INTERPLANETARY SCINTILLATION

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Abstract. The use of interplanetary scintillations for probing otherwise inaccessible regions of the solar wind is reviewed. A comparison with space-craft observations in the ecliptic is used as a calibration for the scintillation observations. Recent observations at high latitudes and near the Sun are discussed from this viewpoint. A new analysis which uses both scintillation and angular scattering observations to estimate the electron density spectrum is introduced. The spectrum appears to have a high frequency 'cutoff' which varies slowly with solar distances and may also have a relatively flat region just below the cutoff frequency.

The phenomenon of interplanetary scintillation, IPS, was discovered over a decade ago by Hewish *et al.* (1964). It was quickly realized that these observations had the potential to probe the solar wind and to measure radio source structure. However, it has been only in the last few years that such measurements have been quantitatively verified, in the former case by comparison with in-situ observations and in the latter by comparison with long baseline interferometry. This review will concentrate on the application of IPS to the slowly varying solar wind from about $5R_\odot$ to $200R_\odot$.

IPS is the same phenomenon as optical twinkling scaled to radio wavelengths. In both cases a wave travelling through an inhomogeneous medium is scattered into an angular spectrum which causes a loss of resolution in an optical telescope or decorrelation in a radio interferometer. More prominent in the radio case is the intensity scintillation that results from interference between the plane waves that make up the angular spectrum. The scintillation index, M, is the ratio of the rms intensity to the mean. This index is reduced if the source is not perfectly coherent. If the index for a perfect source is $\ll 1$, then the scintillation is said to be weak. In this case, most of the power from the source passes through the medium with negligible scattering and the first Born approximation is valid.

It is useful to consider a uniform turbulent medium illuminated by a monochromatic plane wave. If one starts with weak scintillation ($M \ll 1$) and steadily increases the turbulence (say the rms electron density), then M will increase until it approaches unity. At this point the spatial spectrum of intensity will begin to widen. This is caused by interference between scattered plane waves which produces higher frequencies than interference between scattered and unscattered components. The scintillation index can exceed unity by 5% or more depending on the shape of the spectrum, but it must asymptotically approach unity. In fact, this overshoot has not been observed probably because the sources are not ideal. As the turbulence is increased still further, the index approaches unity and the individual components of the angular spectrum arrive at the observing plane with random phases. At this point

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the electric field is a normally distributed complex random variable and the problem is easily treated theoretically. Both finite bandwidth and finite source diameter have the effect of reducing the source coherence and thus reducing the intensity fluctuations. It is found both experimentally and in theory that the index, M, for a real source increases in weak scattering, reaches a peak where the index for an ideal source would saturate, then begins to decrease as the spatial intensity spectrum starts to widen. The theory of strong scintillation has been significantly improved recently, largely by groups studying laser propagation, and this work has now been applied to IPS (Prokhorov *et al.*, 1975; Rumsey, 1975; Marians, 1975). It should be noted that there are objections to using 'turbulence' as a description of the solar wind density fluctuations, but it is so convenient from the propagation theory viewpoint that it will be used in the remainder of this review.

In addition to angular scattering and intensity scintillation, one can observe related phenomena if the source is sufficiently coherent. For example, a pulsed plane wave will be scattered so that the signal received is broadened in time by the differential path delay. This is presently observable only in pulsars which are scattered in the interstellar medium. However, a monochromatic source will be received with a Doppler broadened spectrum if the scattering medium is moving. Spectral broadening has been observed from spacecraft beacons and may be useful as a means of probing very near the Sun (Goldstein, 1969).

The present state of scattering theory can be summarized as follows. One either works from or seeks to estimate the spatial spectrum of electron density, i.e. the 'turbulence spectrum'. The angular spectrum is related to the turbulence spectrum by a relatively simple closed form which can be inverted. Thus a measurement of the angular spectrum is a particularly powerful tool for estimating the turbulence spectrum. Doppler broadening is easily deduced from the angular spectrum if the medium moves uniformly with respect to the observer but an integration over wave components transverse to the pattern velocity is required. Hence a spectral broadening observation can be used to probe the turbulence spectrum if the velocity is uniform and the anisotropy of the angular spectrum is known. In weak scattering the spatial spectrum of intensity is linearly related to the turbulence spectrum. If the velocity and anisotropy are known, the temporal spectrum of intensity can be used to estimate the turbulence spectrum. In strong scattering the intensity spectrum is easily calculated but, in practice, it is completely dominated by source coherence. Thus the turbulence spectrum cannot be estimated, but information on source structure can be obtained. At the transition point where the index first saturates the intensity, statistics can only be computed numerically. Thus the problem is not easily inverted, although model calculations can be done.

It will be convient to discuss first those observations for $R > 60 R_\odot$. These can be done at meter wavelengths where telescopes are inexpensive and multiple telescopes can be dedicated to IPS. It is easy to see that a velocity can be deduced from three or more spaced observations of a drifting pattern (although in practice there are some difficulties). Furthermore, the velocity can be estimated regardless of the strength of scattering. If the scattering is weak, then the turbulence spectrum can also be estimated.

The first such work was done at Cambridge (Dennison and Hewish, 1967) and at Moscow (Vitkevitch and Vlasov, 1970). At present, observations are made at La Jolla (Armstrong and Coles, 1972) and Toyokawa (Watanabe and Kakinuma, 1972). The early work gave velocities in the same range as space-craft observations but efforts to make detailed comparisons failed (probably because the IPS data were not sufficiently regular). These attempts were renewed when, in 1973, suitable data were available (Coles *et al.*, 1975). This simplest possible comparison is shown in Figure 1. Here velocity observations from the ecliptic source 3C144 are compared with IMP 7 observations. The IMP 7 data are plotted at the time a stream observed at the earth would have been at the point where the IPS line-of-sight passes closest to the Sun.

