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STRUCTURE AND DYNAMICS OF THE SOLAR WIND

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Abstract

Due to high temperature and very small temperature gradient with height, the solar corona is not in hydrostatic equilibrium but is continuously expanding into the inter-planetary space. The expanding coronal plasma is known as the solar wind and its characteristics are studied by 'insitu' and indirect methods. In this paper, we shall highlight capabilities of indirect measurements carried out by the interplanetary scintillation (IPS) technique. A new method for estimation of the solar wind speed using IPS observations of a single station is described. The advantage of this method which is based on refractive scattering approach over the earlier procedures is discussed. It seems that this method can be satisfactorily used in almost all situations of scattering in the solar wind. The determination of solar wind speed requires theoretical simulation of the observed spectra in most cases, but some of the observations which happen to satisfy the diffractive scattering limits are easier to deal with the new method.

1. Introduction

The solar wind is that part of the solar plasma (corona) which is not confined by the solar magnetic field and therefore escapes into the interplanetary space. The escaping plasma is heated by sources of solar origin (presumably low frequency waves) to $(0.5-4)\times10^6$ °K within a distance less than (1/20) $R_\odot$ from the surface of the Sun. The literature on the solar wind has grown considerably in the last two decades and there are several exhaustive reviews (c.f. Parker 1965; Axford 1968; Hewish 1972; Ananthakrishnan and Kaufmann, 1982). Experimental investigations of the solar wind plasma can be broadly divided into two categories: (1) the direct or 'insitu' measurements and (2) indirect measurements. The most commonly used indirect method is the technique of Interplanetary scintillation (IPS). The unique advantage of IPS technique is its capability of providing information about the solar wind plasma in and out of the ecliptic. As of today, 'insitu' measurements are in the ecliptic plane and only after 1986-87 ISPM (International Solar Polar Mission), called 'Ulysses' will provide for the first time 'insitu' measurements out of the ecliptic plane.

The solar wind plasma contains turbulent inhomogeneities, some of which could originate close to the sun while others probably develop by dynamical plasma processes in the interplanetary medium. Radio waves originating from a distant, subarc second angular diameter celestial source, get phase distorted on traversing through this inhomogeneous medium. These phase distortions develop into intensity fluctuations when the wave has propagated a distance equal to the Fresnel distance $Z_F = a^2/\lambda$. For this reason very large scale irregularities do not produce IPS. The intensity pattern on the ground propagates at the velocity V of the solar wind itself, and flux density fluctuation rate is $\sim a/V$. The temporal study of these intensity fluctuations is usual in the following:

(1) to estimate the density deviation and the scale sizes of the plasma inhomogeneities in the medium (Cohen et al. 1967).

(2) to estimate the solar wind velocity by comparing the spatial fluctuations of the pattern as it drifts (Dennison and Heish, 1967).

(3) to estimate the angular structure of radio sources in the range 0.01 - 1 arc sec (Little and Hewish, 1966).

The scope of the paper limits us to discuss only the first two of the above aspects. In the following sections we shall discuss the currently available methods for reduction of IPS data and the important results, pertaining to the dynamics, size, spectra and density of the solar wind.

2. Dynamics of the Solar Wind

The first measurements of the solar wind outside the ecliptic plane was carried out by Dennison and Hewish (1967). They used three observing sites with separation of 85, 60 and 52 kms. On the vertices of a triangle. Later, this configuration was used at observatories in Australia, U.S.A. and Japan, but only two of these observations (in U.S.A. and Japan) currently carry out synoptic solar wind measurements. Similar obsevations with a larger collecting area will soon start in India (Alurkar et al. 1982). A large number of statistical methods have been developed to determine various parameters of the plasma irregularities e.g. apparent and true velocity, random velocity, size and axial ratio of the irregularities. Most of these calculations are based on the correlation analysis of the simultaneous records at three sites. Solar wind velocity obtained using the ecliptic source 3C 144 during 1973 are shown in Fig.1. Also shown here are the observation of the IMP 7 spacecraft velocities mapped to the point of closest approach. The agreement between these two is quite good. In particular, the IPS observations have detected all the large scale velocity structures, present in the solar wind. the velocity on an average is 400 km/sec, but it could varyfrom 250 km/sec to 1000 km/sec.

