Part 8

Pulsars and the Interstellar Medium

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Pulsars and Interstellar Scintillations

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Abstract. In this paper, I review our current understanding of interstellar scintillations (ISS) of pulsars. The emphasis is on new results that have appeared during the last five years. The topics covered include (i) review of the understanding of refractive ISS (ii) the shape of the spectrum of electron density fluctuations in the interstellar medium (iii) the distribution of scattering plasma in the Galaxy (iv) resolving pulsar emission regions using ISS and (v) ISS and pulsar velocities.

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. Most observations of pulsars at distances more than about 100 pc and at frequencies below about 1 GHz, fall in the strong scintillation regime whereby the compact nature of the pulsar emission regions allows both diffractive scintillation (DISS) and refractive scintillation (RISS) effects to be seen (see Rickett 1990, for a review of ISS theory). DISS is due to the small scale electron density irregularities in the ISM and produces effects such as angular broadening of the pulsar, which can be observed using VLBI instruments; intensity scintillations with typical decorrelation time scales (τ_d) and bandwidths (ν_d) of $\sim$ 100 seconds and $\sim$ 100 kHz, respectively, for nearby pulsars at metre wavelengths; and broadening of the pulsar profiles due to delayed arrival of the scattered radiation.

RISS effects are produced by large scale electron density irregularities in the ISM and are generally broad-band in frequency. The associated time scales are quite long ($\sim$ weeks to months) for nearby pulsars at metre wavelengths. RISS effects include angular wandering of the scattered image; random modulations of flux and 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.

Observations of these 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 $P(\kappa) = C_n^2(z)\ \kappa^{-\alpha}, \quad \kappa_{out} \ll \kappa \ll \kappa_{inn}$. 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). I will review the various constraints on the detailed shape of the spectrum and new results about the distribution of scattering material.

The study of pulsar scintillation also allows us to infer some properties about pulsars themselves, using the ISM as a tool. Thus, ISS can be used to resolve pulsar magnetospheres as well as to infer transverse space velocities of pulsars. I will describe below recent developments in these areas.

2. Understanding RISS

Though it is now fifteen years since Rickett, Coles, & 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. Measurements of these quantities for a number of pulsars are now available in the literature (e.g. Gupta, Rickett, & Lyne 1994; LaBrecque, Rankin, & Cordes 1994; Gupta, Rickett, & Coles 1993; Kaspi & 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 & τ_d) due to RISS, where the measured modulation indices (e.g. Bhat, Gupta, & Rao, 1999a) are significantly larger than those expected for a Kolmogorov spectrum (Romani, Narayan & Blandford 1986).

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, & McKinnon 1996) showed that this may indeed be true. However, more extensive measurements for about 20 pulsars, recently reported by Bhat, Rao, & 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. 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).

3. Constraining the Power Spectrum

Although there is now considerable support (see for example, Armstrong, Rickett, & 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 summarise 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, Weisberg, & Boriakoff 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 & 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 & Reid 1988b) give $\alpha \simeq 3.67$ upto 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 & 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 & 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, & Gupta 1997), extreme scattering events (ESEs) from pulsar timing observations (e.g. Lestrade, Rickett, & 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 spectrum is Kolmogorov like for small scales (upto $\approx 10^{11}$ m) and it 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 a better understanding of the spectrum.

4. Distribution of Scattering Plasma in the Galaxy

Studies of the scattering measure (SM $\equiv \int C_n^2 dz$) of a large number of pulsars in different directions and at different distances can be used to contrain the distribution of scattering plasma in the Galaxy. Earlier models (e.g. Cordes et al. 1991) consisted of axisymmetric disks of uniform scattering material along with randomly distributed clumps of enhanced scattering material. A major improvement on these was the model of Taylor & Cordes (1993), which incorporated discrete enhanced scattering structures such as galactic spiral arms.

