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Pulsar scintillation and the local interstellar medium

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Abstract. Ever since their discovery, pulsars have been proved to be excellent tools to study the Interstellar Medium. Results from new observations using the Ooty Radio Telescope at 327 MHz are used to investigate the properties of the Local Interstellar Medium; in particular, the distribution of radio wave scattering material and the spatial power spectrum of plasma density fluctuations. The morphology of the scattering structure inferred from the observations shows a striking similarity with that of the Local Bubble. The observations suggest that the overall nature of the spectrum is *Kolmogorov-like* in the spatial scale range ~ 10^6 m to 10^{11} m, with *excess* power at larger scales (~10^{12} – 10^{13} m). Data are also used to test the quantitative predictions from refractive scintillation theory.

Key words : pulsars, bubbles, turbulence, scattering

1. Introduction

Propagation effects on pulsar signals, such as dispersion and scattering, are useful in probing the distribution of thermal plasma in the ISM. Interstellar Scattering (ISS) results from propagation of radio waves through the electron density inhomogeneities in the ISM, and has been extensively studied for understanding the distribution and the spectrum of plasma density fluctuations in the ISM. These density fluctuations are thought to arise from plasma turbulence process in the ISM.

Due to their unique properties such as pulsed nature of signals and spatial coherence, pulsars are expected to show a wide variety of observable effects due to ISS, which manifects itself in two basic forms, known as Diffractive Interstellar Scintillation (DISS) and Refractive Interstellar Scintillation (RISS). These are propagation effects due to small-scale (~10^6–10^8m) and large-scale (~10^{10}–10^{12}m) electron density inhomogeneities. While DISS was recognized soon after the discovery of pulsars, RISS has been recognized only during 1980's and continues to be an active area of research (Rickett 1990).

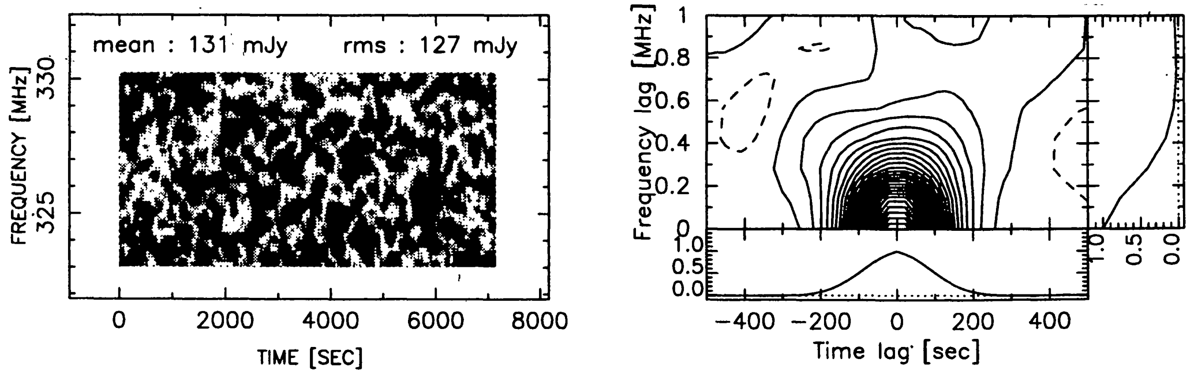

Figure 1. Dynamic scintillation spectrum of PSR B0919+06 as recorded on 24 May 1994 using the Ooty Radio Telescope (*left*), and its ACF in frequency and time lags (*right*).

Following its recent up-gradation and the subsequent boost in sensitivity, the Ooty Radio Telescope (ORT) has become a very powerful instrument for pulsar studies. By taking advantage of this, a program of long-term pulsar observations was undertaken with the objectives of understanding the ISS phenomena and properties of the Local Interstellar Medium (LISM). These observations mark a considerable improvement in the volume and quality of pulsar scintillation data, the analysis and interpretation of which have produced several interesting results. This paper gives a brief description of the observational aspects and some of the important results.