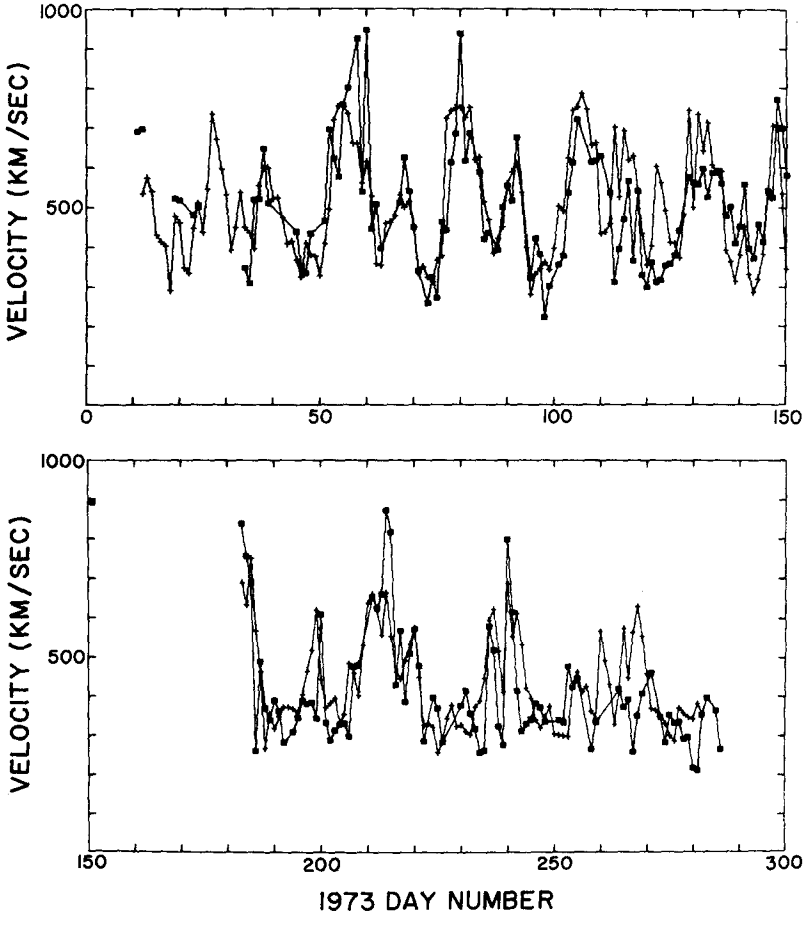

Fig. 1. Solar wind velocities measured by IPS using the ecliptic source 3C144 (■), and by the earth orbiter IMP-7 (+) shifted for direct comparison.

Although the time lag of +7 to −2 days allows ample time for decorrelation, there is remarkable agreement between these data. Fortunately, this was a period of stable stream structure so the comparison is easily made and the correlation can be regarded as an independent calibration of IPS data.

When the solar wind is particularly stable, as it was in 1973, one can use a more detailed comparison to examine the distribution of turbulence within a high-speed stream. The spacecraft data, observed near the Earth, are used to estimate the plasma parameters along the IPS line of sight by a simple idealized extrapolation. However, these data do not include the high frequency fluctuations in electron density which cause IPS. Consequently, some assumption about the distribution of these fluctuations must be made. The IPS pattern is then calculated and the normal analysis applied to the calculated pattern. The result is then compared with the observations. It has been found that lower frequency fluctuations are proportional to the mean density (Sullivan *et al.*, 1975). In particular, they show the same pronounced peak just before a stream and they are significantly reduced in the high-speed region itself. However, if it is assumed that the high frequency fluctuations have a similar distribution, then a poor match with observations is found. The agreement is much better if it is assumed that the high frequency components follows the mean density but remains high in the body of the stream. Of course, this means that the shape of the spectrum must change systematically during a stream passage (Coles *et al.*, 1975). It should be possible to quantify this result more precisely now that a great deal of simultaneous IPS and spacecraft data are available.

The IPS observations can be used to examine stream morphology at high latitudes using the ecliptic spacecraft data as a form of calibration. One can then attempt a correlation with coronal features using the extra dimension of latitude. The Japanese group (Watanabe *et al.*, 1974), have approached this question statistically by correlating IPS velocities with the brightness of the EUV corona in Fe XV. Here an inverse correlation was found which is consistent with the hypothesis that high speed streams originate in cool coronal holes. The La Jolla group has used a point-by-point comparison of streams observed at various latitudes and, by mapping the data back to the corona, attempted direct identification with features such as coronal holes. These results are also consistent with the coronal hole hypothesis (Rickett *et al.*, 1976). However, if there is a one-to-one correspondence between holes and streams, some streams must diverge 30° from their holes and some holes must produce streams of only one day in width.

The IPS observations have proved to be remarkably sensitive to long lived structures because the line-of-sight integration tends to smooth out rapid variations. The velocity and its autocovariance are shown in Figure 2 for several 6 month periods in 1972 and 1973. Figure 2(a) shows virtually no recurring features in the latter half of 1972 whereas Figure 2(b) shows a very stable structure in the ecliptic a few months later. At this time there was also a stable structure at southern latitudes as shown in Figure 2(c). It has not been possible as yet to show differential rotation or any simple latitude dependent pattern from these data, (Armstrong, 1975).

