PULSAR SCINTILLATION: OVERVIEW AND SOME RECENT RESULTS

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Abstract. Radio signals from pulsars are significantly affected by scattering in the interstellar medium. A review of this phenomenon of pulsar scintillation forms the main objective of this paper. The basic concepts are described and some new results related to the following aspects are presented: (i) understanding of refractive scintillation effects and (ii) constraining the spectrum of electron density fluctuations in the interstellar medium.

1. Introduction

Radio signals from pulsars are significantly affected by propagation effects in the tenuous plasma of the interstellar medium (ISM). These effects include interstellar dispersion, faraday rotation and scintillations. Interstellar scintillations (ISS) are produced by the scattering of radio waves due to the random electron density fluctuations in the ionized phase of the ISM. The phenomenon of pulsar scintillation was recognized soon after the discovery of pulsars (e.g. Scheuer, 1968) and the field has grown significantly since then (see Rickett, this volume, for a road map of this progress). It continues to be an area of active research, with the main drivers being the following:

1. A better understanding of the phenomena of pulsar scintillation.
2. Improved knowledge of the ionized phase of the ISM:
   a) Determining the detailed nature of the spectrum of electron density fluctuations in the ISM.
   b) Detailing the Galactic distribution of ionized plasma.
3. Pulsar scintillation also allows us to infer some properties of pulsars themselves, using the ISM as a tool:
   a) Distinguishing intrinsic versus extrinsic intensity fluctuations.
   b) Measuring pulsar transverse speeds using scintillation data.
   c) Estimating the size and location of pulsar emission regions.

Some of these aspects (e.g. 2b), 3b) and 3c)) are treated in detail in other sessions in this meeting and will not be emphasized in this paper.

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2. Some Basic Concepts

Consider spherical wavefronts from a pulsar propagating through a layer of scattering plasma in the ISM. The random refractive index fluctuations produced due to the electron density irregularities in the plasma cause random phase perturbations of the wavefront. These are characterized by the phase structure function:

$$D_\phi(s) = \langle[\phi(r+s) - \phi(r)]^2\rangle. \tag{1}$$

This leads to a finite decorrelation scale of the electric field

$$C_f(s) = \exp\left[-\frac{1}{2}D_\phi(s)\right] \ ; \quad D_\phi(s_0) = 1. \tag{2}$$

Here s_0 is the coherence scale. Such a distribution of the electric field is equivalent to an angular spectrum of plane waves $[B(\theta)]$ whose width $[\theta_d]$ (also called the scattering angle) is given by $\theta_d = 1/(k\,s_0)$, where k is the wavenumber of the radiation. Interference between different components of the angular spectrum, as they propagate towards the observer from the scattering medium, produces random intensity fluctuations in space and frequency domains at the observing plane. The spatial variations are mapped to temporal variations by the relative motion between the scintillation pattern and the observer – called the scintillation velocity $[V_{iss}]$ – which is a combination of the motions of the pulsar, scattering screen and observer.

2.1. Diffractive and Refractive Scintillations

Depending on the magnitude of phase perturbation produced by the scattering screen, we distinguish two kinds of scattering: weak scattering ($\phi_{rms} \ll 1$) and strong scattering ($\phi_{rms} \gg 1$) (see Rickett, 1990, for a detailed review of ISS theory). The strength of scattering increases with wavelength and with distance through the scattering medium and most observations of pulsars at distances more than about 100 pc and at frequencies below about 1 GHz, fall in the strong scattering regime. In this regime, pulsar scintillation is characterized by two kinds of effects: diffractive and refractive interstellar scintillation (DISS and RISS).

