CHAPTER TWO

INTERPLANETARY SCINTILLATION AND RELEVANT THEORY

2.1 Interplanetary Scintillation

The phenomenon of interplanetary scintillation (IPS) is a radio analog of the twinkling of stars in the night sky and atmospheric scintillation of laser beams. As shown in Figs. 2.1 and 2.2, when radio waves from a distant compact source enter the interplanetary medium (IPM) containing solar plasma they are scattered by the plasma density irregularities. If the radio source is sufficiently small in diameter so that the plasma density irregularities are illuminated coherently, phase modulations are imposed on the plane wavefront. Emerging out from the main bulk of
source

incident plane wavefront

density irregularities of size $a$

corrugated wavefront (phase distortion)

wavefront modulated in amplitude and phase

Fig. 2.1 IPS geometry
the scattering medium, these phase-modulated waves propagate in the IPM and interfere with one another, consequently causing at the Earth variations of intensity of the radio source. As a result of the solar wind flow across the line of sight to the source, the spatial distribution of the plasma density variation in the scattering medium is converted into temporal fluctuations of intensity at the observing site, with a typical fluctuation period of one second.

Thus, the IPS method provides essentially a 1-dimensional scan of the scattering region. Radio sources with angular sizes of about 1.0 arcsec. or less cause IPS yielding a temporal spectrum ranging from, say 0.1 to about 3 Hz. The scintillators are mainly extragalactic radio sources, such as radio galaxies and quasars, a fraction or whole of which is effective as scintillating radio sources.

Since the discovery of IPS (Hewish et al. 1964), many systematic studies have been made. The method of IPS and the results obtained have been reviewed extensively by Cohen (1969), Hewish (1972), Jokipii (1973), Coles et al. (1974), Lotova (1975) and Little (1976). The IPS observations have been used for

(a) investigating the IPM (Houminer, 1971; Armstrong, 1975; Coles and Rickett, 1976; Dennison and Wiseman, 1968)
Fig. 2.2 Schematic of spectra at various planes during IPS observations.

\[ M_{2\phi}(q_x, q_y) = \frac{4\pi^2}{\lambda^2} \cdot L \cdot M_{3N}(q_x, q_y, q_z = 0) \]

\[ M_{2I}(q_x, q_y) \approx 4 \sin^2 \left( \frac{q_x \lambda z}{4 \pi} \right) M_{2\phi}(q_x, q_y) \]
(b) determining the structure of compact galactic and extragalactic radio sources (Cohen et al. 1967; Little and Hewish, 1966; Armstrong et al. 1973; Duffett-Smith, 1976), and

(c) estimation of solar wind velocity (Hewish and Symonds, 1969; Lovelace et al. 1970; Coles and Maagoe, 1972; Armstrong and Coles, 1972; Watanabe et al. 1973).

Recently, attempts have also been made to study ion-tails of comets using the IPS technique.

In the present thesis some of the above mentioned studies have been presented. All the work presented in this thesis is based on the interpretation of weak scattering intensity scintillation data. Here a brief review of fundamentals of scintillation theory is given. Weak scattering theory has been well understood for quite sometime and here it will not be repeated. The reader is referred to Ratcliffe (1956), Tatarski (1961), Salpeter (1967), Readhead (1971 and Ishimaru (1972) for further details of the theory.

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.

2.2 Relevant Theory

A plane wave propagating from a distant compact
radio source is incident on a thin phase changing slab of the plasma turbulence. Immediately outside the slab the wavefront gets corrugated due to phase deviations. After propagating a certain distance, called Fresnel distance \( z_F = \frac{2\pi a^2}{\lambda} \) (where 'a' is the scale-size of irregularities and \( \lambda \) is the operating wavelength) through free space to the observer, amplitude modulations start building up, forming a spectrum of intensity on the ground (Fig. 2.2).

The statistical quantity of the medium that is of interest, here is the 3-dimensional spatial spectrum of refractive index fluctuations at operating radio wavelength \( \lambda, M_{3ne}(q) \). In a plasma, it can be related to the 3-dimensional electron density spectrum by

\[
M_{3N}(q) = r_e^2 \lambda^2 M_{3ne}(q) \quad ...(2.a)
\]

where \( q = (q_x^2 + q_y^2 + q_z^2)^{\frac{1}{2}} \), is 3-dimensional wavenumber and \( r_e \) is the classical electron radius.

