const}$ for $k < k$; alternatively, the strip scan of $F(k)\ G(k_1, k_2)$ shown in figure 1 might peak at some wave number higher than the Fresnel cutoff at the highest frequency.

Until more refined data become available it is probably simplest to assume a gaussian spectrum, although this may not be spherically symmetrical. It is clear, however, that the small irregularity sizes deduced from scintillation data correspond to a real plasma scale length, rather than to some limit imposed by diffraction theory. As such, they constitute a regime quite separate from the much larger irregularities detected by space probes.

Scintillation data, of course, do not preclude the existence of large-scale density structure having wave numbers less than the Fresnel cutoff at the lowest observational frequency. Such structure will merely deviate the wave front without producing scintillation. However, it will contribute to the angular spectrum. As shown below, observations of scintillation close to the sun indicate scale sizes in good agreement with those inferred from angular spectrum data. This means that the angular spectrum is not greatly influenced by large-scale irregularities and it follows that some limit can be placed on the density variations in large irregularities. This limit is estimated in a later section.

Having established that the observed scale of the diffraction pattern is representative of the irregularities themselves, we can deduce that the variation of scale size with radial distance, implicit in figure 4, is also real. In figure 5 we combine all the data, including measurements of both the correlation distance of the diffraction pattern at spaced sites and the temporal spectra at a single site. When the latter are used a solar wind of 330 km/sec has been assumed. Also included, close to the sun, are values derived from angular spectrum measurements at low frequency, combined with values of m at high frequency, as described by *Hewish and Symonds* [1969]. All the measurements are in reasonable agreement and indicate a scale that increases approximately linearly with radial distance within the observational uncertainty. Further evidence, based on the sharp reduction of scintillation index close to the sun when the finite angular size of radio sources becomes important, suggests that a somewhat steeper variation gives a better fit to m versus solar elongation

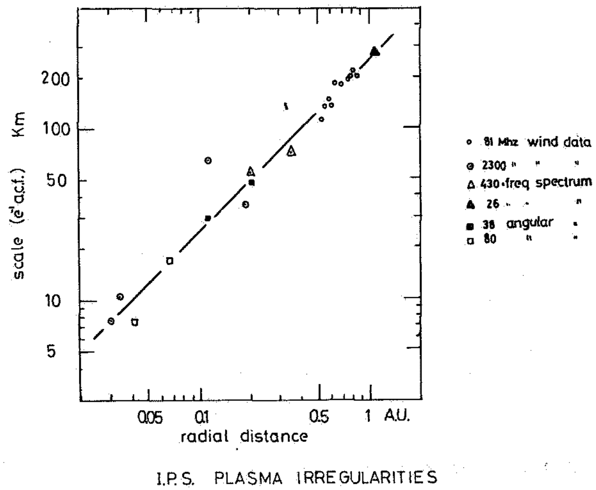

Figure 5. *The width of the autocorrelation function of the scintillation diffraction pattern obtained by different methods. 2300 MHz and 81.5 MHz data from spaced-site observations [Symonds, 1970; Little, 1971], 430 MHz and 27 MHz points from temporal power spectra [Cohen et al., 1967; Cronyn, 1970]; 38 MHz and 80 MHz points from interferometric angular spectrum measurements [Hewish and Symonds, 1969].*

curves. [*Cohen and Gundermann*, 1969; *Readhead*, 1971]. Model fitting gives best agreement for $\ell \propto R^{1.5}$, and the scatter in figure 5 barely precludes this law. More data are needed to improve the determination of scale size for radial distances within 0.2 AU.

There is evidence that the irregularities show spatial anisotropy. Early spaced-site observations by *Dennison* [1969] indicated an axial ratio of ~1.8:1 extended roughly radially from the sun. More recent measurements using larger baselines by *Symonds* [1970] show axial ratios of the same order for individual occasions, but with no significantly preferred direction. Certainly some anistropy is expected since angular spectrum measurements closer to the sun indicate filamentary irregularities significantly aligned in a radial direction [*Hewish and Wyndham*, 1963; *Harries et al.*, 1970].

VARIATION OF SCATTERING POWER WITH RADIAL DISTANCE

The relation between scintillation index m and radial distance in figure 3 shows that $m \propto R^{1.5 \pm 0.05}$ over distances from a few solar radii to 1 AU. Since the observations measure the integrated scattering along a line of sight, it is important to derive the corresponding radial variation of scattering power S of the medium itself.

Since $m^2 \propto \int S^2(z)dz$, where z is distance along a line of sight extending from the earth to infinity, the solution of this integral equation is required. Now m varies with R as a simple power law $m \propto R^{-1.5}$ and hence we obtain $S^2 \propto R^{-4.0}$, giving $S \propto R^{-2}$. For a plasma in which the electron density variations have an rms value ΔN and a correlation distance ℓ, we also have $S \propto \lambda \Delta N \ell^{1/2}$ [*Chandrasekhar,* 1952] $\Delta N \ell^{1/2} \propto R^{-2}$. The implication of this result will be discussed later.

The law $S \propto R^{-2}$ allows an estimate to be made of the relative importance of different portions of the line of sight in determining the parameters of the solar plasma by scintillation methods. Calculations using this law are illustrated in figure 6, which indicates the relative weight of each element along the line of sight. Because the

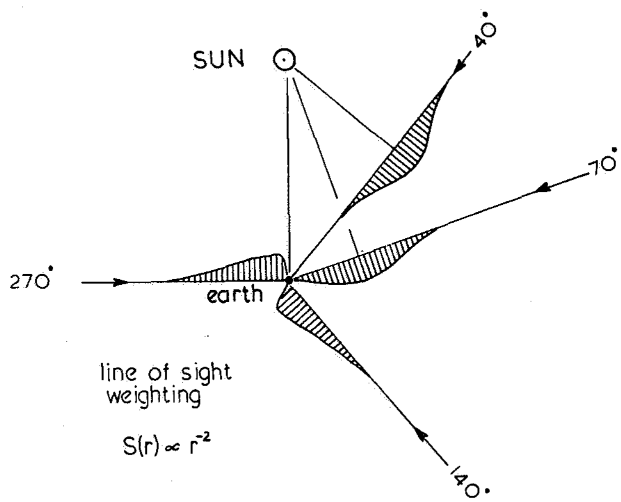

Figure 6. *Relative contribution of different elements of the line of sight to the total scintillation.*

radial variation of S is pronounced, lines of sight at elongations less than 90° effectively sample the solar plasma over a small region centered on the point of closest approach to the sun. For elongations exceeding 90°, on the other hand, the earth is imbedded in the irregularities that scatter most strongly and thus it is not possible to sample the solar plasma at distances greater than abount 1.5 AU.

