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Pulsars and the ISM

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Abstract.

Radio signals from pulsars are significantly affected by propagation effects such as dispersion, faraday rotation and scintillations in the interstellar medium (ISM). In this paper, I review some aspects of our understanding about pulsars and interstellar scintillations (ISS). The study of pulsar scintillation has dual benefits in that it allows us to learn about the properties of the ISM using pulsars as probes, as well as to infer some properties about pulsars, using the ISM as a tool. Both these aspects are addressed in this paper. The main emphasis is on recent developments in the following topics : (i) the shape of the spectrum of electron density fluctuations in the interstellar medium (ii) the distribution of scattering plasma in the local ISM and (iii) resolving pulsar emission regions using ISS.

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. Studies of these provide valuable information about the properties of the ISM. Interstellar dispersion produces smearing of pulses observed with a finite bandwidth, due to the frequency dependent travel time in the plasma. Detailed studies of dispersion measures of pulsars located in different directions and at different distances are useful to understand the large scale distribution of free electrons in the Galaxy. Interstellar Faraday rotation produces variation of the angle of linear polarization with frequency for pulsar radiation. Rotation measure studies of pulsars have been used to understand the large scale magnetic field structure in the Galaxy.

In this paper, I will be concentrating only on scintillation studies of pulsars. 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. These scintillations produce a variety of observable effects in the detected radio signals from pulsars. Most observations of pulsars at distances more than about 100 pc and at frequencies below about 1 GHz, fall in what is referred to as the strong scintillation domain wherein the scintillations exhibit two clearly separated regimes : diffractive scintillation (DISS) and refractive scintillation (RISS) (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), which can be most easily seen in pulsar dynamic spectra data – two-dimensional records of pulsar intensity as a function of time and frequency ; 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.

The compact nature of the pulsar emission regions allows both diffractive and refractive scintillation (RISS) effects to be seen. For most other kinds of radio sources, the diffractive scintillations are generally quenched due to their relatively large angular sizes.

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 supports a power-law form for the electron density power spectrum, quantified as

$$\mathrm{P}(\kappa) \;=\; \mathrm{C}_\mathrm{n}^2(\mathrm{z})\,\kappa^{-\alpha}, \qquad \kappa_\mathrm{out} \ll \kappa \ll \kappa_\mathrm{inn} \quad . \tag{1}$$

Here $\mathrm{C}_\mathrm{n}^2(\mathrm{z})$ 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 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. For example, ISS can be used to infer transverse space velocities of pulsars. Also, under favourable conditions, scintillations provide an effective interferometer in space with a baseline large enough to resolve the compact emission regions of pulsars. I will describe below recent developments in the latter application.

2. 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 summarize here.

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

(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, Gupta & Rao 1999; 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 of 10^{11} m.

The evidence *against* a pure Kolmogorov spectrum is as follows :

(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. 1999; 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 $< \alpha >= 3.84 \pm 0.02$. These measurements probe 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. 1999; 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 spectrum having $\alpha = 11/3$, at scale sizes of $\approx 10^{12}$ m.

At first sight it would appear that the above evidence is inconclusive. However, 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, one plausible solution that offers itself is a spectrum that is Kolmogorov like for small scales (upto $\approx 10^{11}$ m) and either steepens ($\alpha \approx 4$) or has 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 these aspects of the spectrum.

3. Distribution of Scattering Plasma in the local ISM

Studies of the scattering measure ($\mathrm{SM} \equiv \int \mathrm{C}_\mathrm{n}^2 \mathrm{dz}$) 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 (defined to be the region within ~ 1 kpc of the Sun). The first evidence for large variations in the scattering properties within the LISM came from Philips & Clegg (1992) who found the line of sight average value for 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, found clear evidence for non-uniform distribution of scattering plasma in the local ISM. They infer the presence of an ellipsoidal shell of enhanced scattering material, surrounding a cavity of low density plasma of reduced scattering strength. The morphology of their scattering structure is very similar to that of the local bubble (in which the Sun also resides) as known from other studies. This could be an important step forward in our understanding of the scattering in the local ISM. Subsequently. Bhat et al. (2000) have shown that the anomalous scattering 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 (e.g., Britton, Gwinn & Odeja, 1998) 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.

4. 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. The basic technique relies on the assumption that the emission regions at different pulse longitudes are at different transverse locations when the radiation from them is being directed to the observer, as will happen for a case when radiation is beamed tangential to the local magnetic field lines in a dipolar field geometry. Cordes et al. (1983) looked for this effect by looking for a shift of the diffractive scintillation pattern as a function of the pulse longitude. A more sensitive 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 transverse shifts of the 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 $\geq 0.05 R_{LC}$. 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 (e.g. Gwinn et al. 1997), which show the size of the emission region for the Vela pulsar to be ≈ 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.

5. Summary

I have discussed in detail some aspects of the interstellar scintillations of pulsar signals. The summary of our current understanding of the shape of the power spectrum of electron density fluctuations in the ISM is that there are evidences both in favour and against a pure Kolmogorov spectrum. A model where the spectrum is Kolmogorov like at smaller scales (upto $\approx 10^{11}$ m) and either steepens ($\alpha \approx 4$) or has an extra bump of power at larger scales ($10^{11} - 10^{14}$ m) appears to be consistent with these. Clearly, more work is needed to better understand the spectrum. In addition to our existing understanding of the large scale distribution of scattering plasma in the Galaxy, new results have shown clearly that the distribution is not uniform in the local ISM. There is now clear evidence for enchanced scattering from the boundary of the local bubble, as well as from that of the LoopI bubble. These are significant results as they can help in better understanding of the scintillation phenomenon and the spectrum. Interstellar scintillations continue to be a useful technique for studying the size and location of pulsar emission regions. Recent results have yielded estimates which are in better agreement with estimates of emission altitudes from other techniques.

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