If the slab thickness \( L > a \), correlation scale of the medium (scale-size of the irregularity), \( \lambda \) outside the slab 2-dimensional spatial phase spectrum for thin screen \( (L << z, \text{Salpeter, 1967}) \) is expressed as

\[
M_{2\phi}(q_x, q_y) = \frac{4\pi^2}{\lambda^2} r_e M_{3N}(q_x, q_y, q_z=0) \quad ...(2.b)
\]
Free space propagation of the phase distorted waves results in intensity scintillation (spectrum of intensity) on the observer's plane. Under weak scattering conditions (r.m.s. phase deviation, $\phi_0 << 1$ radian), 2-dimensional intensity spectrum can be written as

$$M_{2I}(q_x, q_y) = 4 \sin^2 \left( \frac{q^2 \lambda Z}{4\pi} \right) M_{2\phi}(q_x, q_y) \quad \ldots(2.c)$$

where the term $4 \sin^2 \left( \frac{q^2 \lambda Z}{4\pi} \right)$ is a high-pass "propagation filter" which removes the lower spatial frequencies from the spectrum.

Scintillation index, $m$ is defined as (Readhead et al. 1978)

$$m^2 = \iint M_{2I}(q_x, q_y) \, dq_x \, dq_y \quad \ldots(2.d)$$

In the direction of propagation along the $x$-axis (Fig. 2.2), 1-dimensional intensity temporal spectrum becomes

$$M_I(f) = \frac{4\pi}{V} \int_{-\infty}^{\infty} M_{2I}(q_x = \frac{2\pi f}{V}, q_y) \, dq_y, \text{ for } f > 0 \quad \ldots(2.e)$$
where \( V_x \) is the \( X \)-component of the velocity of the plasma density irregularities.

Actually, the pattern received by the observer is made up of contributions from scattering volume all along the line of sight. In the case of weak scattering, the spectrum can be approximated as (Sime, 1976)

\[
M'_I(f) = \int_0^Z M(f,z) \, dz 
\]

Some of these equations in modified form have been used in subsequent chapters.

2.2(a) Effect of source size

Finite source size reduces the scintillations. This effect can be used for deducing angular size of scintillating sources. If \( M_{2I_{ext}}(q) \) and \( M_{2I_{pt}}(q) \) are 2-dimensional intensity spectra for an extended and a point source respectively, then

\[
M_{2I_{ext}}(q) = M_{2I_{pt}}(q) \left| V(q,z) \right|^2 
\]

(commonly known as Cohen-Salpeter equation, Salpeter, 1967),

where \( V(q,z) \) is called the source visibility defined as
where $m_{\text{ext}}$ and $m_{\text{pt}}$ are scintillation indices for extended and point sources respectively. Thus, $m_{\text{ext}}$ acts as a low-pass filter, reducing higher spatial frequencies from the irregularity spectrum.

2.2(b) Effect of finite receiver bandwidth

Finite receiver bandwidth also reduces scintillations,

$$M_{2I}(q) = M_{2I}(q) \rho^2(\tau) \quad \ldots(2.h)$$

as given by Cronyn (1970). The term $\rho^2(\tau)$ is called the bandwidth filter.

The effect of both finite source diameter and bandwidth is to cause a reduction of the scintillations as they both act as low pass filters on the spatial spectrum. To judge the relative importance of these two filters one can compare the effects of an isotropic gaussian source to a rectangular bandpass. By equating the $e^{-1}$ widths of these two filters one may express the bandwidth effect in terms of an effective source diameter (Full width at $e^{-1}$). This equivalent diameter is given as $\phi_e = \frac{1}{\pi} (\frac{2f \Delta f \lambda}{f^2 Z})^{\frac{1}{2}}$ where $\phi_e$ is the equivalent diameter in radians, $\lambda$ is the
centre wavelength, \( Z \) is the distance to the screen and \( \frac{\Delta f}{f} \) is the fractional bandwidth (full width) of the rectangular band pass (Scott, 1970).

All the equations described earlier are valid for gaussian and power-law models of the IPM.