THE SOLAR WIND VELOCITY

Observations of the solar wind using the spaced-site method have been made for a number of years [*Dennison and Hewish,* 1967; *Vitkevich and Valsov,* 1970]. No evidence has yet been obtained for a departure from strictly radial outflow. Recently, *Symonds* [1970] used three sites as shown in figure 7. Working on a number of radio sources to achieve a greater coverage of ecliptic latitude and solar distance, he obtained the measurements shown in figure 8. Detailed examination of the day-to-day variations of velocity for different radio sources suggests the presence of localized streams in which the velocity may differ significantly. The high velocity peak in late September on 3C287, for example, appears to be related to a class 3 solar flare that occurred on September 25.

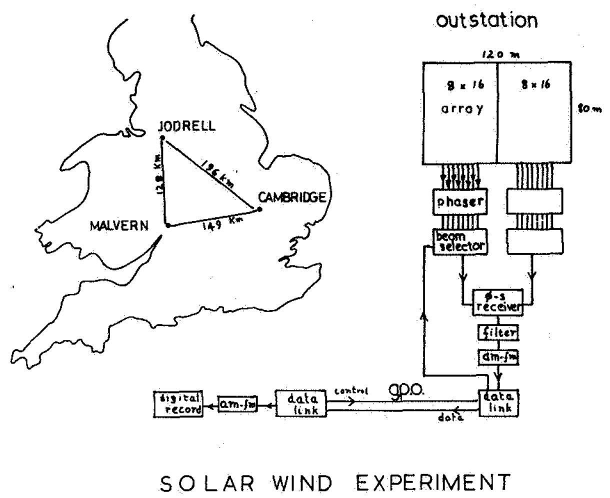

Figure 7. *Schematic diagram of the Cambridge solar wind experiment.*

Averaging the data shown in figure 8 to investigate the solar wind as a function of ecliptic latitude and radial distance reveals no significant departure from a uniform spherical outflow at constant velocity. The results are illustrated in figure 9. The velocity histogram for all the data is compared with space-probe data for the same observing period in figure 10. The histograms are generally similar, but our data give a mean velocity of 330 km/s as compared with 397 km/s for spacecraft measurements. Integration along the line of sight must give a mean value somewhat lower than the true velocity and part of the difference can arise in this way, but the weighting function shown in figure 6 scarcely can account for all the discrepancy. Most of our data refers to ecliptic latitude > 20°, which is not the region sampled by spacecraft, but figure 9 gives no evidence of systematic effects that might be relevant. It will be interesting to see whether more extensive scintillation data continue to show significantly lower velocities.

Some observations close to the sun, where the solar wind should be accelerating, have been made by *Ekers and Little* [1971] using two sites spaced by 16 km and

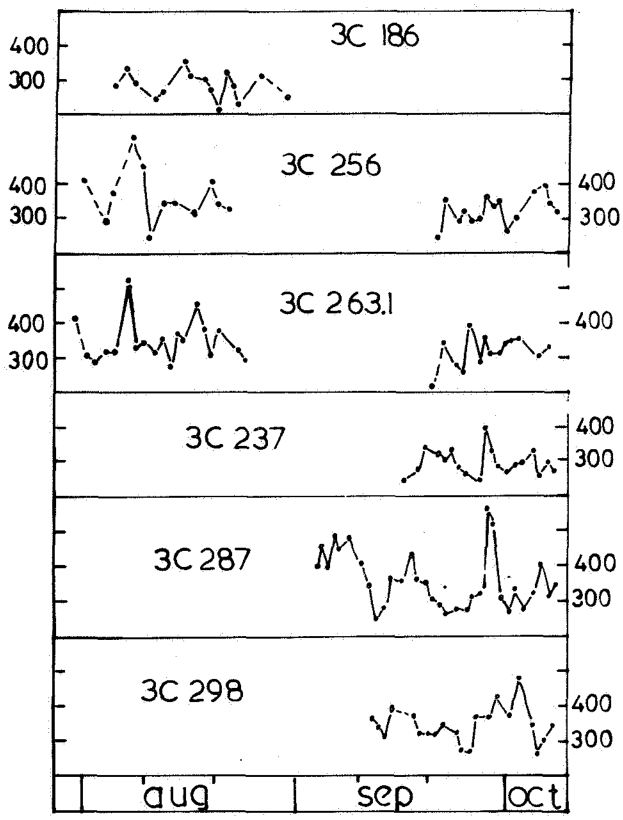

Figure 8. *Solar wind observations obtained from spaced-site observations of scintillation on a variety of sources.*

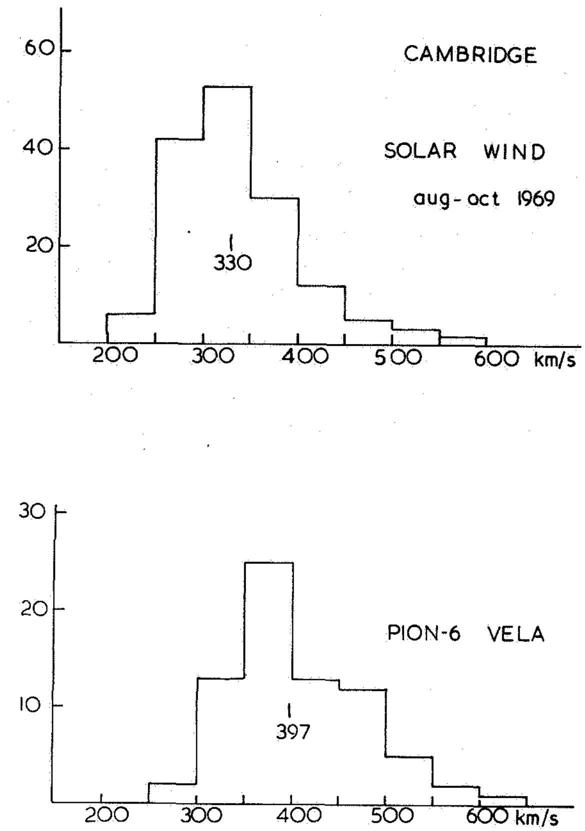

Figure 10. *Histogram of Cambridge solar wind data compared with space-probe measurements for the same period.*

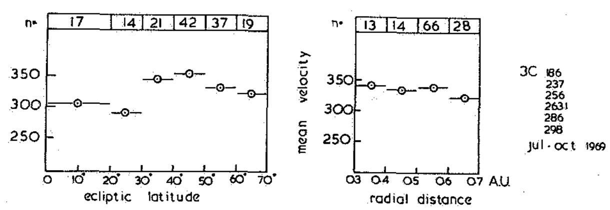

Figure 9. *Average solar wind velocity as a function of ecliptic latitude and distance from the sun. Horizontal bars and the numbers above denote the averaging interval and the number of independent measurements included.*