2. Observations and data analysis

Within the sky coverage and sensitivity limits of ORT, there are 20 nearby pulsars that were found suitable for studying the LISM. For these pulsars, the dynamic scintillation spectra – records of intensity variations in the frequency-time plane – were obtained at ~ 10 – 100 epochs, spanning ~ 100 – 1000 days during 1993-95. Such spectra display intensity scintillation patterns that fade over short time intervals and narrow frequency ranges, arising from diffractive scintillation effects. This is illustrated in Fig. 1.a. To quantify the average characteristics of scintillation patterns at a given epoch of observation, the two-dimensional auto co-variance function (ACF) of the dynamic spectrum is computed (see Fig. 1.b), and fitted with a two-dimensional elliptical Gaussian function, to yield the parameters, *viz.*, decorrelation bandwidth (ν_d) and scintillation time scale (τ_d), which are the widths of the ACF along zero time and frequency lag axes, respectively, and the drift slope ($dt/d\nu$), which corresponds to the orientation of the ACF. Time series of these 3 quantities and the mean flux density (F) are used to study the various observable effects due to diffractive and refractive scintillations. From the present observations, it has been possible to estimate the scintillation observables with accuracies much better than that which has been possible from most earlier data. A more detailed account of the observations, data analysis and the basic results can be found in Bhat et al. (1999a).

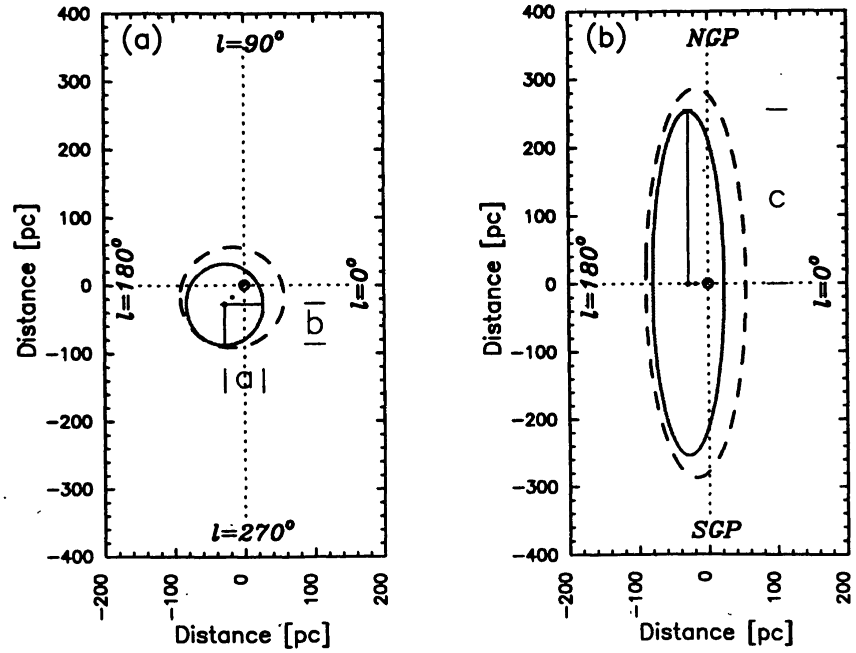

Figure 2. Geometry of the local scattering structure which best reproduces the observed results. Panels (a) and (b) are sections along the Galactic plane and along a plane perpendicular to the Galactic plane and passing through the Galactic poles, respectively.

3. Interpretation of the results and discussion

The results from the present observations have been used to study several aspects of the LISM (region within ~ 1 kpc of the Sun) and ISS phenomena. The main results are summarized below :

3.1 Structure of the local interstellar medium

There is a variety of evidence from observational data at X-ray, UV and optical bands suggesting that the Solar system resides in a hot X-ray emitting cavity that is virtually devoid of neutral hydrogen (Cox & Reynolds 1987; Snowden et al. 1990). Despite much observational progress, several aspects of this region, also known as the Local Bubble, are still not well understood. Nearby pulsars form potential tools in this regard.