Parker's model shows that the rate of expansion and outward flow starts from completely negligible value. The velocity increases steadily outward, reaching its full interplanetary value of several hundred kms/sec beyond many solar radii. There are very limited observations close to the Sun where the acceleration of the plasma is expected. Some observations close to the Sun have been made by Ekers and Little (1971). These are shown in Fig.2a (velocity as function of distance) and Fig.2b (random velocity as function of distance). The solar wind velocity increases radially outward and seems to attain a value 400 kms/sec. An important result of these observations (Fig.2b) is the random component of velocity which persists out to about 30 $R_{\odot}$ just where the acceleration of the interplanetary plasma is decreasing. It is plausible to suppose that the turbulent energy is responsible for random velocity and it is eventually dissipated either in heating the plasma or increasing its velocity., At greater distances there have been no evidence for significant random velocity of the solar wind. The irregularities are elongated along a radial direction from the Sun. The axial ratio provides information about the elongation, but there are very few measurements.

There is one more very interesting aspect of solar plasma dynamics, (Rickett and Coles 1982) i.e. the solar cycle variations of solar wind. Generally polar regions of the Sun are found to be the sources of long-lived fast streams through most of the solar cycle. This is evident from the average wind speed plots against the solar latitude both to the north and south (Fig.3). Here fast polar streams have the higher average speeds at high latitudes. Through out declining solar activity (1972-75) fast polar streams are a persistent feature. For solar maximum (1978-81) these polar fast streams are not seen. This pattern matches that of the polar coronal holes which persists through most of the cycle except during solar maximum.

3. Scale Size of the Plasma Irregularities

From the temporal diffraction pattern, it is possible to make deductions about the size and shape of the irregularities in the solar wind. The common assumption has been that the irregularities are frozen i.e. they do not rearrange themselves as they are convected along. The observed scale of the diffraction pattern is representative of the irregularities themselves, the variation of scale size with radial distance is shown in Fig.2. Here all data is combined including the measurements of both the correlation distance of the diffraction at three sites and temporal spectra at a single site. For the latter a solar wind of 350 km/sec was assumed. This shows that the scale size of the irregularities in the solar wind increases with radial distance. The irregularity size deduced from IPS data corresponds to a real plasma scale length, rather than some limit imposed by the diffraction theory. It can also be emphasized here that this is the size of irregularities that produces the scintillation. It, of course do not preclude the existence of large-scale density structure. The large scale irregularities contribute to (i) the angular spectrum and (ii) the refraction or bending of the wave front reported recently by Alurkar et al. (1985). Here it may be mentioned that the irregularities causing scintillation and those causing bending of the wavefront need not be present in same medium. Because of this, Alurkar et al. (1985) have considered the possibility of large scale plasma irregularity both in the ionosphere and interplanetary medium. But most likely, the latter is more plausible. These observations of Alurkar et al. (1985) are shown in Fig.5. The top panel shows the fringe pattern of the telescope and bottom panel shows the typical records of 3CV 298. The detailed analysis indicates that this kind of angular displacement is caused by plasma irregularities as large as 5×10^5 kms, if these are in the interplanetary medium. A comparison of Fig.5, b and c reveals that if one of these is caused by the plasma irregularity having density greater than the ambient the other one will be caused by a rarer irregularity. Thus it seems that the large scale plasma irregularity could have the density greater or smaller than the ambient medium. Since the effect has solar elongation dependence, we believe that these are in the solar wind. It is nevertheless plausible to explain these effects in terms of ionospheric plasma irregularities.

4. Spectrum of the Irregularities

Temporal power spectrum of the interplanetary scintillation, caused by the plasma irregularities in the solar wind, undoubtedly varies with the distance from the Sun, but the observations indicate that this is not a function of the observing frequency. Fig.6 shows width of the scintillation temporal spectrum and proves that width is not a function of observing frequency, but decreases with the radial distance. Most of the observed IPS spectra are Gaussian except at distances within 0.2 AU (Cohen et al. 1967). Lovelace et al. 91970) reported that under suitable conditions it may be possible to derive the speed of the solar wind. In this approach, it is suggested that the characteristics of the diffractive pattern of the interplanetary medium may be identified as sequence of minima in the Bessel spectrum or power spectrum. The first minima γ_F can be related to the transverse solar wind V as follows:

$$V = \gamma_F / \sqrt{\pi \lambda z} \tag{1}$$

where λ is the radio wavelength and Z is the distance between the observer and the irregularities. This approach requires that (1) the scintillation level is sufficiently low and (2) the spectra should have high resolution and low noise.