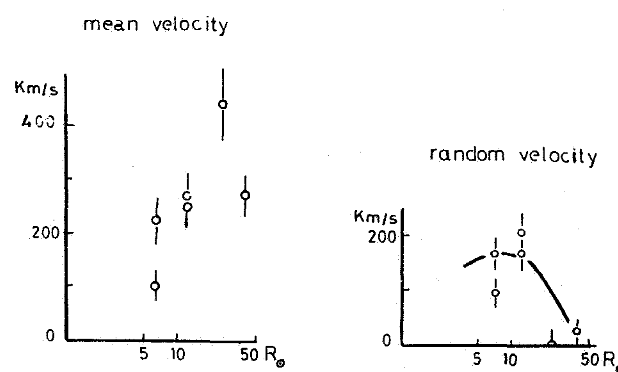

Figure 11. *Solar wind observations close to the sun obtained by Ekers and Little [1971].*

22 km. Their results are shown in figure 11, and the increase of mean velocity with distance agrees with a Parker model for $T \sim 1 \times 10^6$ °K. A significant random velocity component was also found at $10 R_\odot$, but this decreased rapidly with distance and was insignificant

beyond about $30\,R_{\odot}$ (0.14 AU). This finding is consistent with other observations at greater distances that have given no evidence for turbulent velocities greater than the small spreading due to variation of projected velocity across the line of sight.

EVIDENCE FOR COROTATING STRUCTURE

In view of the well-known sector structure of the magnetic field about the sun, it is natural to seek similar effects as revealed by plasma irregularities. Some observations of day-to-day variations of scintillation index have already been used to suggest the presence of corotating structure, but the data have not been sufficiently extended to establish the effect conclusively [*Burnell,* 1969; *Dennison and Wiseman,* 1968]. It seems probable that if such structure exists, its presence might be most readily detected by observing at elongations exceeding 90° where the line of sight runs almost parallel to the local spiral magnetic field, rather than perpendicular to it as is the case at small elongations. At 81.5 MHz it is possible to measure M at all solar elongations, and daily observations for two months on suitably disposed sources made by *Houminer* [1971] are shown in figure 12. Variations of m on a time scale of several days are clearly evident and there is a time shift between corresponding features observed on the two sources. This time shift is entirely consistent with a corotating structure, and there is evidence that features repeat with a 27-day period, but more extended data are needed for detailed analysis.

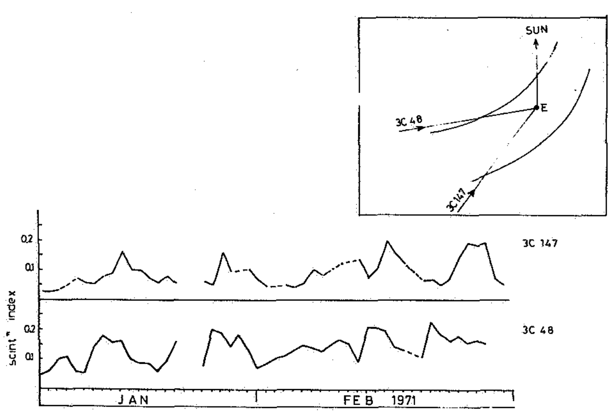

Figure 12. *Day-to-day variation of scintillation index on 3C 147 and 3C 48 showing time-displaced correlation indicating the presence of corotating structure.*

CONCLUSIONS

Results obtained from a study of the solar plasma by interplanetary scintillation techniques show that the solar wind appears to be independent of ecliptic latitude for radial distances of 0.4 to 1.0 AU. Small-scale irregularities of plasma density are a notable feature at all distances from a few solar radii to the earth. Both the scale and density modulation of the irregularities vary systematically with distance from the sun and their origin is so far unexplained.

It is difficult to account for the irregularities by density variations associated with "frozen-in" magnetic field irregularities which are imposed near the sun and then convected outward. Since the radial variation of B^2 is considerably faster than that of kinetic pressure NkT, this type of irregularity is progressively smoothed out with increasing distance from the sun. Some type of plasma instability that continually generates density fluctuations on a scale close to the proton gyroradius appears to be necessary. It is natural to inquire whether the increase of scale size with distance varies in the same way as the proton gyroradius. We have $r_p \propto B^{-1} T^{1/2}$ and putting $B \propto R^{-2}$, $T \propto R^{-1/2}$, gives $r_p \propto R^{1.75}$, which is somewhat steeper than the observed behavior.

With regard to the density modulation produced by the irregularities, the observations described earlier give $\Delta N \ell^{1/2} R^{-2}$. Also $R^{1.0}$ (see fig. 5) so that $\Delta N R^{-2.5}$. For a gaussian irregularity spectrum the observed scintillation index m corresponds to $\Delta N = 4.10^{-2}\ R^{-2.5}$ cm^{-3} where R is in AU [*Little,* 1971]. This value is about 1 percent of the mean density at 1 AU.

It is interesting to compare ΔN derived from scintillation with the value that might be expected from space-probe measurements of plasma-density power spectra. Taking the data of *Intriligator and Wolfe* [1970] and extrapolating their spectrum linearly to 1 Hz (appropriate to scintillation scales) gives ΔN about ten times larger than our value above. Evidently, the irregularity power spectrum must steepen considerably in the range 10^{-3} to 10^{-1} Hz before flattening out in the region of 1 Hz.

We now consider the upper limit that angular scattering data impose on the density in large-scale irregularities as mentioned earlier. It has already been shown [*Hewish and Symonds,* 1969] that the angular spectrum determined by interferometer measurements within 0.2 AU is consistent with the observed autocorrelation function of the diffraction pattern. Similar evidence may be drawn from the agreement of scale sizes determined by both methods in figure 5, where the uncertainty is within a factor of 2. It follows that the angular deviations produced by large-scale irregularities are less than, or of the same order as, those caused by the small-scale irregularities. Now the angular deviation produced by irregularities varies as scale size$^{-1/2}$; thus, irregularities of scale 50 km with $\Delta N \sim 2$, as derived from scattering and scintillation studies at 0.2 AU, would produce the same angular deviations as irregularities of scale 5×10^5 km with $\Delta N \sim 200$. The latter value is comparable to the mean electron density at 0.2 AU. It follows that the large-scale irregularities detected by space probes cannot significantly modify the radio-scattering properties of the interplanetary medium, which are dominated by the small-scale features.

It is evident that radio scattering and scintillation techniques using a variety of modes of observation and analysis yield very good agreement. Such measurements provide information that forms a valuable complement to that obtained by *in-situ* space observations.