However, such a global picture is still too simplistic to explain the observed scattering in the local ISM (within 1 kpc of the Sun). The first evidence for this came from Philips & Clegg (1992) who found $\overline{C_n^2}$ for PSR B0950+08 to be 5-10 times smaller than that for other nearby pulsars. Recently, Bhat, Gupta, & Rao (1998), from a detailed study of the scattering properties of 20 nearby pulsars, find clear evidence for non-uniform distribution of scattering plasma in the local ISM. Their inference of an ellipsoidal shell of enhanced scattering material, with a morphology very similar to that of the local bubble as known from other studies, is an important step forward in understanding the local ISM. Subsequently, Bhat et al. (this volume) have shown that the scattering properties of many pulsars in the direction of the Loop I bubble can be understood if the boundary of this bubble also has enhanced scattering similar to that found for the local bubble. There are, however, other reports (Britton, Gwinn, & Odeja, 1998; also Minter, this volume) that argue against enhanced scattering at the boundary of the local bubble. Clearly, this area of work promises to be of interest in the near future. It is also possible that a better understanding of scattering in the local ISM may help resolve some of the other mysteries regarding the shape of the spectrum and anomalous RISS effects.

5. Resolving Pulsar Emission Regions Using ISS

Cordes, Weisberg & Boriakoff (1983) were among the first to show that ISS can be used as a tool to resolve pulsar emission regions. Their technique was to look for a shift of the diffractive scintillation pattern as a function of the pulse longitude. Another technique is to wait for multiple imaging events when strong refractive effects produce two well separated scatter broadened images of the pulsar. The interference pattern produced by these two images provides an interferometer in space with a baseline long enough to resolve the compact emission regions. Results from early applications of this method (e.g. Wolszczan & Cordes 1987; Wolszczan, Bartlett, & Cordes 1988) for pulsars PSR B1133+16 and PSR B1237+25 gave the transverse extent of the emission regions as $\Delta S \sim 10^6 - 10^7$ m, which for a dipole geometry, translate to emission heights $\sim$ the light cylinder radius (R_{LC}) of the pulsars. These results are 1 - 2 orders of magnitude more than emission altitude estimates from other techniques (e.g. period to pulse width relationship – see, for example, Kijak & Gil, 1998).

However, recent observations of ISS effects have led to revised estimates of the sizes and altitudes of the emission regions. Most recently, Gupta, Bhat, & Rao (1999) have reported a high quality multiple imaging event for PSR

B1133+16 where they estimate the extent of the emission region as $\Delta S \geq 3 \times 10^5$ m, which corresponds to an emission altitude of $\geq 0.05R_{LC}$. Similar estimates ($\Delta S \approx 10^5$ m) have been obtained from ISS observations at 102 MHz by Smirnova & Shishov (1989). It is interesting to note that these conclusions are also supported by results from VLBI observations of scintillation patterns (Gwinn et al. 1997; also Gwinn et al. this volume), which show the size of the emission region for the Vela pulsar to be $\approx$ 500 km. Thus, ISS observations can be useful for probing the structure of pulsar emission regions and future observations, with better modelling, should provide tighter constraints on the size and location of pulsar emission regions.

6. ISS and pulsar velocitites

Scintillation velocity (V_{iss}) is the net relative velocity between the scintillation pattern and the observer and can be estimated from measurements of DISS parameters. It is a combination of the velocities of the pulsar and observer and of the location and bulk motion of the scattering material (e.g. Gupta et al. 1994) and is usually dominated by the typically large transverse velocity (V_{pm}) of the pulsar. Lyne & Smith (1982), Cordes (1986) and, more recently, Gupta (1995) showed that V_{iss} and V_{pm} are quite well correlated and hence scintillation velocities can be used to estimate transverse velocities of pulsars. One recent useful application of this has been the conclusion that millisecond pulsars have velocities significantly smaller than those of normal pulsars (Johnston, Nicastro, & Koribalski 1998; Gothoskar & Gupta, 1999).

However, Gupta (1995) also noted some discrepancies between V_{iss} and V_{pm} which could be explained as being due to the presence of discrete enhanced scattering structures along different lines of sight. This provides a potential tool for studying the distribution of scattering material in the Galaxy. In this context, Cordes & Rickett (1998) and Deshpande & Ramachandran (1998) have presented techniques for establishing the detailed relationship between V_{iss} and V_{pm} for an arbitrary distribution of scattering material along the line of sight. Using these tools, it should be possible to obtain new results and insights about pulsar proper motions and also distribution of scattering material in the Galaxy.

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