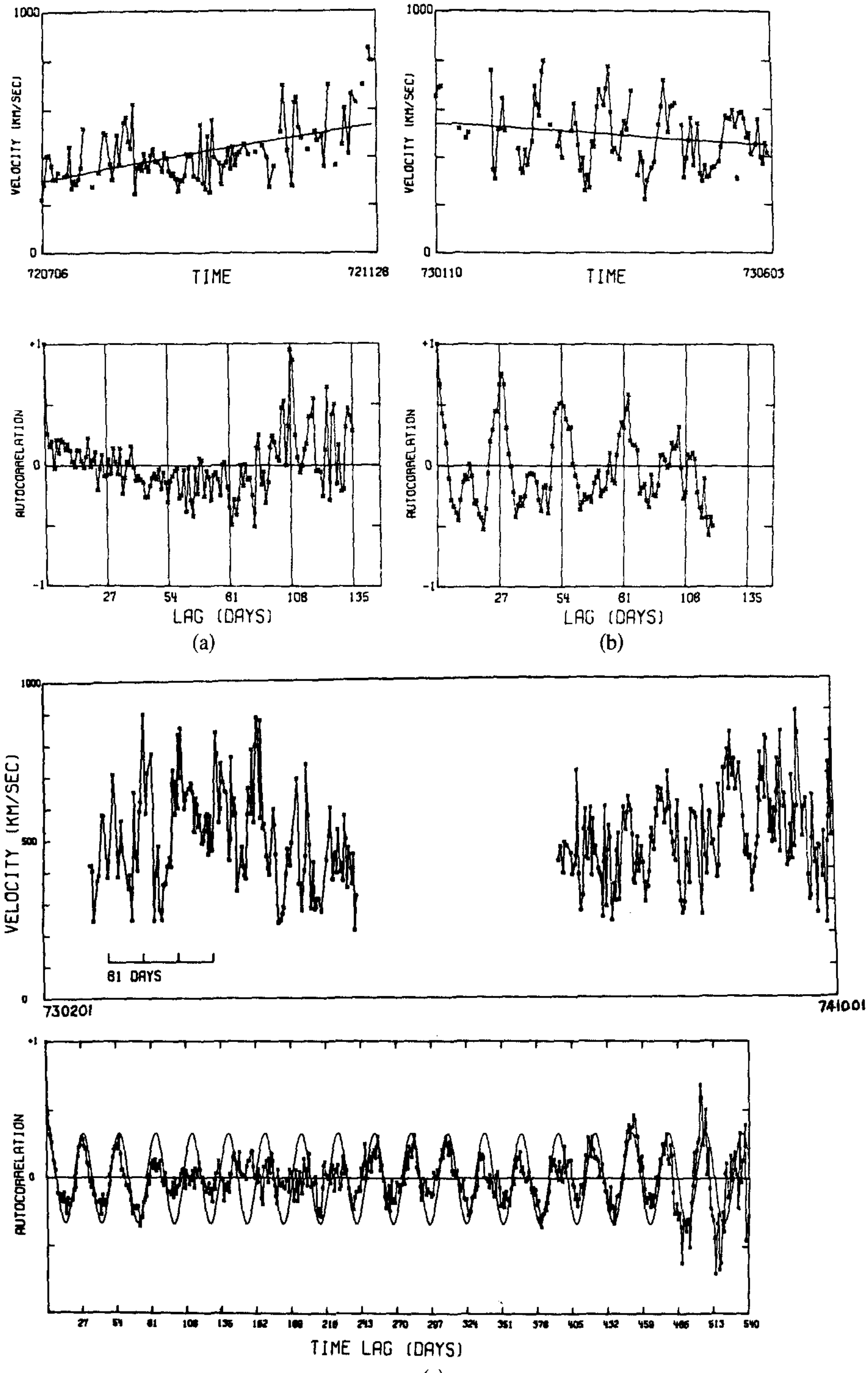

Fig. 2. The IPS midpoint velocity and the autocorrelation of velocity for the ecliptic source 3C144 (a), (b) and for the southern source 3C161 (c).

Similar analyses for space-craft velocities show lower recurrence probabilities, in general, unless the data are smoothed over 4 or 5 days. This confirms that the IPS data smooths out the shorter period transients. One can also use the density or scintillation index. These data show much less correlation at 27 days lag. Clearly the interaction region can evolve more rapidly than its driving force, the high-speed stream.

Since it is clear that IPS measures real velocities and there is now a 5-year data base, it is tempting to estimate the distance and latitude dependence of the mean velocities. The average speed for 4 ecliptic sources is given versus distance in Figure 3(a). It should be remembered that this is a mean over a set with a daily rms of