Recently Booker and MajidiAhi (1981) distinguished between refractive and diffractive scattering depending on whether the irregularities are greater or less than the Fresnel scale $F = (\lambda Z / 2\pi)^{1/2}$. When diffractive scattering dominates and spectral index is less than 4, the intensity spectrum maximizes in the vicinity of Fresnel scale. The lower oll-off may then be taken to occur at the angular spatial frequency F^{-1} and the upper oll-off at $(1/2F)^{-1}$. For spectral index 4 (which is the case for interplanetary scintilla-tion), whether refractive or diffractive scattering dominates, the lower frquency roll-ff in the intensity spectrum occurs at the angular spatial frequency

$$\mathrm{Max}\,[(F,P)]^{-1} \tag{2}$$

while the upper roll-off occurs at the angular spatial frequency.

$$\mathrm{Min}[(1/2F,L)]^{-1} \tag{3}$$

Here P and L are peak and Focal scales respectively. These are defined for spectral index = 3 as follows:

$$P = \frac{F^2}{L_0}\,[(\Delta\phi)^2\ \ell n\ (\Delta\phi)^2]^{1/2} \tag{4}$$

and

$$L = \frac{L}{[(\Delta\phi)^2\ \ell n(\Delta\phi)^2]^{1/2}} \tag{5}$$

With the IPS spectra recorded with the Thaltej radio telescope, this concept of upper roll-off was used to calculate the solar wind velocities given in Table 1. In the last column of Table some near simultaneous values of solar wind velocity from the three station data of Japan are given. The agreement between the two estimates seems to be satisfactory. Further assessment of this approach requires simultaneous three station and spectral calculations, which we plan to undertake in the near future.

5. Plasma Density in the Solar Wind

It has been shown that the scintillation measure can be used to calculate the plasma density along the line of sight to a source (Gapper et al. 1982). Hewish et al. (1985) defined a parameter called enhancement factor. This factor specifies day-to-day perturbations in plasma density about the mean and is determined as follows:

$$g = \frac{\Delta S}{\overline{\Delta S}} \tag{6}$$

where ΔS is the rms flux density integrated over the band 0.1-3.0 Hz during an interval of about 30-50 sec. at the transit and $\overline{\Delta S}$ is the average value for a give source at a particular elongation. Figure 7 shows the strong correlation between plasma density (N) and g. Here N is the insitu plasma density and the results satisfy a relation

$$g = \frac{(N)^{0.52\pm0.05}}{(9)} \tag{7}$$

where N is in el/c.c. Thus with this parameter, g and daily monitoring of several sources in different directions it is possible to track the dynamics and evolution of solar coronal plasma. Using the observations of 900 radio sources, Hewish et al. (1985) have investigated the shape and movement of large-scale interplanetary transients associated with shock disturbances at 1 AU. The work carried out at different frequencies can easily be combined to provide a more complete and clear picture of the phenomenon. This is quite evident from Fig.8 (from Little and Hewish (1966), to which we have added some recent observations at 103 MHz *). Here the product of scintillation index m radio frequency is plotted. The results indicate that scintillation index $m \propto 1.0 \pm 0.05$. In general the scintillation index decreases with the radial distances from the Sun.

Table 1

Values of the solar wind velocity calculated by spectral method at Thaltej and three station method at Japan

Thaltej Observations					Japan Observations (3 stations)	
Source	Date	ν_F Hz	Z_{au}	V kms/sec	$V_{km/s}$	
3C 48	8.4.85	0.35	0.89	393	305 ± 36	
	11.4.85	0.30	0.90	339	382-	
	12.4.85	0.35	0.91	396	-	
	17.4.85	0.30	0.92	343	-	
	20.4.85	0.37	0.93	424	428 ± 31	
	24.4.85	0.33	0.93	379	477-	
3C 459	10.4.85	0.35	0.88	390	378 ± 66	326-
	12.4.85	0.30	0.86	331	457 ± 28	330-
	15.4.85	0.40	0.83	434	349 ± 20	267 ± 5
	20.4.85	0.25	0.79	263	374 ± 24	354 ± 23
CTA 21	12.4.85	0.25	0.87	277	330-	
	15.4.85	0.30	0.89	337	267 ± 5	