DISS is produced by the small scale irregularities in the medium and is essentially the diffraction pattern produced by the interference between different components of the angular spectrum. DISS intensity fluctuations are characterized by a modulation index, $m_d \approx 1$, and typical decorrelation scales in time and frequency domains, given by

$$\tau_d = \frac{s_d}{V_{iss}}\ , \quad s_d = s_0 = \frac{1}{k\theta_d}\ ; \quad \text{and} \quad \nu_d = \frac{c}{\pi Z \theta_d^2}. \tag{3}$$

Typical values for τ_d and ν_d are $\sim$ 100 seconds and $\sim$ 100 kHz, respectively, for nearby pulsars at metre wavelengths. A related effect is the observed broadening of pulsar profiles, produced by the delayed arrival of scattered radiation. The pulse broadening time, τ_p, is inversely related to the decorrelation bandwidth such that $2\pi\nu_d\tau_p = 1$. Many of these observables of pulsar scintillation are most readily studied using pulsar dynamic spectra which are two dimensional records of pulsar intensity as a function of time and frequency (e.g. Gupta, Rickett and Lyne, 1994; Cordes, Weisberg and Boriakoff, 1985).

RISS effects are produced by large scale ($\sim 10^{11}$ m) electron density irregularities in the ISM and are generally broad-band in frequency. They produce low amplitude ($m_r \sim 0.2$) modulations of pulsar flux. The associated time scales are quite long ($\tau_r \sim$ weeks to months) for nearby pulsars at metre wavelengths. Other RISS effects include angular wandering of the scattered image; random modulations of the DISS parameters τ_d and ν_d; systematic drift slopes of the intensity scintles in pulsar dynamic spectra data and slow variations thereof; and the relatively rare occurrence of multiple imaging events which can produce periodic intensity modulations in time and frequency in pulsar dynamic data. Below, I will critically review our understanding of RISS.

2.2. THE SPECTRUM OF ELECTRON DENSITY FLUCTUATIONS

Observations of DISS and RISS effects can be used to infer properties of the scattering medium, such as the nature of the spatial power spectrum of the electron density fluctuations in the ISM and the strength and distribution of the scattering plasma in the Galaxy. Current understanding points to a power-law form for the electron density power spectrum, quantified as

$$P(\kappa) = C_n^2(z)\kappa^{-\alpha}, \quad \kappa_{out} \ll \kappa \ll \kappa_{inn}. \tag{4}$$

Here $C_n^2(z)$ is a measure of the strength of scattering and can be a function of location in the Galaxy, z; κ is the spatial wavenumber (inversely related to the length scale) and κ_{out}, κ_{inn} correspond to the outer and inner cut-off scales of the spectrum.

The value of the power-law index, α, has important implications for the physics of the ionized medium. For example, a Kolmogorov spectrum ($\alpha = 11/3$) extending from the outer to inner scale cut-off would support turbulent cascade models. Steeper spectra ($\alpha \approx 4$) could be produced due to a medium having random superposition of discontinuities, such as a collection of shock fronts (see Rickett, 1990). Below, I will review the various constraints on the detailed shape of the spectrum.

3. Understanding RISS

Though it is now fifteen years since Rickett, Coles and Bourgois (1984) first identified the effects of refractive interstellar scintillations in pulsar data, several aspects of RISS continue to elude a satisfactory explanation. One of these is the apparent discrepancy between the measured and predicted time scales (τ_r) and modulation indices (m_r) of refractive flux variations. From measurements of DISS parameters of a pulsar, the expected values for m_r and τ_r can be calculated, assuming a standard Kolmogorov model (Romani, Narayan and Blandford, 1986). Measurements of these quantities for a number of pulsars are now available in the literature (e.g. Gupta *et al.*, 1994; LaBrecque, Rankin and Cordes, 1994; Gupta, Rickett and Coles, 1993; Kaspi and Stinebring, 1992). Most results show *larger* than expected modulation indices and *shorter* than expected time scales, especially for nearby pulsars. A similar discrepancy is seen in the strength of modulation of DISS parameters (ν_d and τ_d) due to RISS, where the measured modulation indices (e.g. Bhat, Gupta and Rao, 1999a) are significantly larger than those expected for a Kolmogorov spectrum.

Theoretical models for refractive scintillations predict correlated fluctuations of ν_d, τ_d and pulsar flux with epoch (e.g. Romani *et al.*, 1986). One of the first reported measurements of this for one pulsar (Stinebring, Faison and McKinnon, 1996) showed that this may indeed be true. However, more extensive measurements for about 20 pulsars, recently reported by Bhat, Rao and Gupta (1999b) show that, in general, the agreement with the predictions is poor. They find that though the ν_d, τ_d correlation is present fairly often, the correlations of flux with ν_d and τ_d are generally poor for many pulsars.