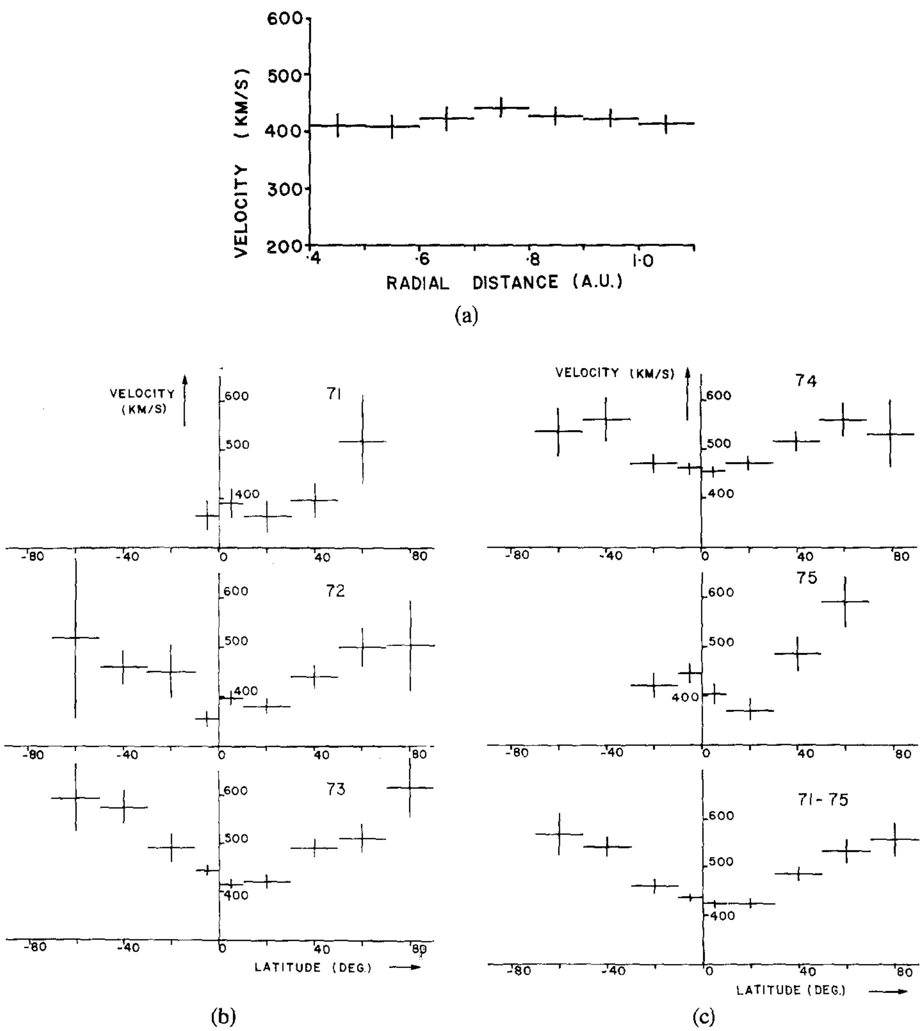

Fig. 3. (a) Average velocity versus solar distance for 4 ecliptic IPS sources 1971–75; (b) & (c) Average velocity versus latitude for 4 high latitude IPS sources.

100 km sec^{-1}. There is no evident variation with distance. Thus sources which reach higher latitudes as they approach the Sun will show only latitude variations. Figures 3(b,c) show yearly averages of these data and a 5-year mean taken from Coles and Rickett (1975). Nominally, these results disagree both with comet tail observations, which show no latitude effect (Brandt *et al.*, 1975), and spacecraft data, which show a much larger effect (Rhodes and Smith, 1975). However, the comet results are averaged over many solar cycles, whereas the spacecraft results involve only a few solar rotations (and a very small latitude range). The IPS data are consistent with the presence of two persistent high-speed regions diametrically opposite on the Sun but centered on latitudes of 60°. These can produce a very large apparent latitude gradient particularly over a short interval. It is by no means clear that a mean latitude gradient exists, or is a useful concept, over longer intervals; but it is clear that there has been a tendency from 1972 to 1975 for streams to be centered at mid-latitudes rather than in the ecliptic (Sime, 1976).

The multi-antenna observations have been used to estimate the electron density spectrum for frequencies above 3×10^{-4} km^{-1}. Here the velocity is used to relate the temporal and spatial fluctuations. The inversion process requires weak scattering and an isotropic spectrum. It is easy to satisfy the former, but the isotropic assumption will not always be accurate. However, the observations themselves can be used to bound the anistropy. The axial ratio of the IPS pattern is seldom found to exceed 1.3 (Kaufman, 1976). Two extreme examples of reconstructed spectra are shown in Figure 4. Somewhat more than half of the observed spectra are different from the straight power-law of Figure 4(a) with 95% confidence (Harmon, 1975). There are limited space-craft data from OGO-5 which cover the IPS frequency range (Unti *et*

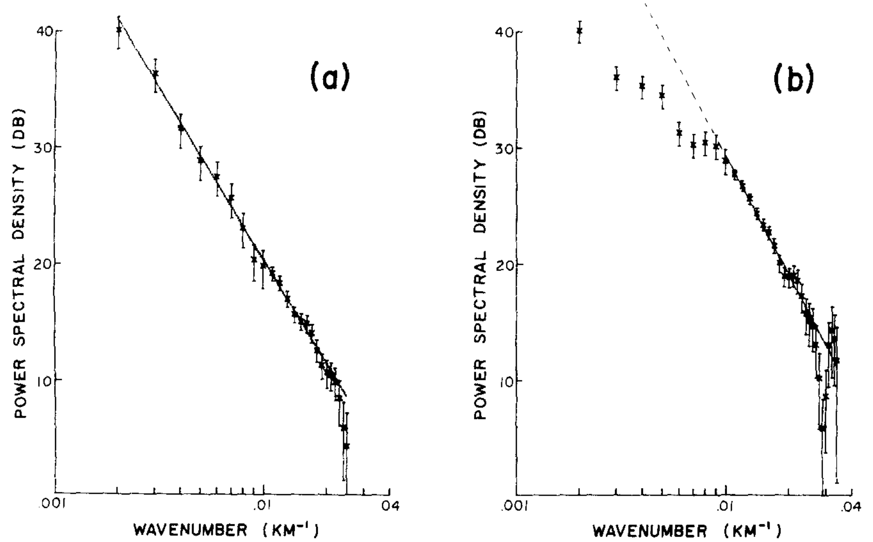

Fig. 4. Examples of estimated electron density spatial spectra. (a) for 3C144 on August 18, 1972. The line of best fit has slope −2.95. (b) for 3C144 on March 15, 1973. The line has slope −3.42.