REFERENCES

Chandrasekhar, S.: A Statistical Basis for the Theory of Stellar Scintillation. *Monthly Notices Roy. Astron. Soc.*, Vol. 112, 1952, p. 475.

Burnell, S. J.: Enhancements of Interplanetary Scintillation, Corotating Streams and Forbush Decreases. *Nature*, Vol. 224, 1969, pp. 356-357.

Cohen, M. H.; and Gundermann, E. J.; Hardebeck, H. E.; and Sharp, L. E.: Interplanetary Scintillations, 2. Observations. *Astrophys. J.*, Vol. 147, 1967, pp. 449-466.

Cohen, M. H.; and Gundermann, E.: Interplanetary Scintillations, 4. Observations Near the Sun. *Astrophys. J.*, Vol. 155, 1969, pp. 645-663.

Cronyn, W. M.: The Analysis of Radio Scattering and Space-Probe Observations of Small-Scale Structure in the interplanetary Medium. *Astrophys. J.*, Vol. 161, 1970, pp. 755-763.

Dennison, P. A.; and Hewish, A.: The Solar Wind Outside the Plane of the Ecliptic. *Nature*, Vol. 213, 1967, pp. 343-346.

Dennison, P. A.: Observation of Fine Structure in the Interplanetary Medium. *Planet. Space Sci.*, Vol. 17, 1969, pp. 189-195.

Dennison, P. A.; and Wiseman, M.: Preliminary Observations of the Effects of a Corotating Stream on Interplanetary Scintillation. *Proc. Astron. Soc. Australia*, Vol. 1, 1968, pp. 142-145.

Ekers, R. D.; and Little, L. T: The Motion of the Solar Wind Close to the Sun. *Astron. Astrophys.*, Vol. 10, 1971, pp. 310-316.

Harries, J. R.; Blesing, R. G.; and Dennison, P. A.; 80 MHz Observations of Coronal Broadening of the Crab Nebula. *Proc. Astron. Soc. Australia*, Vol. 1, 1970, p. 319-320.

Hewish, A.: The Spectrum of Plasma Irregularities in the Solar Wind. *Astrophys. J.*, Vol. 163, 1971, pp. 645-647.

Hewish, A.; and Wyndham, J. D.: The Solar Corona in Interplanetary Space. *Monthly Notices Roy. Astron. Soc.*, Vol. 126, 1963, pp. 469-487.

Hewish, A.; and Symonds, M. D.: Radio Investigation of the Solar Plasma. *Planet. Space Sci.*, Vol. 17, 1969, pp. 313-320.

Houminer, A.: Corotating Plasma Streams Revealed by Interplanetary Scintillation. *Nature*, Vol. 231, 1971, pp. 165-167.

Intriligator, D. S.; and Wolfe, J. A., Preliminary Power Spectra of the Interplanetary Plasma. *Astrophys. J.*, Vol. 162, 1970, pp. L187-190.

Jokipii, J. R.; and Hollweg, J. V.: Interplanetary Scintillation and the Structure of Solar Wind Fluctuations. *Astrophys. J.*, Vol. 160, 1970, pp. 745-753.

Little, L. T.: Small Scale Plasma Irregularities in the Interplanetary Medium. *Astron. Astrophys.* Vol. 10, 1971, pp. 301-305.

Little, L. T; and Hewish, A.: Interplanetary Scintillation and its Relation to the Angular Structure of Radio Sources. *Monthly Notices Roy. Astron. Soc.*, Vol. 134, 1966, pp. 221-237.

Lotova, N. A.; and Chashey, I. V.: On the Spectrum of the Small Scale Irregularities in the Interplanetary Plasma. Lebedev Institute preprint 11, 1971.

Lovelace, R. V. E.; Salpeter, E. E.; Sharp, L. E.; and Harris, D. E.; Analysis of Observations of Interplanetary Scintillations. *Astrophys. J.*, Vol. 159, 1970, pp. 1047-1055.

Readhead, A.: Interplanetary Scintillation of Radio Sources at Metric Wavelengths, II Theory. *Mon. Notic. Roy. Astron. Soc.*, 1971, In Press.

Salpeter, E. E.: Interplanetary Scintillations 1, Theory. *Astrophys. J.*, Vol. 147, 1967, pp. 433-448.

Symonds, M. D.: An Investigation of the Solar Wind Near Sunspot Maximum. 1970 Cambridge Ph.D dissertation.

Vitkevitch, V. V.; and Vlasov, V. I.: Solar Wind Observations. *Soviet Astron.* Vol. 13, 1970, p. 669.

DISCUSSION

J. C. Brandt I would point out that the latitude variation that one gets in solar wind velocity from the comets also implies absolutely no significant variation. We had a disagreement with you on the earlier data published, but I am happy to see now that has been resolved also.

K. H. Schatten I would like to comment on the random velocity that you observed. I noticed that it dropped down to near zero right past where the Alfvén point is. I was thinking perhaps it might be related to these coronal magnetic bottles that may exist close to the sun. We found a transport time that would provide a velocity of the order of 200 km/sec, and we suppose these bottles were then sort of held stationary by the magnetic tension and then maybe pulled back to the sun. Your random velocities there were of the same order as your velocities, suggesting that some things were stationary and some were moving around. We might get random velocities of that magnitude. So this is what you may be seeing close to the sun. Do you have any comment on that?

A. Hewish Can you accommodate that within the fact that you also have a mean derivative of the same order of magnitude? You see, at the place where the random motions were around 200 km/sec the mean solar wind was also around that value. Would that be appropriate for a magnetic bottle?

K. H. Schatten Well, we observed them to be on the order to 200 km/sec, but presumably they stopped meantime between the sun and perhaps 10 $R_{\odot}$ distance out.

A. Hewish I'm still a little bit bothered. Might not the solar plasma in the bottle be slowing down as you approach the limit of the bottle? But apparently we see acceleration smoothly on out. Although there is a random velocity component, there is a mean acceleration behind it all.

K. H. Schatten Well, there's a mean acceleration of the solar wind.

A. Hewish Yes, there is. Magnetic bottles will be okay under those conditions, will they? Okay.

W. M. Cronyn I have two questions. First of all with regard to pattern lifetimes in the random velocities, I notice that the size of your observing triangle seems to be approaching the limits imposed by the size of the island you are located on. Do you think that the correlations are still sufficiently high that it would be worthwhile to go to substantially longer base lines to see if possibly you could see any decay in the pattern lifetimes, either as a result of velocity smearing or actual decay in the medium? The second question is about the scintillation index. If the scintillation index for small or relatively small elongation angles is a parallel function of radial distance from the sun then it seems to me that by the time one gets out to observations of an elongation angle of 90° one is only integrating through half of the total effective path line relative to the inner measurements, and therefore one might expect that the scintillation index would be some roughly 30 percent lower than such an extrapolation would indicate. But these measurements at 1 AU were taken at a longer wavelength, and the fact that there didn't seem to be any 30 percent drop might indicate that there is a stronger than linear dependence on wavelength. Would you comment on that?

