Kodaikanal Obs Bull (1988) 9, 125 132

INTERPLANETARY SCINTILLATION*

S K Alurkar
Physical Research Laboratory
Ahmedabad 380 009, India

Abstract

In this tutorial talk the ground based, inexpensive method of interplanetary scintillation (IPS) is described, starting with a general background of scattering of e m radiation in turbulent media This is followed by the observational scenario of IPS and some important features of the theory of this phenomenon relevant to the scope of the lecture Four important applications of IPS are presented, substantiated by recent observations

1 Introduction

Atmospheric scattering of a laser beam twinkling of stars scintillation of radio waves caused by their scattering in turbulent ionized media exhibit some common characteristic

1 Small fluctuations of variations of refractive index (R I) from mean, 10^{-6} 10^{-12}

2 Refractive index of scattering medium remains constant over a distance and time equal to the wavelength and period of the incident wave

3 Angular broadening of a point source is small, 10^{-5} rad

The measurables in scintillation are statistical moments of the incident electric field, like scintillation index, intensity spectrum, etc Theory relates these to statistics of the random medium

2. Scenario of IPS Phenomenon

A plane wave from a distant compact radio source is incident on a thin slab of the random medium containing plasma density inhomogeneities Immediately outside the slab the phase of the wavefront develops perturbations After propagating through free space to the observer, it builds up amplitude scintillations, forming a diffraction pattern on the ground (Figure 1)

In the solar wind (SW) plasma,

$$M_{3N}(q) = (r_e \lambda)^2 M_{3n_e}(q) \tag{1}$$

where $M_{3N}(q)$, $M_{3n_e}(q)$ = 3 D spatial density and R I spectra (q) - 3 D wavenumber = $(q_x^2 + q_y^2 + q_z^2)^{1/2}$

If the slab thickness dz<<a, correlation scale of the medium, then outside the slab 2 D spatial phase spectrum is expressed as

$$M_{2\phi}(q_x, q_y) = \frac{2\pi}{\lambda} \; dz \; M_{3N}(q_x, q_y, q_z = 0) \tag{2}$$

* Invited talk delivered at the Second National Workshop on Solar Physics Kodaikanal 24 29 September 1987

dz << z is the "Thin screen' approximation (Salpeter, 1967) Free space propagation of the phase perturbed waves results in intensity scientillations on the observer's plane

Under weak scattering condition, that is when scintillation index, S I $m_p < 1$, or $\phi_0 < 1$ rad, m_p being the point source S I,

$$M_{2I}(q_x, q_y) = \sin^2 [\frac{q^2 \lambda z}{4\pi}] \quad M_{2\phi}(q_x, q_y) \tag{3}$$

where, $4 \sin^2 [\frac{q^2\lambda z}{4\pi}]$ is a high pass 'propagation filter" which removes lower spatial frequencies from the spectrum

In the direction of propagation, the 1 D temporal spectrum becomes

$$M(f) = \frac{2\pi}{V} \int_{\infty}^{\infty} M_{2I} [\frac{2\pi f}{V}, q_y] \, dq_y \tag{4}$$

Effect of Source Size

Finite source size reduces scintillations This effect is used for deducing angular size of scintillating sources

$$M_{2I_{ext}}(\vec{q}) = M_{2I\,p}(\vec{q}) | V(\vec{q}, z)|^2 \tag{5}$$

$$\text{Source visibility } | V(\vec{q}, z)|^2 = \frac{m_{ext}}{m_p}$$

where m_{ext} S I of finite size source, acts as a low pass "source filter", reducing higher spatial frequencies from the irregularity spectrum

Effect of Finite Receiver Bandwidth

Finite receiver bandwidth also reduces scintillations :

$$M_{2I_{ext}}(\vec{q}) = M_{2I\,p}(\vec{q}) \rho^2(\tau)$$

$\rho^2(\tau)$ is a low pass "bandwidth filter' = Fourier transform of receiver passband, $R(\lambda)$

3 Observations of the Medium

Scintillation Index :

Amplitude scintillations are developed beyond Fresnel distance

$$Z_F = \frac{a^2}{\lambda}$$

Very large irregularities produce no IPS (only phase modulations)

The diffraction pattern on the ground moves with velocity V of SW,

Intensity fluctuates with amplitude ΔS and periodicity (a/V) The S.I is defined as

$$m = \frac{\Delta S}{<s>} = \frac{\text{rms scintillating flux}}{\text{mean source flux}}$$