al., 1974; Neugebauer, 1976). For comparison with these data (and lower frequency spacecraft data), the IPS estimated spectra have been modeled as a broken power-law, normalized to a yearly average 'interstream' level at 1 AU, and converted to a space-craft reference frame. The result is curve (a) in Figure 5. During the passage of an interaction region, the level can increase 10 dB as shown by curve (b). This comparison can only be made in a mean sense as the spacecraft data are very limited. One can see that the agreement both in level and in shape is quite satisfactory.

Observations of the solar wind for $R < 60R_{\odot}$ are much more difficult. Here there are no in-situ observations for comparison. The solar wind changes much more dramatically in this range than outside of it. Furthermore, IPS must be done at cm-wavelengths where telescope time is limited and multiple observations are rare.

There have been a few multi-station observations at the Goldstone site in California (Ekers and Little, 1971; Scott, 1975). The complete set is shown in Figure

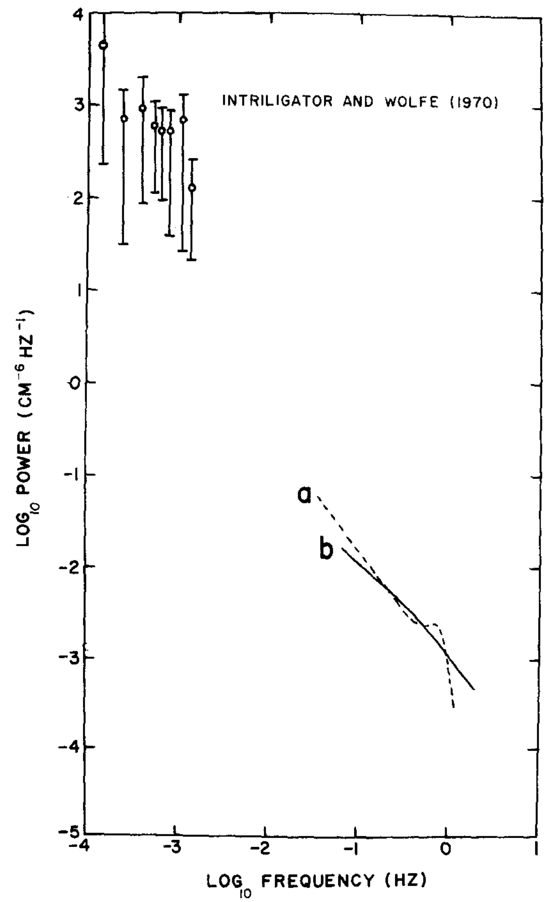

Fig. 5. Comparison of IPS and spacecraft spectra. Curve (a) is from Neugebauer (1975); (b) is the equivalent spectra calculated from IPS observations; the points in the upper left are from Intriligator and Wolfe (1970).

6. As one expects of the solar wind the daily variations are by far the dominant effect. It is interesting that during the total of perhaps two weeks of observations at high latitudes the velocity is higher and the turbulence level is lower than one would have observed at low latitudes. When V is available one can also estimate the spectrum.

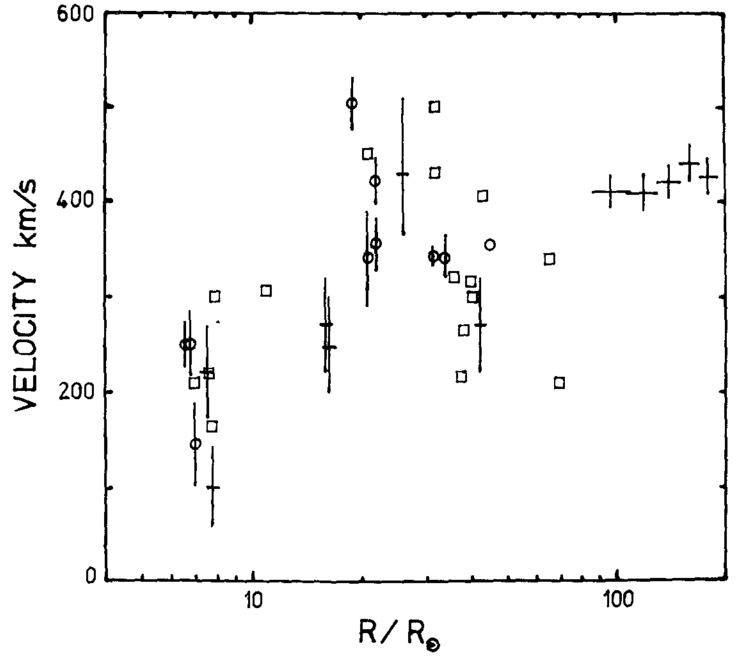

Fig. 6. Velocities from IPS observations. The points outside of $80R_\odot$ are from Figure 3(a). The two antenna observations of Ekers and Little (1971) are shown by (+). Three antenna observations of Scott (1975) are shown by (⏀). The vertical bars indicate the error estimates. The points marked (□) are two antenna observations of Scott (1975) for which error estimates are not reliable.