A. Hewish Well, let's take your first question first. With regard to the scale size of the pattern and whether it's worthwhile to go to longer base lines, I think we reached the limit, not only because we're going to hit the sea in all directions but also that we are running out of correlation in the pattern. When the wind is not blowing along the line of two sights the correlation that you get on the other one is usually poor. But, of course, if you wanted to determine the lifetime of the pattern it might well be worth going to a very long base line because you do know that the solar wind is strictly radial. This is something I didn't mention in my talk. We can't measure radial flow angles with great accuracy. But there is no evidence that they are other than within ±10° from the radial direction. So if you assume a strictly radial outflow from the sun you can arrange your source that you're looking at to have the pattern drifting in that direction and can do a transcontinental correlation if you feel like it.

With regard to the other question about the spherical integration and should the scintillation index drop as you come out to 90°, yes, of course it should drop. These effects are not very noticeable, but if you follow around the scintillation index from elongations of 0° to 180° you can perform the spherical integration and find out precisely what it should do. In fact curve fitting the observations to calculations of that sort gives an extremely good fit right around to 180°. So within the sampling range I showed on that slide [fig. 12], which is roughly speaking within 1.5 AU, there is no hint that we are other than following the same radial variation.

J. R. Jokipii I have just one comment on this last point, then I want to ask a question. I'll be talking in a little while about this fitting of the scintillation index versus elongation to the sun. I was going to comment on the earlier point. I think one of the very interesting points about the work by Ekers and Little is that we do see this turbulence down where the solar wind is apparently being driven by hydromagnetic waves. It might be worthwhile for some of the experts on this to see if they can get some quantitative estimates, and see whether this is actually telling us that there are indeed waves close to the sun which are driving the solar wind. This may be the interpretation of the Ekers and Little result.

D. S. Intriligator I just wanted to say that I thought that the histograms comparing the interplanetary scintillation velocity with the spacecraft measurements were really remarkably good. Since the two spacecraft data you lumped together were Pioneer 6 and Vela, which at that time were actually separated by more than 120° with respect to the sun, they were really measuring quite different sorts of plasma.

L. Davis I would like to ask a brief question about these fluctuating velocities you see near the sun. What is the rough frequency of these observations? What frequencies are you sensitive to? And supposing one assumes fluctuations near the sun perpendicular to the radial direction, will you see velocities of that kind at all or do you see mainly velocities parallel to the radial direction?

A. Hewish Well, one only sees the resultant component across the line of sight. But with regard to the actual spectrum, I can't put a number on this immediately, but I think they were able to take out to about 20 Hz in the power spectra. Does that answer your question?

L. Davis Can you go down to 1 Hz? Can you go down to 0.1 Hz?

A. Hewish Oh, yes, that part is easy. But not much below 0.1 Hz because you run into other difficulties.

J. V. Hollweg The order of magnitude of the velocities that you showed looked very much like the Alfvén speed at the appropriate distances. I think around 7 $R_\odot$ the Alfvén speed is something like 200 km/sec, and then at 50 $R_\odot$ it would be down to maybe 75 km/sec or so. So this might be consistent with hydromagnetic waves.

A. Hewish Would you expect them to accelerate?

J. V. Hollweg The local Alfvén velocity is decreasing as you go out.

E. N. Parker I was very much interested in your remark that you felt the high frequency oscillations, the 100- and 200-km variations, were something distinct from the large-scale fluctuations. Could you repeat the arguments that lead you to believe they are distinct? For instance, if you were to extrapolate the spacecraft power spectrum would it decrease at high wave number and leave your high frequency stuff as a spike, or what is the basis for the distinction?

A. Hewish Well, I'll come back to this. We shall be hearing more about trying to fit our data to spacecraft data, but my basic argument is as follows: In the presence of a spectrum that is a steep power of wave number, if you take the existing spacecraft data, which give a wave number dependence of about k^{-1} or slightly faster, then the medium itself is varying as k^{-3}. If you take a simple analysis, now, that means that in our two-dimensional work on the ground we would be dealing with a wave number spectrum in our diffraction pattern that is going as wave number to the –2, if you take the space data. Now, when you look at widely different wavelength variations you are really sampling the spectrum at points governed by the Fresnel cutoff, which varies as the square root of the wavelength $\sqrt{k}$ so that by observing over a wide range of wavelength if the scale size of your pattern is a function of the observing wavelength you are essentially sampling that wave number spectrum at different points. Now, I can find no evidence of a variation that would support a steep power law in that spectrum. I say from our scintillation data that the wave number spectra that we are observing on the ground is more or less flat. It certainly can't be sloping as much as k^{-1}, and k^{-2} is what you would get if you extrapolate spacecraft data. That is the basic argument, and I guess there will be discussion on this as we go along.

K. H. Schatten With regard to the comment concerning the Alfvén velocity being similar to your random velocity, the magnetic bottle is essentially a big Alfvén wave where the plasma pushes out the magnetic field and then it moves back and pushes the plasma in. So I think that would be consistent with the velocities being on the order of the Alfvén velocity as you move out.

J. V. Hollweg Would you describe the bottle, though, as a turbulent motion or as a systematic moving out and back, rather than a hopping back and forth?

K. H. Schatten I think it would be a systematic moving out and back, but I don't think we have enough evidence to say one way or the other.

A. Barnes One thing I don't quite clearly understand is whether the random velocities are essentially different in velocity measured at the same time but for different scale sizes, or whether they are measurements taken at different times and these represent temporal fluctuations. Or is it some mixture of these?

A. Hewish In the analysis of drifting diffraction patterns you can determine both a regular drift component of velocity and at the same time in the same analysis you can determine to what extent the diffraction pattern is changing as it moves. The rate at which the pattern changes as it moves is customarily defined in terms of a random velocity component, but really what it is saying is that the diffraction pattern is bubbling, boiling, as it moves along and that if the random velocity was comparable to the mean velocity, then by the time the pattern has moved one scale length it's a different pattern. So it's a measure of the non time-stationary property of the medium.

G. Newkirk Is it possible to combine these observations, which are essentially total power observations, with polarization measurements, or do the same thing for different states of polarization in order to see the fluctuations in the direction of the long axis of the singularities in space?

A. Hewish Well, for radio polarization, of course, you have to have a polarized source, and we are not looking really at polarized sources. Some quasars do indeed have a percentage of polarization. But what you want is a completely linearly polarized source to do work of this kind. But in any case I would not really expect any difference because we are dealing here with weak scattering and I think the sense of polarization is going to be quite irrelevant.