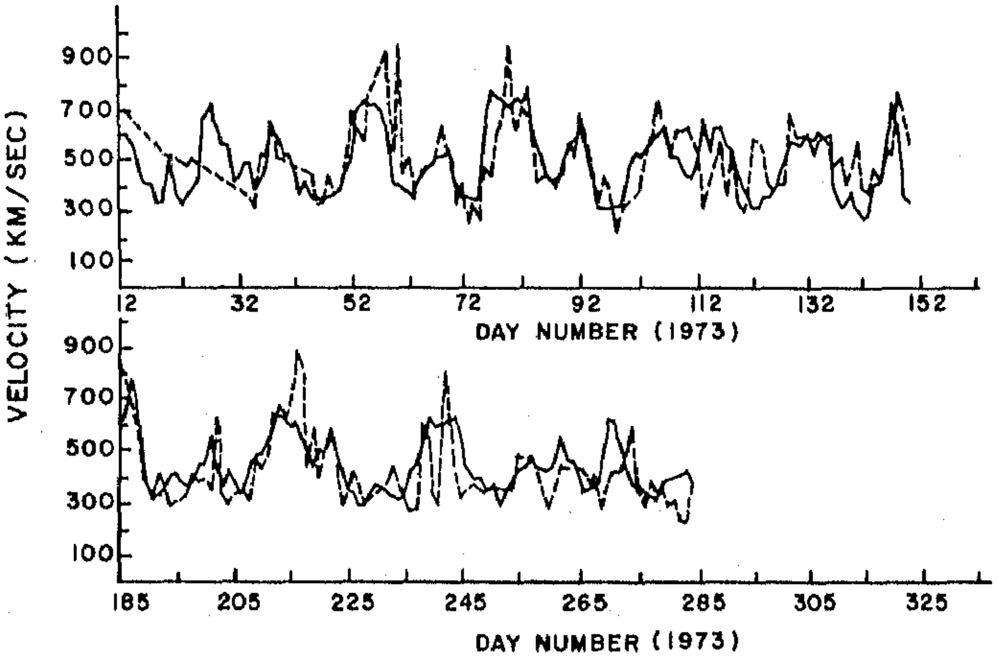

Fig.1. Comparison between the IPS velocity observed with 3C 144 and the IMP 7.