However in view of the limited data only simple model fitting procedures have been tried. Figure 7 shows the results of such a fit at $43R_\odot$ on a day when there was little velocity variation. The solid lines drawn over the spectrum in Figure 7 are computed from a simple model of a spherically diverging solar wind with radial velocity 400 km s^{-1} and a power law spatial spectrum with an exponent of 3.3. The effect of source structure is included.

Much of the available data in this region is given only as a scintillation index or an apparent angular diameter. In order to use these observations it is much more convenient to use the structure function than the spatial spectrum. For any plasma, the refractive index change n, is related to the electron density, Ne, by $n \approx f_\rho^2/2f^2$ provided $f \gg f_\rho$. Here $f_\rho^2 = 81\ Ne$ (S.I.). If the refractive index is a function of position $\bar{r} = (x, y, z)$, then the phase change for a pàth along the z axis, $\theta(\bar{t}) = k\int dz\, n(\bar{r})$, is a function of the transverse coordinate $\bar{t} = (x, y)$ and is proportional to λ. The phase structure function is $D_\theta(\bar{s}) = \langle(\theta(\bar{t}) - \theta(\bar{t} + \bar{s}))^2\rangle$ where $\bar{s}$ is also in the (x, y) plane.

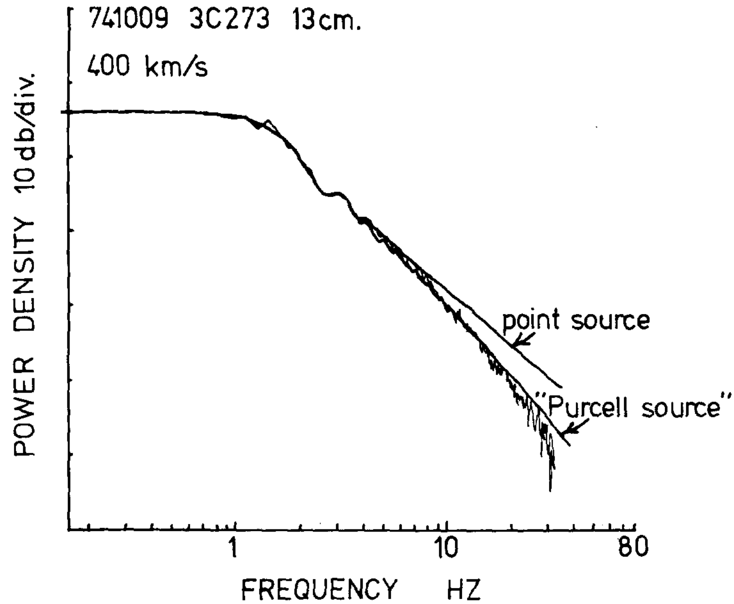

Fig. 7. A measured IPS spectrum at 13 cm from Scott (1975). The source was 3C273 on October 9, 1974. The solid lines are computed assuming a velocity of 400 km s^{-1}, as measured from three antenna IPS, and a simple power-law spectrum of exponent -3.3. The effect of source diameter is shown.

Clearly $D_\theta(\bar{s})$ is proportional to λ^2. If the spatial spectrum $\Phi(\bar{q}, \bar{r})$ is a slowly varying function of $\bar{r}$, then the structure function for a thin layer of thickness $\mathrm{d}z$ is $D_{\theta'}(\bar{s}, z) = \mathrm{d}z\, 4\pi k^2 \int \mathrm{d}^2\bar{q}(1-\cos(\bar{q}\cdot\bar{s}))\Phi(\bar{q}, z\,|\,q_z = 0)$, where possible variation of $\Phi(\bar{q}, \bar{r})$ in the (x, y) plane is ignored. The total phase structure function for a finite path length, L, is just $D_\theta(\bar{s}) = \int_0^L \mathrm{d}z\, D_{\theta'}(\bar{s}, z)$. If the spectrum does not change its shape with z so $\Phi(\bar{q}, z) = \Phi(q)A(z)$, then $D_\theta(\bar{s}) = D_{\theta'}(\bar{s})\int_0^L \mathrm{d}zA(z)$. If the covariance function for phase, $R_\theta(\bar{s}) = \langle\theta(\bar{t})\theta(\bar{t}+\bar{s})\rangle$ exists, then $D_\theta(\bar{s}) = 2(R_\theta(0) - R_\theta(\bar{s}))$. The structure function has the advantage that it exists for spectra such as $\Phi(\bar{q}) \simeq q^{-\alpha}$ which have no Fourier transforms in the interesting range $3<\alpha<4$. In fact, $D_{\theta'}(\bar{s}) \simeq s^{\alpha-2}$ for such spectra and the propagation equations for the angular spectrum and intensity spectrum can be solved. This is true because the low frequencies which cause $\Phi(\bar{q})$ to diverge do not dominate either angular or intensity spectra although they do affect other field statistics. The Fourier transform of the angular spectrum is the field covariance, i.e. the complex visibility for an interferometer $V(\bar{s}) = \langle E^*(\bar{t})E(\bar{t}+\bar{s})\rangle = \exp[D_\theta(\bar{s})/2]$. Thus one can estimate $D_\theta(\bar{s})$ directly from interferometer observations. Furthermore, $D_\theta(\bar{s})$ scales exactly as λ^2 regardless of the shape of the spectrum so it is easily scaled to some reference frequency for comparison. All data presented here have been scaled to 74 MHz. The structure function is also directly related to the scintillation index as computed from the first Born approximation, M_B, even when this is not a good approximation to the actual index (if $M_B > 1$). If the scattering is confined to a thin layer at distance z_0 from the observer and the spectrum is a power law, then $M_B^2 = C(\alpha)D_\theta\sqrt{(z_0/k)}$ where $C(\alpha)$ is a constant of order unity. This is easily extended to thick media, but the simpler form is sufficient for solar wind observations. Thus if M_B can be estimated from observations, an estimate of $D_\theta\sqrt{(z_0/k)}$ can be made.