COMMENTS

W. A. Coles I would like to describe briefly the work being done on interplanetary scintillations at UC San Diego. We have made regular three-station observations at 74 MHz since June 1970. These data are not completely analyzed, in the sense that we haven't calibrated or normalized them to our satisfaction. The estimated drift velocity of the scintillation pattern can depend heavily on accurate normalization, so we are not prepared to present velocity measurements at this time.

Our data show exponential behavior in both power spectra and cross-power spectra and corresponding to this, the correlation functions are distinctly bell-shaped rather than gaussian as is often assumed. Our observing system consists of three array antennas located near San Diego (fig. 1) and connected to the laboratory at UCSD by commercial telephone lines. The three stations are separated by roughly 100 km.

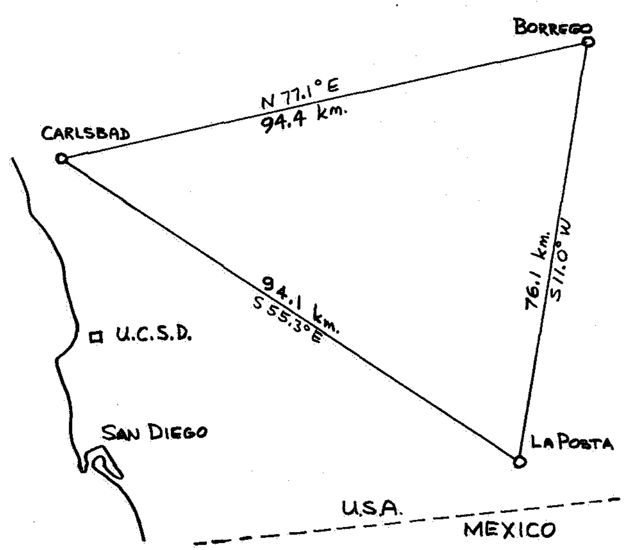

Figure 1. *Geometry of observation sites.*

The received data are digitized and processed by a Sigma 5 computer, which also controls the antennas and the receivers. Each antenna is a square phased array of 256 elements, 70 m on a side. The bean efficiency is about 60 percent corresponding to some 3,000 m^2 of effective area. The feed system, which will operate over bands of several megahertz, forms 512 discrete pencil beams, each 3.5° in diameter. Figure 2 shows one days's observations on 3C 144 as recorded. The receivers are switched from beam to beam as the source drifts through the pattern causing the obvious modulation on each record. Since the sites are not identical, the switching times are chosen to maximize the time during which all three sites have a strong enough signal to analyze.

The receiver design is straightforward except that special care has been taken to reduce intermodulation interference, because at 74 MHz one is fairly close to the television band. The receiver parameters, such as bandwidth and gain, are remotely controllable. Normally, the receivers operate in a total power mode, since the gain variation is much slower than the scintillation rate. For longer observations such as drift scan calibrations the radiometer mode is used. The telephone lines have limited dynamic range, so a controllable offset voltage has to be added to data before transmission. Telephone line data are filtered and read into the Sigma 5 for preliminary processing. The data are also

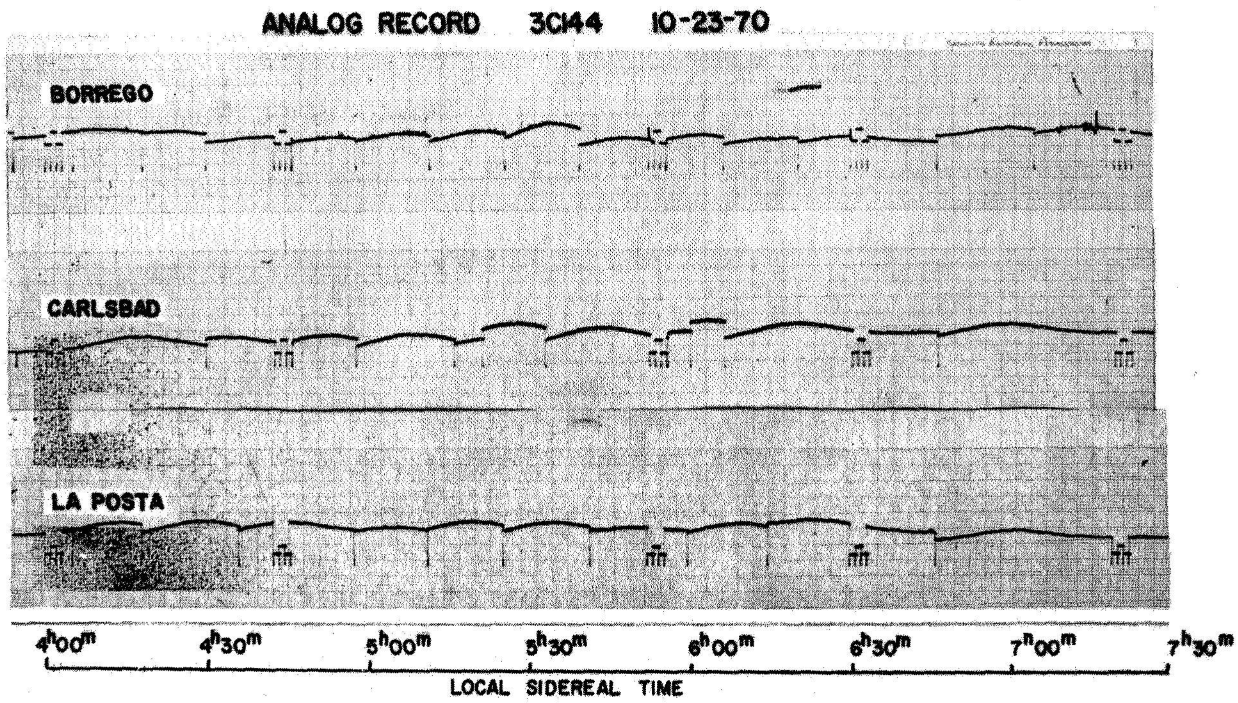

Figure 2. *3-½ hr drift scans taken from the three sites in figure 1.*

recorded on magnetic tape since frequent interference and limited reliability prohibit real-time data reduction without some backup storage. The computer operates on a time-sharing mode so that the observations and reductions may be done simultaneously.

The basic sensitivity limitation for scintillation observations is estimation error for strong sources. For example, the scintillation variance for 3C 144 and 3C 273 is much greater than the variance due to the noise. This being the case, about 20 min of data is required to obtain an adequate spectral estimate regardless of the source strength. For weaker sources the time required increases greatly since it goes as the fourth power of the source flux. Under optimal conditions for our observing system a 10-flux unit source would be considered strong. So that will give us a large number of sources to look at. At present two of the three antennas are about five times worse than that, primarily because of excessive losses in the feed system. This loss is being eliminated by the use of multiple preamplifiers distributed throughout the feed system.