The behaviour of the line of sight averaged strength of scattering, $\overline{C_n^2}$, with direction (*l*, *b*) and location (DM or distance) forms a useful means of investigating the nature of distribution of plasma density fluctuations in the ISM (Cordes et al. 1991). Prescise estimates of $\overline{C_n^2}$ have been obtained from the present data, and there is about two orders of magnitude fluctuations, much larger than that predicted from current models for the $\overline{C_n^2}$ distribution in the Galaxy. There is a systematic behaviour of $\overline{C_n^2}$ with distance (D), with a turnover near ~ 200 pc, followed by a downward trend up to ~ 1 kpc. Also, there are several examples of anomalous scattering, whereby pulsars with comparable DMs or at similar distances show remarkably

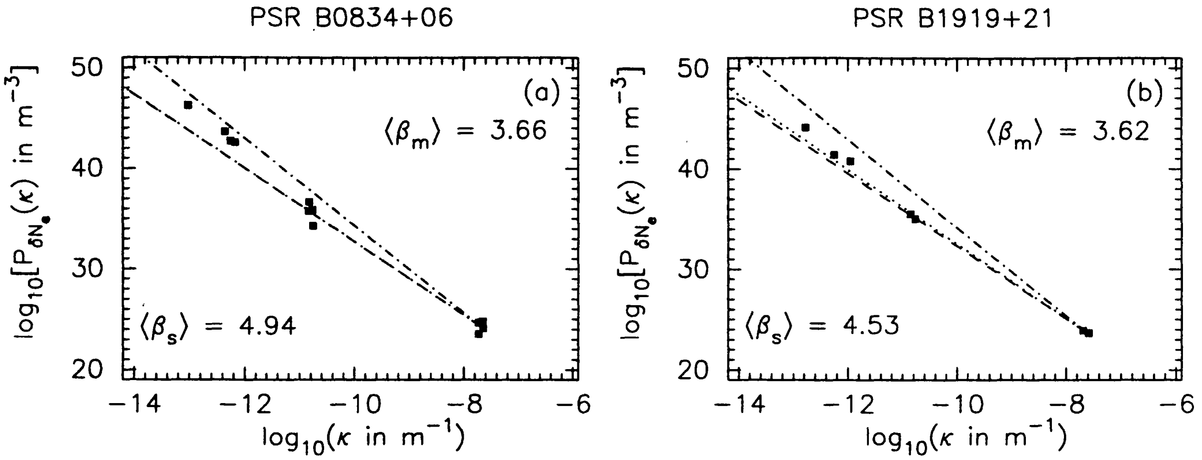

Figure 3. Composite density spectrum inferred for (a) PSR B0834+06 and (b) PSR B1919+21. The dotted and dot-dashed lines are for $\alpha = 11/3$ and $\alpha = 4$, respectively.

different scintillation characteristics. The strength of the anomaly shows a systematic behaviour with DM and D. These results suggest a nonuniform, but organized distribution of plasma density fluctuations in the LISM.

The results are modelled in terms of large-scale spatial inhomogeneities in the distribution of C_n^2 in the LISM. Different types of possible density structures were considered, and the viability of each was examined (see Bhat et al. 1998 for details). Simple models in which the Solar neighborhood has an enhanced or reduced scattering strength relative to the ambient medium fail to reproduce the observational results. The resules are best explained in terms of a 3-component model, where the Solar system resides in a weakly scattering medium, surrounded by a shell of enhanced scattering, embedded in the normal, large-scale ISM. The geometry of the structure is schematically shown in Fig. 2. It has an ellipsoidal morphology, and is more extended away from the Galactic plane. The n_e fluctuations in the shell ($10^{-0.96} < \int_0^d C_n^2(z)\,dz < 10^{-0.55}$ pc $m^{-20/3}$, where d is the thickness) are much larger than those in the interior ($10^{-4.70} < \overline{C_n^2} < 10^{-4.22}$ $m^{-20/3}$) and the outer region ($\overline{C_n^2} < 10^{-3.30}$ $m^{-20/3}$). The morphology of the scattering structure is found to be strikingly similar to that of the Local Bubble, as inferred from various earlier studies based on data at X-ray, EUV, UV and optical wave-bands.