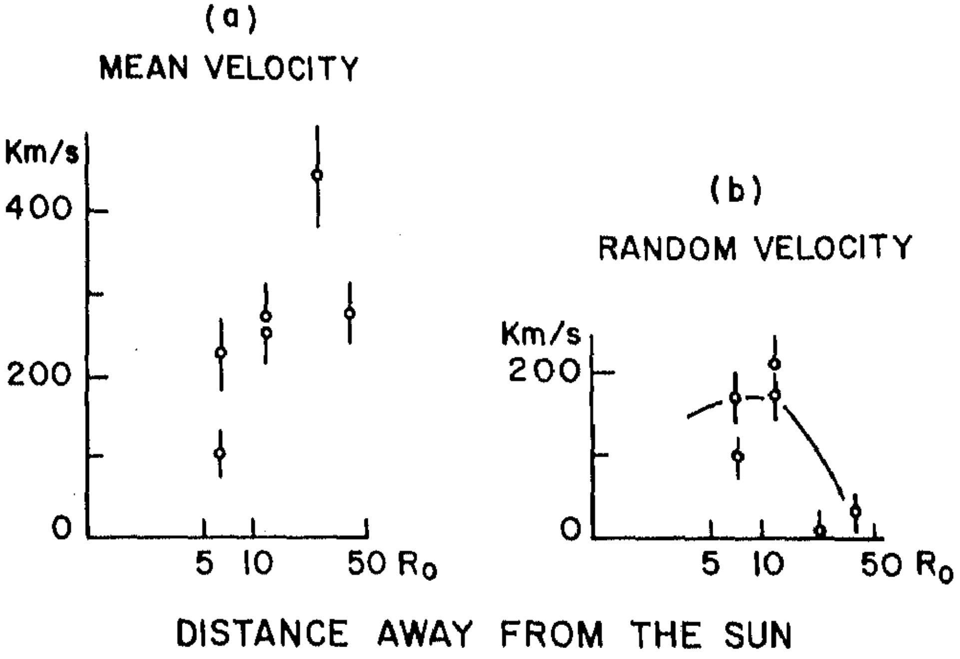

Fig.2. (a) Solar wind velocity (apparent) as a function of radial distance away from the Sun. (b) Random component of the solar wind velocity as a function of radial distance away from the Sun.

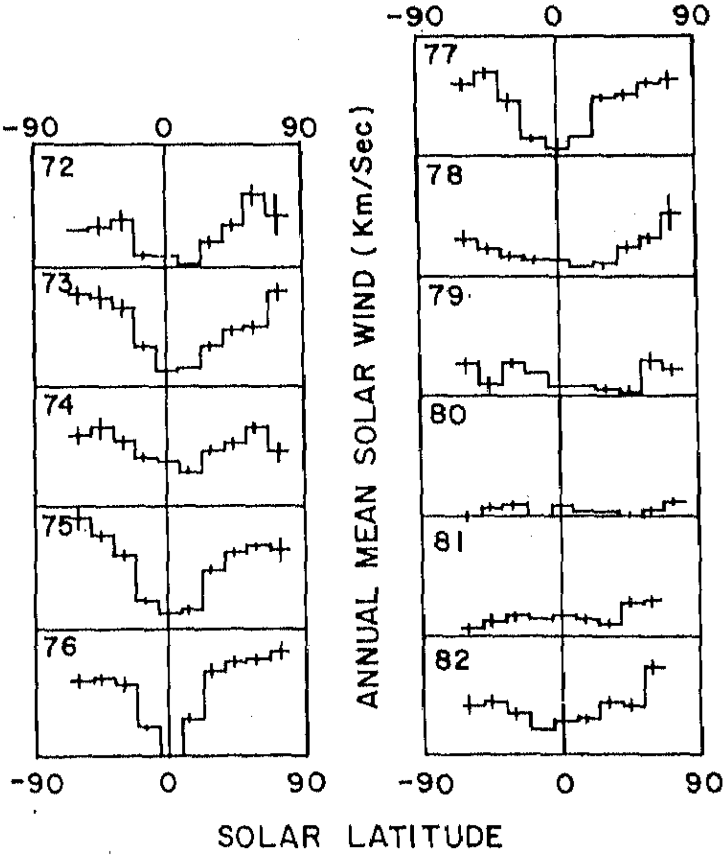

Fig.3. Annual averages of the solar wind speed as a function of heliolatitude in 15 degree bins. The horizontal lines are at 300 kms/sec and 600 kms/sec.