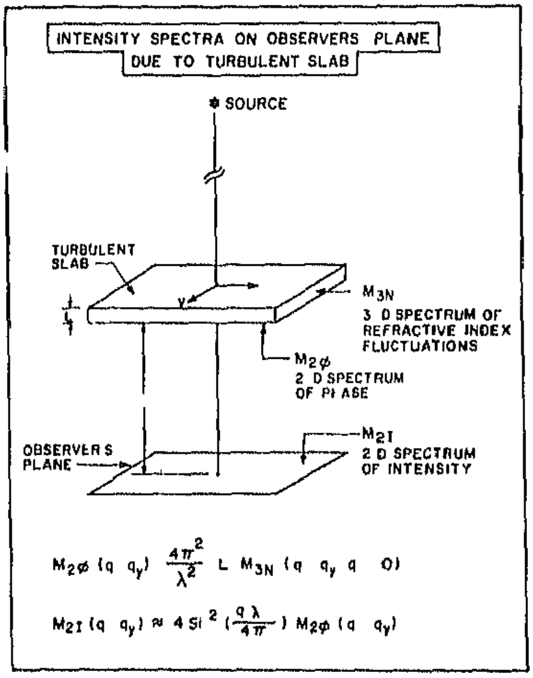

Fig.1 Formation of diffraction pattern of intensity in IPS observation

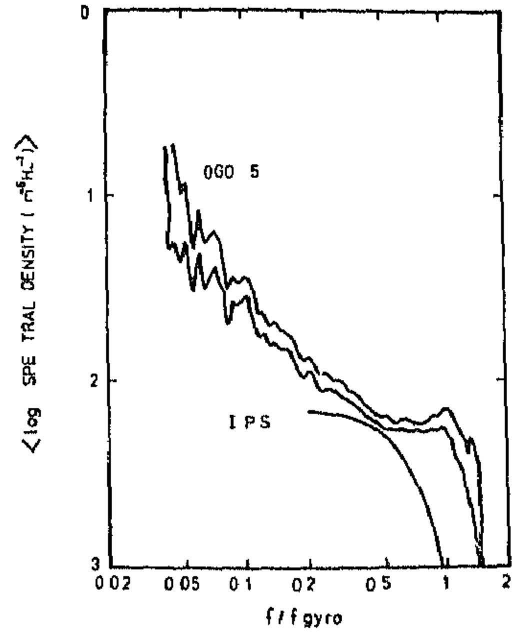

Fig.2 Spatial density spectrum from proton flux measurements by OGO 5 spacecraft

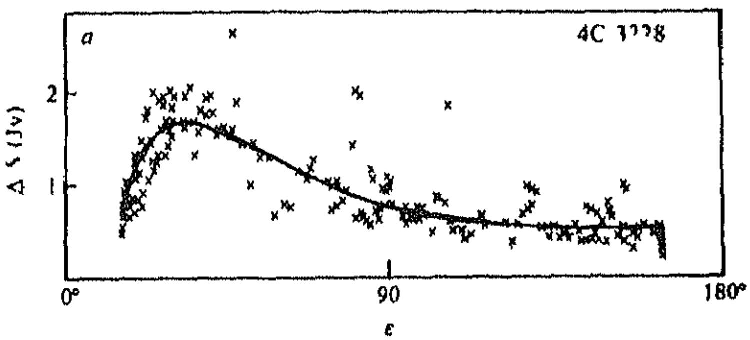

Fig.3 Daily values of rms scientillating flux density versus solar elongation for a typical source

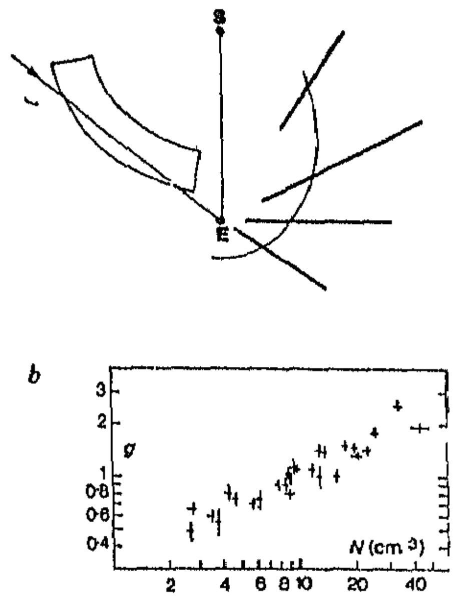

Fig.4(a) Sketch of scientillating weighting function along lines of sight normalized to unity at the locus of maximum scattering (curved line)