The data analysis consists of calculations of power spectra, cross-power spectra, and their Fourier transforms, the covariance functions. Most of the effort required to produce a good set of results goes into such problems such as editing, interference rejection, timing, and calibration. Because the beams from the three sites do not all point exactly in the same direction the effective gain for cross-covariance differs from that for autocovariance, and this makes normalization more critical. After the spectra are computed they are fitted to a gaussian or an exponential shape and from the shape parameters, the pattern scale sizes, orientation, and velocity are determined. A typical rough power spectrum is shown in figure 3. The scintillation represents an enhancement at the low frequency end between 0 and 2 Hz. There was little ionospheric scintillation on this particular day.

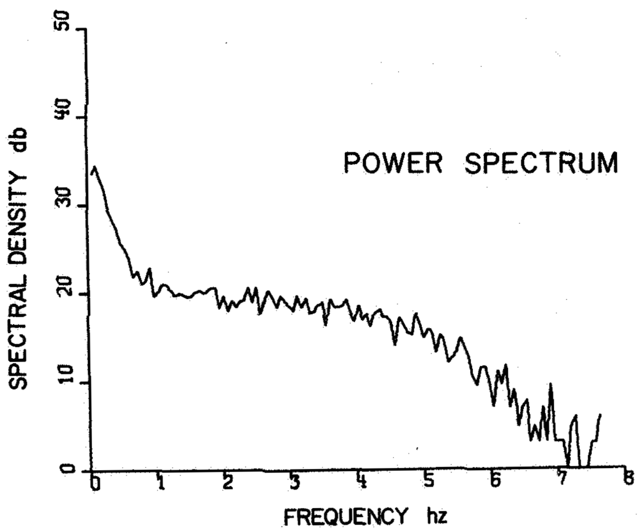

Figure 3. *A typical power spectral density.*

Figure 4 shows the cross-covariance functions for three-site observations. The cross-covariances have the same shape as the autocovariances, but they are delayed by an amount that is small compared to their width. Figure 5 shows a cross-power spectrum for two sites, which gives a good idea of the signal-to-noise ratio and the estimation errors

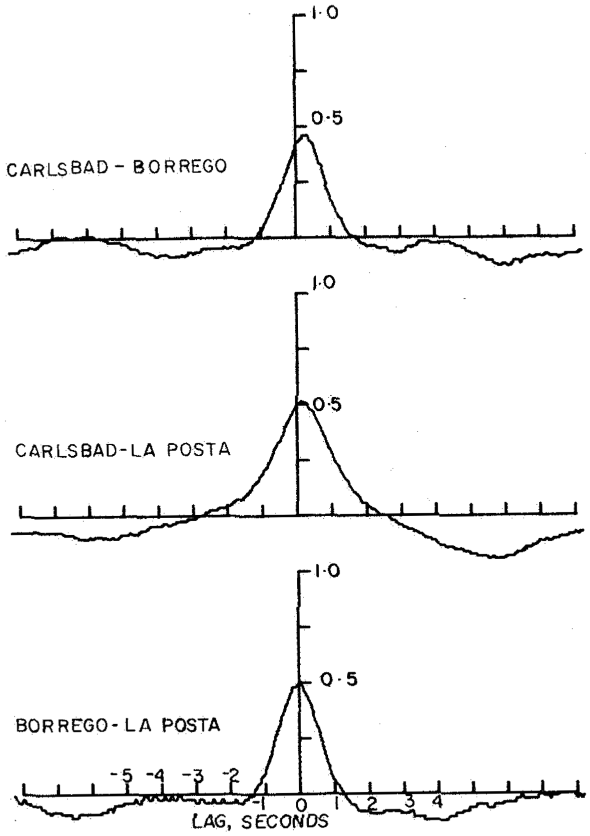

Figure 4. *Cross covariances for three site observations.*

involved. Considered as a measure of the amount of correlated power between the two sites, figure 5 shows that interference and system noise and telephone line effects are essentially negligible. There is a smooth, approximately exponential decay in the cross-power spectrum down to 0 at about 2 Hz.

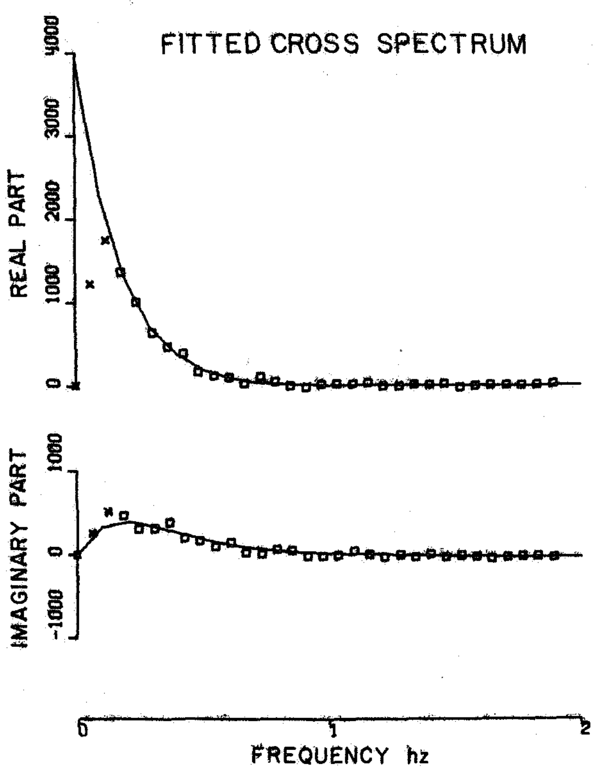

Figure 5. *A cross-power spectrum for two sites.*

Figure 6 shows the spectra for the three sites and the cross spectra between them, with a "best-fit" exponential drawn over the data. One can see that these "fitted" functions all agree within the estimation error, and that the spectra all match the exponential shape well.

Figure 7 shows spectra for three different days on source 3C114 shortly before it was occulted by the sun. The shape of the spectrum remains rather accurately exponential but the width of it increases as the elongation decreases.

The reason that we weren't prepared to present velocity measurements and the reason we are careful about normalization is that we are not presently satisfied that the intensity pattern is indeed "frozen" as was assumed in the work described by Dr. Hewish. If it were, the velocity would be the site separation divided by the displacement of the cross-correlation function. This "apparent" velocity could then be used to estimate a scale size by multiplying it with the width of the autocorrelation function. An independent measure of the scale size comes from the magnitudes of the cross-correlations between the sites at zero time lag. If these two don't agree, then a significant time change must have occurred in the pattern. Alternatively, one can assume that there *is* a time change, estimate the decay time, and see if it is indeed comparable with the drift time. But it is more difficult to get amplitudes than time lags in cross-correlation functions, and therefore it is better to estimate the scale size in these two different ways.