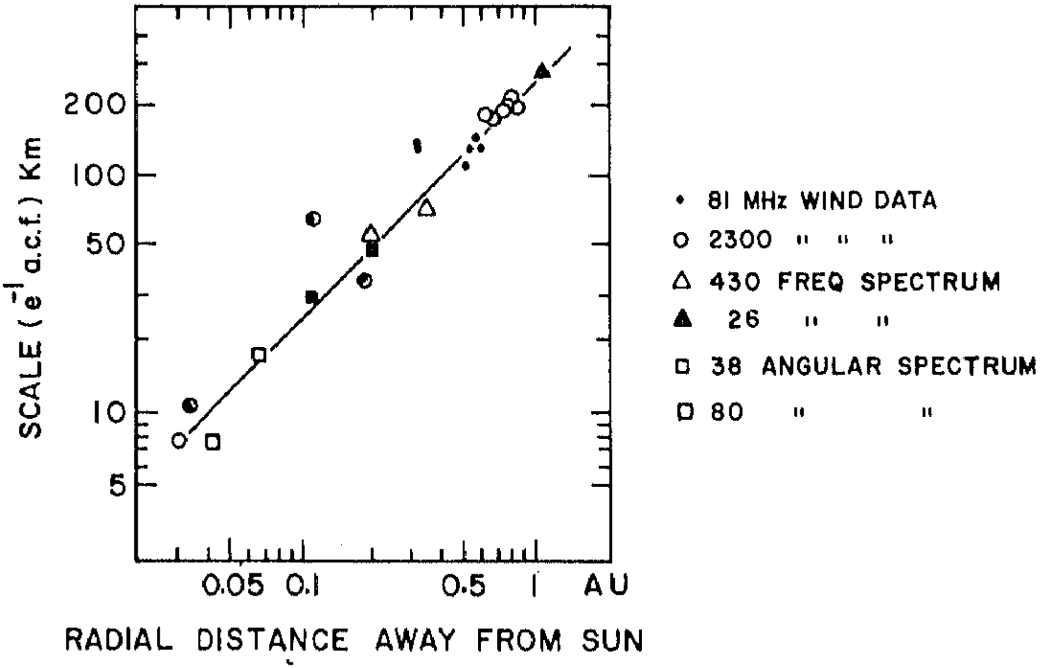

Fig.4. IPS plasma irregularities scale size as function of radial distance away from the Sun.