(b) Correlation of scintillation enhancement factor 'g' with in situ plasma density N

II **RMS Density and Scattering Power**

Single telescope observation show

$$m \propto p^{1\ 5} \tag{6}$$

(Readhead et al, 1978),
where p in AU is the shortest distance of the line of sight from the Sun

Now for gaussian density irregularity spectrum,

$$m = \sqrt{2}\ \pi^{\frac{1}{4}}\ r_e\ \lambda < \Delta N^2 >^{\frac{1}{2}},\ (aL)^{\frac{1}{2}} \propto \lambda \tag{7}$$

(Little, 1976)

$$\Delta N \propto \frac{m}{\sqrt{a}}, \text{ and } a \propto p^1$$

Thus, $\underline{\Delta N \propto p^{2\ 05}}$ (8)

The scattering power $\beta(r)$ is given by

$$m^2 = 2\,\phi_0^2 = \int_{\infty}^{z_0} \beta(r)\, dz \tag{9}$$

(Readhead et al, 1978)

$$m^2 \propto < \Delta N^2 > \propto r^4$$

Thus, $\underline{\beta(r) \propto r^4}$ (10)

$\Delta N \lesssim r^{t}$, the electron density (11)

III **Irregularity Scale size**

The range of scale sizes contributing IPS

$$a < \text{Fresnel size } a_F = \sqrt{\lambda z} = \underline{670} \text{ km for } \lambda = 3\text{m and } z = 1 \text{ AU}$$

Now, for gaussian irregularities $\underline{m \propto \lambda}$ implies that the <u>dominant</u> size of the turbulence is the unique scale size 'a'

OGO 5 observations of proton flux (Neugebauer, 197J) indicated marked flattening of spectrum at spatial frequencies corresponding to scale size near <u>200 km</u> (Figure 2) Also, the Fresnel filter cuts off lower spatial frequencies (larger scale sizes) from the turbulence spectrum These observations suggest a single scale size Gaussian model for IPS in preference to a simple power law

4. Applications of IPS

I(a) Large scale Interplanetary Disturbances
I(b) Forecasting Geomagnetic Activity
II Electron Density Spectra of IPM
III Solar Wind Speed
IV Structure of Compact Radio Sources

I(a) Large scale Interplanetary Disturbances

IPS provides a convenient inexpensive method of tracking interplanetary disturbances associated with coronal mass ejections (CMEs) The rms scintillating flux, ΔS for a wide range of elongation (Figure 3) is measured for each of a large number of source (Gapper, et al, 1982)

An enhancement factor of scintillation

$$g = \frac{\Delta S}{\overline{\Delta S(\epsilon)}}$$

define day to day variations about the mean $\overline{\Delta S}$ which is a long term average for a source at elongation ϵ

Transient disturbance appear as large regions, with well defined boundaries, in which 'g' differs significantly from unity

Comparison of g values with in situ density values measured by spacecraft near the earth (Figure 4) have shown that IPS measures (root of) density

$$g = \left(\frac{N\ cm^{-3}}{9}\right)^{0.52 \pm 0.05} \qquad \text{for} \quad 3 < N < 40\ cm^{-3} \tag{12}$$

and g' values were averaged over 50 100 sources at about 90° elongation (Hewish et al, 1985)

I(b) Forecasting Geomagnetic Activity

Cambridge astronomers very successfully used g maps' to study large scale structure of transient disturbance Such events sometimes cause geomagnetic storm producing severe disruption to communications and power transmissions IPS can detect such disturbances typically a day before the occurrence of a geomagnetic storm (Hewish and Duffett Smith, 1987)

Model of an Interplanetary Disturbance

From a study of a large number of such disturbances a standard model for them has been developed

As shown in Figure 5 a compression region is formed by a fast stream in the SW, which sweep up the 'quiet' wind ahead of it The high density region travels from the Sun to the Earth at 400 450 km/s This is followed by a fast low density stream moving at about 500 km/s with a density of about half the ambient value (Tappin et al, 1983)