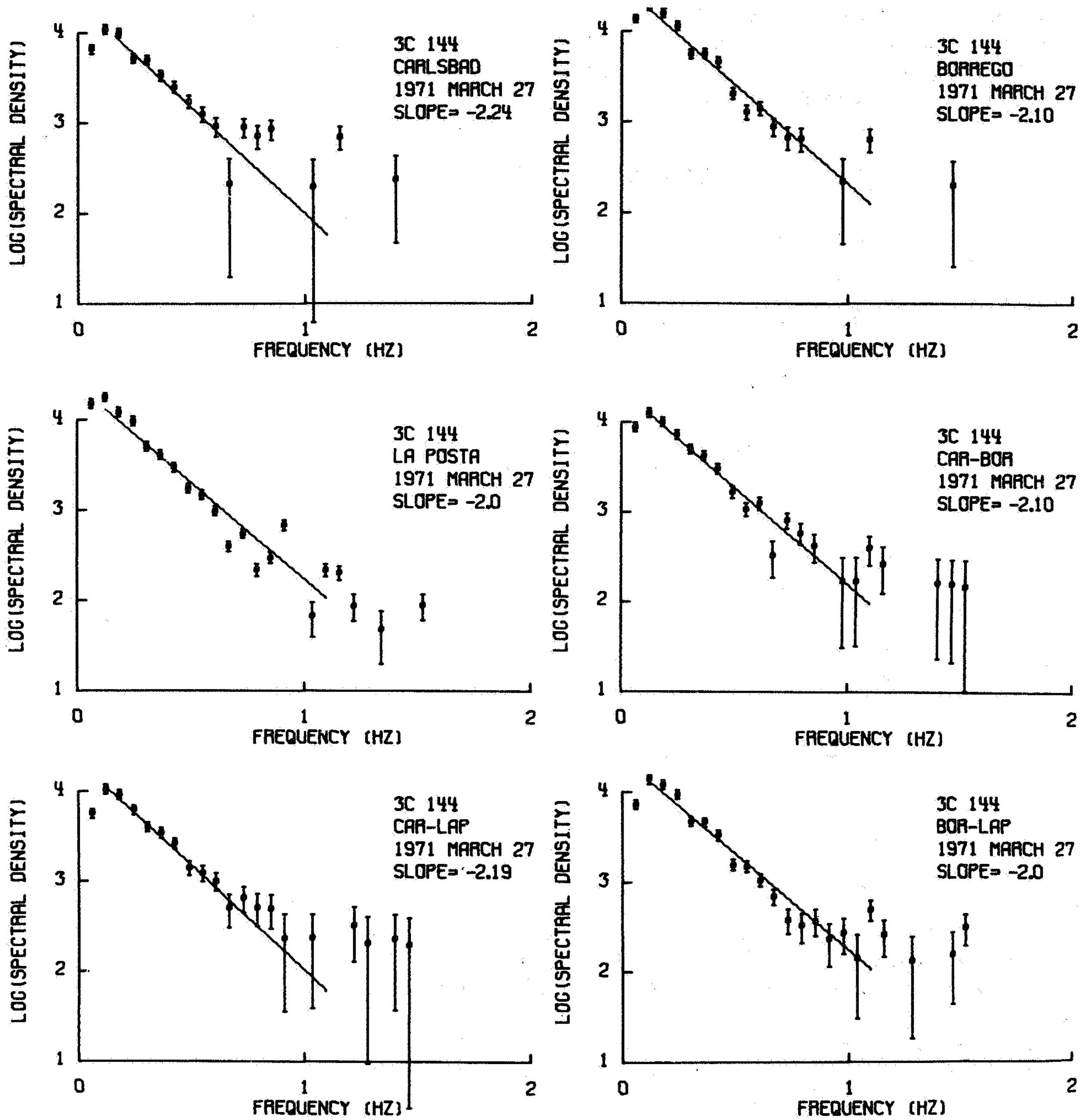

Figure 6. *Auto and cross spectra with exponential fits for the three sites of figure 1.*

Another point, which was mentioned by previous speakers, concerned the effect of integrating along the line of sight. Contributions from equal path lengths add into the final result as the square of the density variation. Hence one might expect high density regions to dominate the scintillation. Now it is known that high density tends to be correlated with low velocity, so one may tend to observe lower velocities on the average than would a space probe. Furthermore, the presence of several streams with different velocities will cause the pattern to appear to rearrange itself. However, if one then

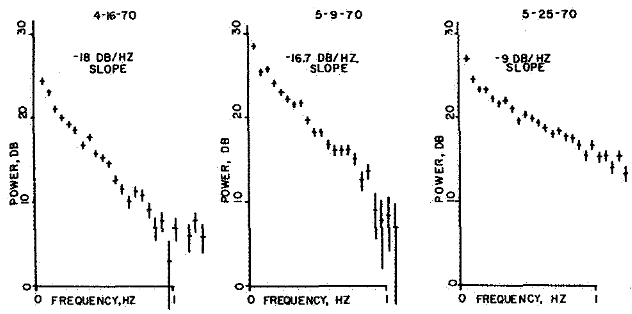

Figure 7. *Spectra taken over three different days of 3C 144 just prior to occulation by the sun.*

calculates the velocity assuming that this is a rearrangement it will tend to be biased below the average of the velocities along the line of sight.

DISCUSSION

A. Hewish From the cross correlograms you showed on the slide (fig. 4) there seemed to be a significant tendency for the correlation to become negative as you dropped away from the central maximum. If this is real, it would suggest some quasiperiodic nature in the irregularities. Do you regard these below-zero indications as significant?

W. A. Coles No, I am not sure they are statistically significant. Those raw correlations I presented in fact are zero mean, because the dc has to be subtracted off the power spectra analysis, anyhow. And we simply correct for that when we fit them to the curve.

E. C. Roelof If the scale sizes at 1 AU are coming out to be the order of a proton gyroradius, this from my simple-minded point of view would sort of suggest that this is not a fluid phenomenon, this is more a kinetic phenomenom. If that is the case then wouldn't one expect these patterns to be quite dynamic and nonstationary? And if so, then why does one seem to derive a well-ordered velocity comparable to the spacecraft velocities?

W. A. Coles Well, you're asking questions which I would prefer to be answered by a plasma physicist. We are simply saying what we observed and we would like somebody to explain it. Can you say why structures on a time scale of 200 km should not last for the required 0.6 sec or 0.3 sec for which we see them?