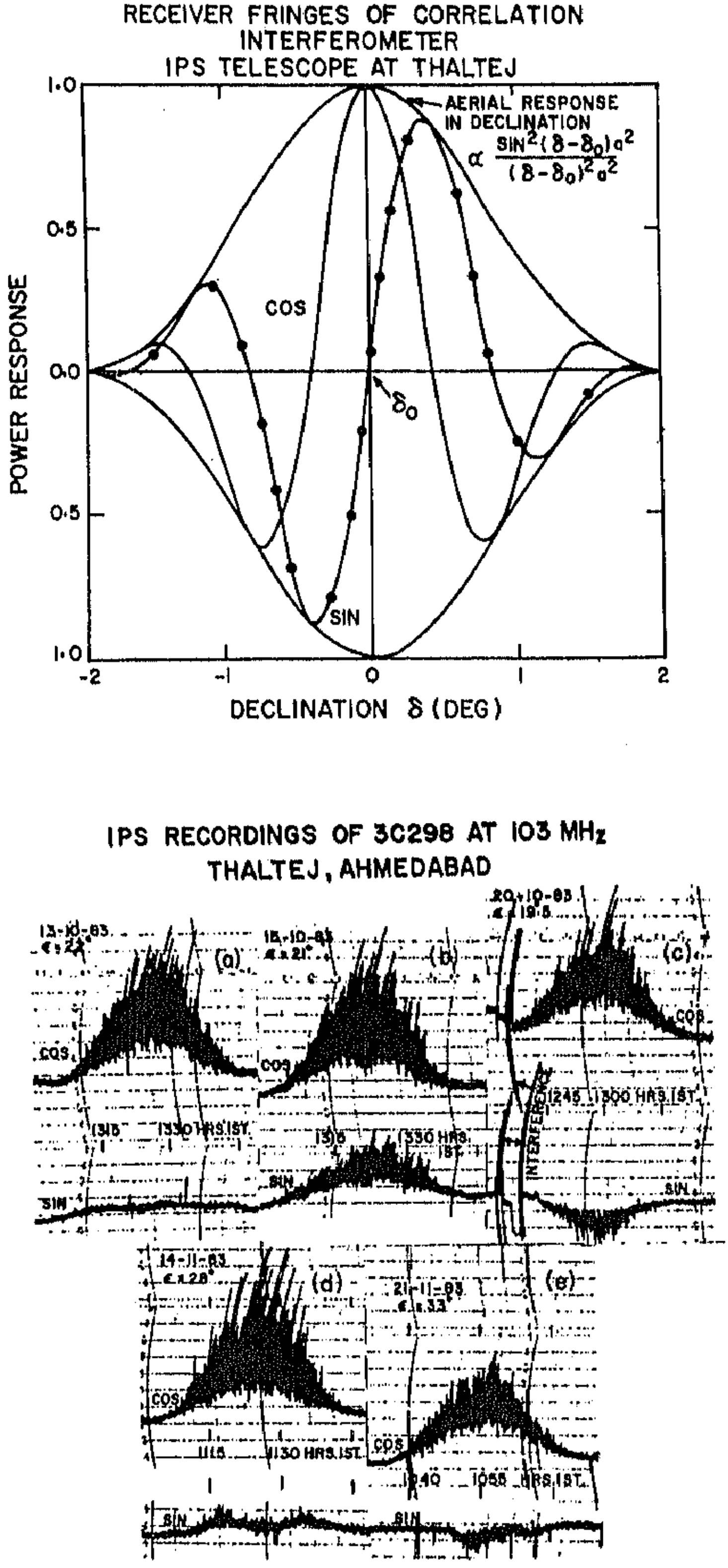

Fig.5. Fringe pattern of Thaltej radio telescope and its typical recording of 3C 298. Note the latter indicate angular displacement of the radio source.

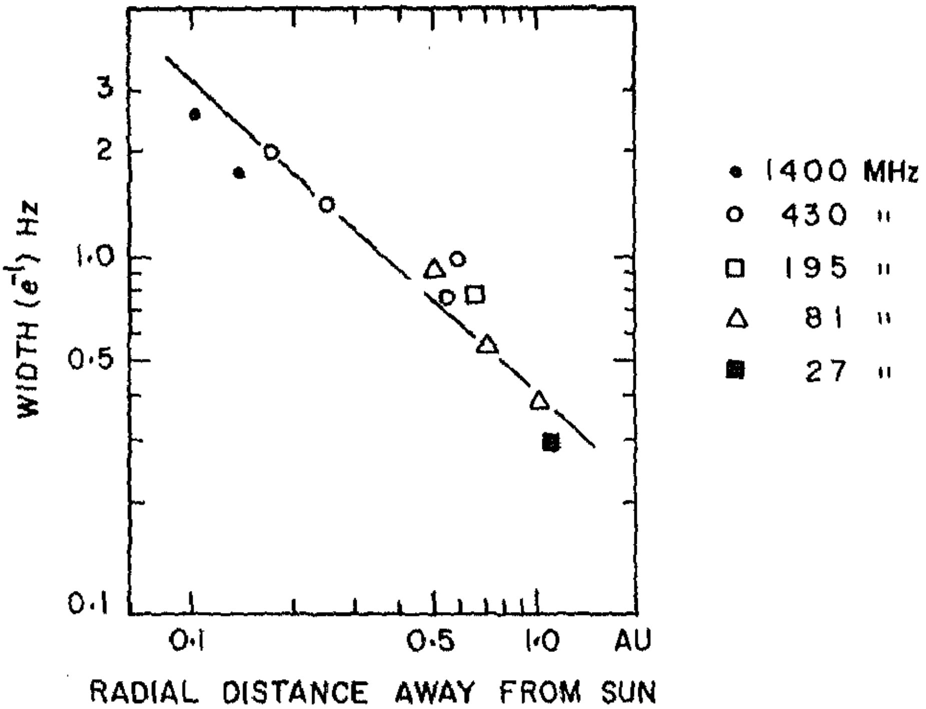

Fig.6. Spectral width at different frequencies as a function of radial distance away from the Sun.