Clearly, we need a better understanding of RISS, especially improvement in theoretical models, to explain the complexity of the observed results. It is also possible that some of these discrepancies may be due to our poor understanding of the detailed shape of the power spectrum. For example, some of the higher refractive modulation indices can be produced if the spectrum is steeper than Kolmogorov (see next section).

4. Constraining the Power Spectrum

Although there is now considerable support (see for example, Armstrong, Rickett and Spangler, 1995) for a power law spectrum with a slope close to the Kolmogorov value ($\alpha \approx 11/3$), the exact slope and the range of wavenumbers over which it is valid, as well as the nature of the spectral cut-offs are still open to debate. There are several conflicting reports in the literature about the nature of the spectrum, which I summarize here.

The evidence in *favour* of a pure Kolmogorov spectrum is:

(i) Measurements of frequency scaling of decorrelation bandwidths and time scales from DISS observations of pulsars (e.g. Cordes *et al.*, 1985; Cordes *et al.*, 1990) are consistent with $\alpha = 11/3$. These measurements probe length scales $\approx 10^6 - 10^8$ m.

(ii) Spectral slope estimates from DISS and RISS measurements (e.g. Bhat *et al.*, 1999a; Smith and Wright, 1985) give $\alpha \approx 11/3$ (though there is some evidence for $\alpha > 11/3$ for nearby pulsars). These probe length scales $\approx 10^7 - 10^{11}$ m.

(iii) VLBI observations of the scattering disc of PSR B1933+16 (Gwinn *et al.*, 1988a) give $\alpha = 3.52 \pm 0.13$ for length scales $10^6 - 10^7$ m.

(iii) VLBI observations of H_2O masers in W49 and Sgr B2 (Gwinn, Moran and Reid, 1988b) give $\alpha \simeq 3.67$ up to length scales 10^{11} m.

The evidence *against* a pure Kolmogorov spectrum is:

(i) Enhanced RISS modulations of pulsar flux (e.g. Gupta *et al.*, 1993) and enhanced modulations of ν_d and τ_d (e.g. Bhat *et al.*, 1999a; Gupta *et al.*, 1994) require $\alpha > 11/3$, or a large ($\approx 10^7 - 10^8$ m) inner scale cut-off.

(ii) Measurements of long term variability of pulsar dispersion measures (Philips and Wolszczan, 1991) imply $< \alpha >= 3.84 \pm 0.02$. This probes length scales $\approx 10^{11} - 10^{13}$ m.

(iii) The observations of persistent drift slopes (which last for much longer than refractive time scales) in pulsar dynamic spectra (e.g. Bhat *et al.*, 1999a; gupta *et al.*, 1994) require $\alpha > 11/3$ (or the presence of discrete structures) for a suitable explanation. These probe length scales $\approx 10^{12} - 10^{13}$ m.

(iv) Multiple imaging events in pulsar dynamic spectra (e.g. Rickett, Lyne and Gupta, 1997), extreme scattering events (ESEs) from pulsar timing observations (e.g. Lestrade, Rickett and Cognard, 1998) and ESEs from extra-galactic radio source observations (e.g. Fiedler *et al.*, 1994) are incompatible with a $\alpha = 11/3$ spectrum, at scale sizes of $\approx 10^{12}$ m.

Though at first sight it would appear that the above evidence is inconclusive, a closer scrutiny reveals the interesting aspect that all evidence for a spectrum steeper than Kolmogorov applies for large scales ($\approx$ refractive scale and larger). Thus it appears that the data are consistent with a spectrum that is Kolmogorov like for small scales (up to $\approx 10^{11}$ m) and either steepens ($\alpha \approx 4$) or has a an extra bump of power at larger scales ($10^{11} - 10^{14}$ m). It is important that future work focuses on resolving some of these details about the spectrum of electron density fluctuations in the ISM.

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