II Electron Density Spectra of IPM

Angular broadening and intensity scintillations of compact radio sources have been extensively used to study the density distribution in the SW

Spacecraft signals, which are monochromatic and coherent, are also used to make observations of phase scintillations and spectral broadening for probing the SW

Phase Scintillations

These contain information on a wide range of scale sizes, therefore they are useful as a probe for studying power spectrum of density variations in the SW Such measurements were made using a dual frequency (2 3 and 8 4 GHz) radio link on the Viking orbiters (Woo & Armstrong, 1979; Armstrong et al, 1979) over heliocentric distances of 2 215 $R_{\odot}$, near the ecliptic plane

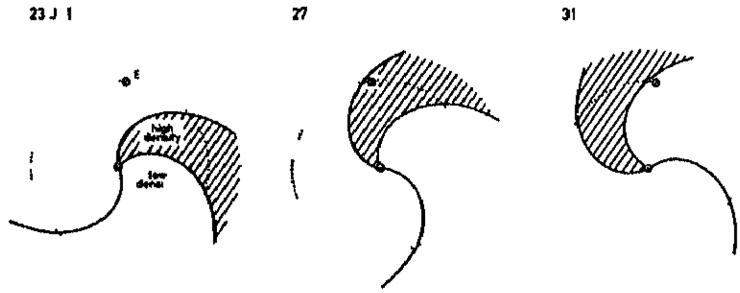

Fig.5 Model of a corotating density structure expected from stream interaction

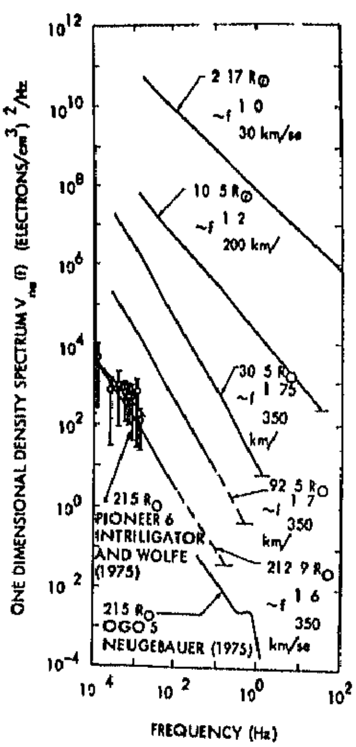

Fig.6. 1 D electron density spectra obtained from Viking phase difference scintillations

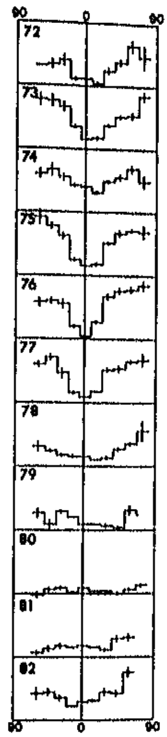

Fig.7 Annual average SW speeds with N & S helio latitudes during 1972 82

Frequency spectra of the Viking phase difference scintillations were converted into 1 D electron density spectra $V_{ne}(f)$, shown in Figure 6 These observations showed that

1 Phase scintillations measure electron density fluctuations over a wide range of scale sizes and heliocentric distances

2 Highest fluctuation frequency determined increases closer to the Sun, reaching a maximum of 100 Hz at about 2 $R_\odot$

3 Over distance range 20 215 $R_\odot$ the spectral index has a constant value of 1 65 comparable to the 1 D Kolmogorov spectrum (spectral index 5/3)

4 Within 20 $R_\odot$, the index is reduced, becoming 1 near 2 $R_\odot$

IPS observations in the range 5 15 $R_\odot$ also yield density spectrum with spectral index of 0 8 + 0 2 for frequency range 1 10 Hz (Coles and Harmon, 1978)

III Solar Wind Speed

SW in and out of the ecliptic can be studied using IPS method, in which most of the scattering occurs at a point P where the line of sight is closest to the Sun For a spherically symmetric SW, IPS 'mid point' speed gives spatial average of the SW centered on the point of closest approach (Whereas the IPS 'peak velocity' is obtained from the time lags between maxima of cross correlation functions, the 'mid point velocity is estimated from mid points of the functions halfway down from their maxima) This point changes its heliographic coordinates and radial distance as the Sun rotates and the Earth orbits the Sun High latitudes are reached together with small solar distances