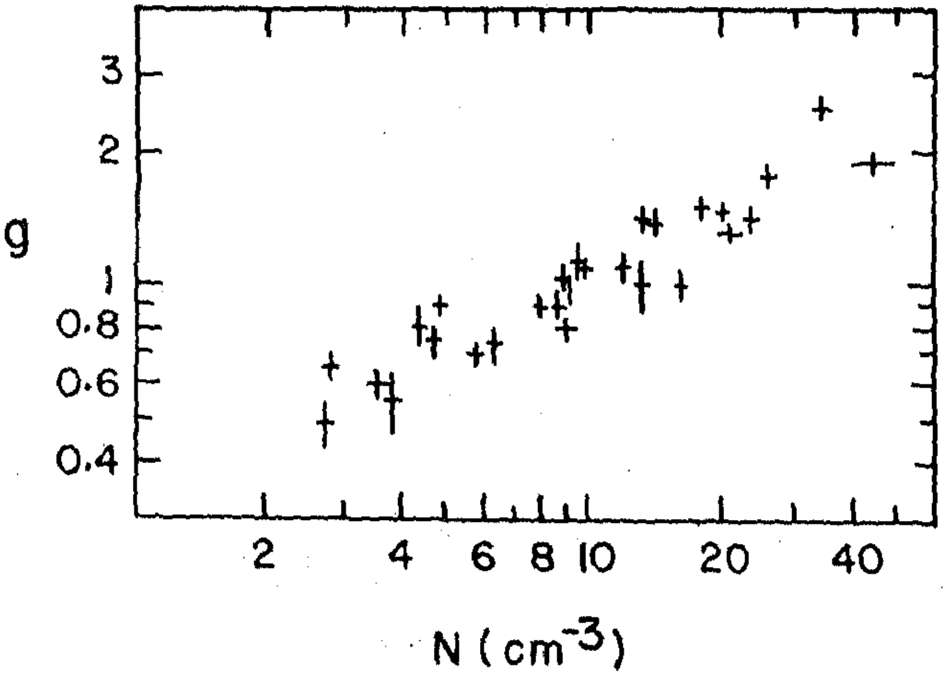

Fig.7. Comparison of scintillation enhancement factor (g) with ins plasma density (N). Each point is the average of observations of 50-100 sources at elongation near 90°.

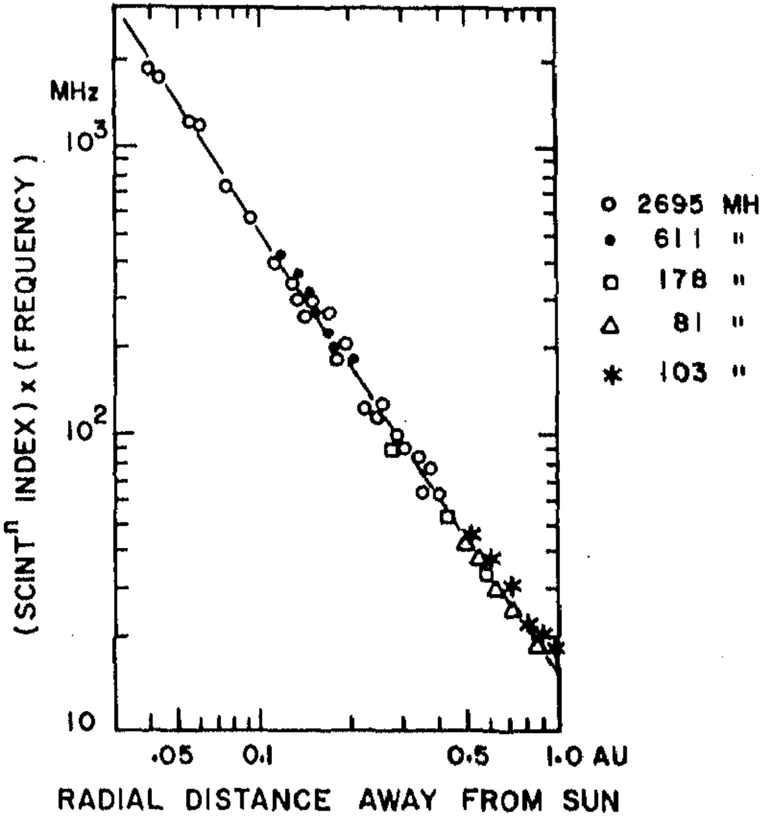

Fig.8. Scintillation index x the observing frequency as a function of radial distance away from the Sun. * are the recent observations at 103 MHz.

6. Summary

From the representative results presented here it is evident that the interplanetary scintillation (IPS) technique provides very useful information about the dynamics and structure of the solar wind. There is a need for coordinated efforts between the IPS observatories. Since the observatories operate at different frequencies an appropriate scaling factor can be applied to compare and consolidate the observations. As the observatories are distributed round the globe, the coordinated observations will provide better temporal coverage. The large scale plasma irregularities should have densities very much larger or smaller than the ambient plasma, in order to account for the observations of Alurkar et al. (1985). The theoretical implications of this phenomenon should be considered. It may also be of interest to investigate the origin, growth and decay of these irregularities. Detailed observations of the dynamics and structure of the plasma irregularities are required close to the Sun. These observations are possible at higher frequencies only. IPS observations out of the ecliptic plane can be compared with the 'insitu' observations of "Ulysses" mission.

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