In order to use the scintillation index data, one must have a systematic way of removing the effects of source structure. This can be done by using observations of index as a function of distance. It is found that at a fixed frequency, most sources undergo a peak, as shown in Figure 8, which occurs at the same distance regardless of the source. This is explained in the theoretical work of Rumsey (1975) and Marians (1975). This peak occurs at the distance for which $M_B^2 = C(\alpha)D_\theta\sqrt{(z_0/k)} = 2$. Thus to establish D_θ from the index observations, one can fit the data with one of a family of curves for different sources and the resulting estimate will not depend on the actual source structure. Examples of this procedure are shown in Figure 8. Once this has been done one can use the strong as well as the weak scintillation data, at least to the extent that the data fit the model curves. This technique is discussed thoroughly by Armstrong (1975). The principal advantages of the method are that it is insensitive to the actual shape of the spectrum and the source structure.

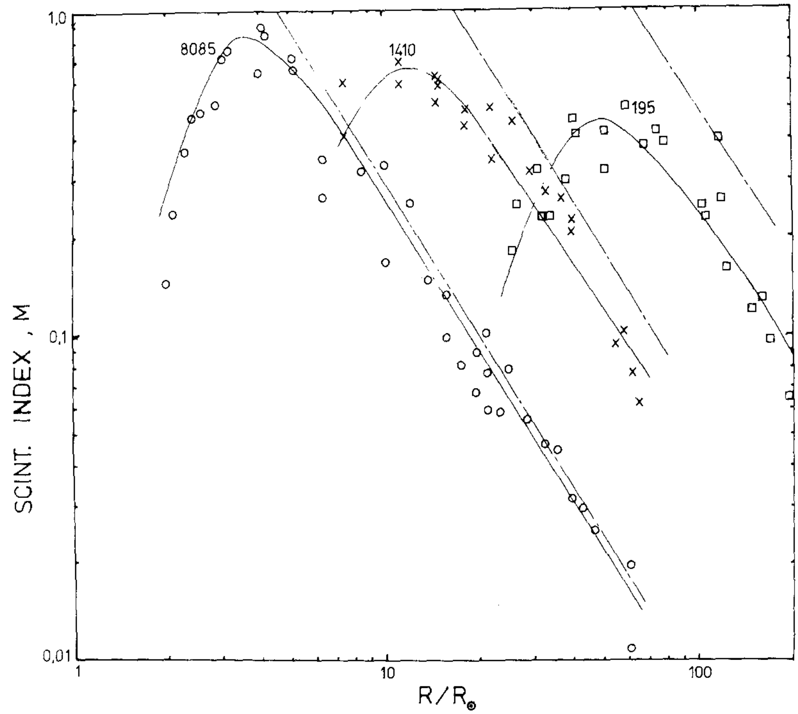

Fig. 8. Scintillation indices versus distance for two sources at three different frequencies. The solid lines are from the model of Marians (1975). The broken lines are the associated values of M_B. The sources used are 3C279 at 8085 MHz and 1410 MHz in 1974; and 3C138 at 195 MHz (Cohen and Gundermann, 1969). The structure of the source is different at each frequency.

All published IPS and angular scattering data are incorporated in Figure 9 (and many unpublished observations). A series of distances differing by factors of 2 was chosen to maximize the number of points which could be obtained for a given R. There are very little data for $R < 7R_\odot$. For $R \geqslant 15R_\odot$, the data are restricted to sources near the ecliptic but this was not possible at $7R_\odot$. The data at 5, 15, and 30 fit single straight line of slope 1.5, but the data at 60 or 120 $R_\odot$ does not. Thus the IPS data at 60 and 120 were used to define a slope of +0.6. It is found that the scintillation index measured at a single frequency and in weak scattering follows a power law variation with distance $M(R) \simeq R^{-1.55\pm0.05}$ (Bourgois, 1969). Similar results were obtained by Armstrong (1975) using both weak and strong scintillations. This implies that $D_\theta(s) \simeq R^{-3.1\pm0.1}$, so the model was scaled inwards to $7R_\odot$ in this way. It is clear that a slope steeper than 0.6 is needed to match $D_\theta(s)$ for small s. This is consistent with the notion that there is an inner scale in the spatial spectrum of electron density; a spectrum with such a cutoff has an associated structure function which behaves as s^2 for small s. Therefore, lines of slope +2 were drawn through