This distance dependence of SW speed was separated by observing 4 ecliptic sources for which the heliolatitude confined within 10° of the equator, during 1971 75 (Coles and Rickett, 1976) It was concluded that there was no variation of average SW speed with radial distance over the range 0 4 1 1 AU

All other sources indicated a definite increase in the average SW speed with latitude both North and South of the Sun's equator with an average gradient of 2 1 km/s/deg lat

Solar Wind Structures

These are studied by mapping each observation from P to the Sun along a spiral assuming a constant radial velocity equal to the observed value Annual average SW speeds were plotted versus N and S heliolatitudes for the years 1972 82 (Rickett and Coles, 1982) It can be seen from Figure 7 that

1 Long lived fast streams are originated from the polar regions through much of the solar cycle,

2 Fast polar streams persisted throughout the declining solar activity (1972 75),

3 Through solar maximum (1978 81), the fast streams disappeared, and

4 With decline of solar activity (1982), they started reappearing

IV Structure of Compact Radio Sources

As mentioned earlier in the expression (5), the finite size of a scintillating source cuts off high spatial frequencies from its IPS spectrum and also reduces the S I due to its broadening These facts are made use of in making high resolution observations of angular structure of compact radio sources in the range 0 1 to 2 arc seconds at meter wavelengths The well known Very Long Baseline Interferometry (VLBI) technique becomes impracticable at these wavelengths, as baselines thousands of kilometers long are required to realize second of arc resolution

Using the S I method, Little and Hewish (1968) studied scintillation data from the Cambridge surveys of 3C and 4C sources at 178 MHz They concluded that

(i) A number of sources possess very small scintillating components (less than 0 1 arc sec) and

(ii) Sources at high ecliptic latitudes scintillate very weakly, as they are far away from the Sun

Recently Cambridge astronomers have combined IPS with background deflexion analysis and determined average scintillation properties of very weak radio sources, whose flux densities at 81 5 MHz were in the range 15 to 1 5 Jy The results were discussed in terms of cosmological interpretations

In the second method suggested by Cohen et al (1967), upper limits of source diameters were estimated from the widths of frequency scintillation spectra First, scintillation visibility is measured If the width of the source spectrum is smaller than that of the point source, then the size of the scintillating component is given by

$$\psi = \left(\frac{V}{1.2\pi f_2 z}\right)\left[1 - \left(\frac{f_2}{f_0}\right)^2\right]^{\frac{1}{2}} \qquad (13)$$

where V = solar wind velocity
f_2 = width of source spectrum
f_0 = width of point source spectrum
ψ = half power width of a Gaussian source

The observed S I of the finite size source is then corrected as

$$m = m_{obs}\left[1 + 0.36\left(\frac{z\psi}{a}\right)^2\right]^{\frac{1}{2}} \qquad (14)$$

This corrected m is used to estimate the fraction of the flux of the scintillating component

References

Armstrong, J W , Woo, R and Estabrook, F (1979) Astrophys J 230, 570
Cohen, M H , Gundermann, E J , Hardebeck, H E and Sharp, L E (1967) Astrophys J 147, 449
Coles, W A and Harmon, J K (1978) J Geophys Res 81, 1413
Coles, W A and Rickett, B J (1976) J Geophys Res 81, 4797
Gapper, G R , Hewish, A , Purvis, A and Duffett Smith, P J (1982) Nature, 296, 633
Hewish, A and Duffett Smith, P J (1987) Planet Sp Sci , 35, 487
Hewish, A , Tappin, S J and Gapper, G R (1985) Nature, 314, 137
Little, L T (1976) Meth Exptl Phys 12 C, 118
Little, L T and Hewish, A (1968) Mon Not R astr Soc , 134, 221
Neugebauer, M (1975) J Geophys Res 80, 998
Readhead, A C S , Kemp, M C and Hewish, A (1978) Mon Not R astr Soc , 185, 207
Rickett, B J and Coles, W A (1982) "Solar Wind Five" ed M Neugebauer, Proc NASA Conf , Woodstock
Salpeter, E E (1967) Astrophys J 147, 433
Tappin, S J , Hewish, A and Gapper, G R (1983) Planet Sp Sci , 31, 1171
Woo, R and Armstrong, J W (1979) J Geophys Res 84, 7288