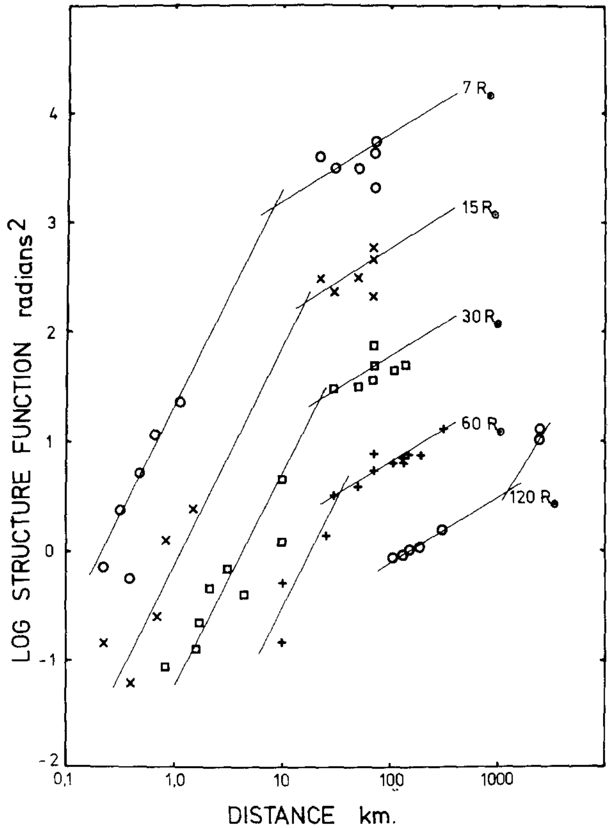

Fig. 9. Estimates of the structure function $D(s)$, versus separation S for different solar elongations. The symbols indicate the elongation at which the observation was taken. All of the points on lines of slope +2 are from angular scattering observations. All others are from IPS except the two at separation of 2500 km which are from VLBI (Vandenburg, 1974).

the small scale data (which are from angular scattering observations). The data match such a slope well and the resulting intersection defines a cutoff scale. This cutoff is found to vary approximately as $\sqrt{R}$, which is much slower than, for example, the proton Larmor radius. The Larmor radius has been used to normalize spectra previously (Neugebauer, 1976) but this result casts doubt on the validity of such normalization. A little more information can be derived from VLBI data at $120R_\odot$. These seem to indicate that the structure function steepens again at large scales. The net result is entirely compatible with an electron density spectrum which falls steeply from 10^{-6} to $10^{-3}\,\text{km}^{-1}$, flattens out substantially, then falls again beyond $10^{-1}\,\text{km}^{-1}$.

There is one final piece in the spectral puzzle. This is the spectral data from Nancay (Bourgois, private communication, 1976). Spectra for a number of very compact sources have been taken at 21 cm. From these data the widths of the spectra 10 dB and 20 db below the peak value have been estimated. These are shown in Figure 10. Thus it is possible to estimate the spectral exponent from F_{10} and F_{20} alone. It is clear

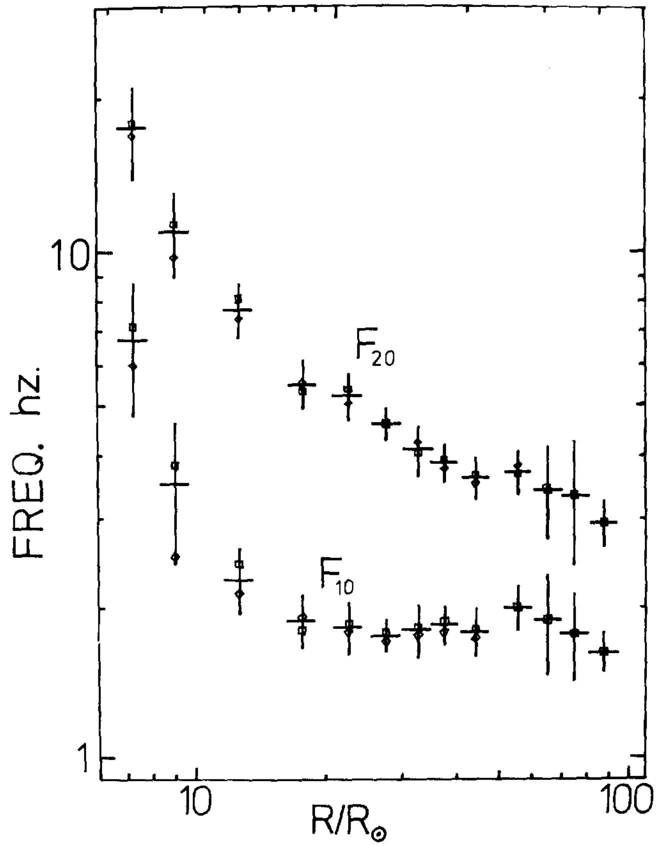

Fig. 10. Spectral widths 10 dB and 20 dB below the maximum taken at 12 cm. The sources are a group of very compact sources selected by Gabriel Bourgois (private communication). The symbols □ and ◇ represent averages of data with signal to noise ratios 20–30 dB and over 30 dB respectively.

that the exponent is flatter at small elongations reaching a slope of −3 at about $30R_{\odot}$. This is consistent with an outer frequency which moves to higher frequencies as elongation decreases. If one uses a speed of 300 km sec^{-1} this is consistent with a scale break point of 10 to 20 km at $30R_{\odot}$. Clearly these spectral width data are consistent with the composite structure function which appears in Figure 9. These data can be used to refine the spectral model considerably. Observations of scintillation and doppler broadening of space-craft beacons will also improve the coverage near the Sun. Thus one can expect substantial progress in the near future.

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