3.2 Plasma turbulence spectrum in the local interstellar medium

Interstellar plasma turbulence is thought to be the cause of electron density fluctuations (δn_e) which give rise to ISS, but the exact mechanism is still not well understood. The spatial power spectrum of δn_e forms a major input in this regard. The information on the nature of the spectrum primarily comes from pulsar scintillation studies. However, observations so far have given conflicting interpretations on the nature of the spectrum (Narayan 1988), and not all the data are in agreement with the expectations of a Kolmogorov from of spectrum, which has been the *de facto* standard (Rickett 1996).

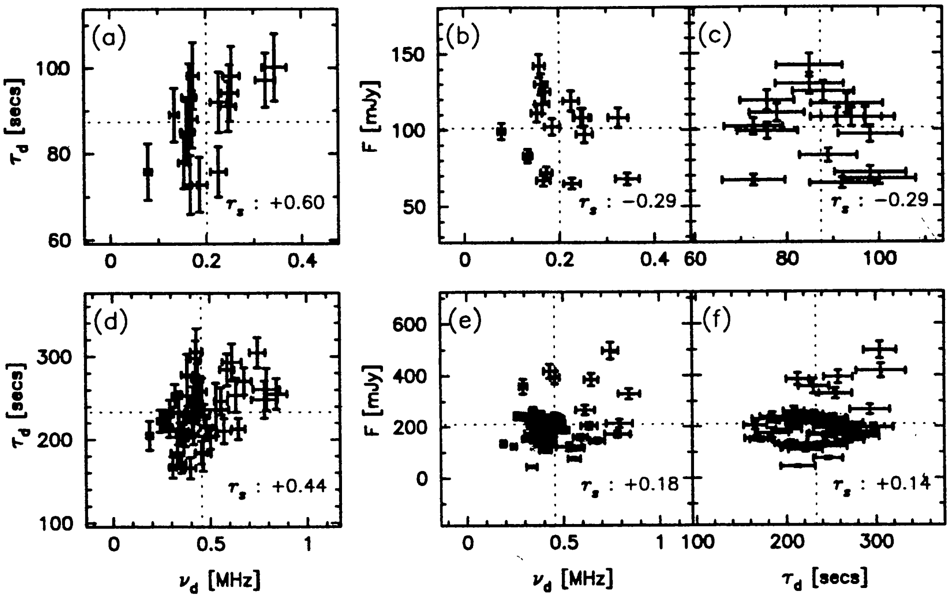

Figure 4. Sample scatter plots illustrating the correlation properties between various observables. Panels (a) – (c) are for PSR B0823+26, and (d) – (f) are for PSR B1919+21.

The unique advantages of present observational data, such as an unbiased sample, simultaneous measurements of DISS and RISS, and a variety of observable effects, allow a fresh investigation of this matter. The main results can be summarized as follows :

1. The observed modulations of ν_d, τ_d and F are larger than the predictions of models based on "thin-screen" scattering and a Kolmogorov power-law spectrum.
2. The estimates of density spectral slope (β) from the measurements of diffractive and refractive angles are closer to the Kolmogorov index for several pulsars. For nearby pulsars (D ~ 200–700 pc), the spectrum is somewhat steeper ($11/3 < \beta < 4$).
3. The anomalous scintillation behaviour of persistent drift slopes seen for some pulsars suggests an *excess* power in the low wavenumber range ($\kappa \sim 10^{-12} - 10^{-13}$ m^{-1}). Another possible interpretation is the existence of discrete plasma structures, with size ~ 10–100 AU and electron density ~ 2 – 4 cm^{-3}.

A careful consideration of all the available results from the literature and the present work leads to the picture of a *Kolmogorov-like* spectrum ($\alpha \approx 11/3$) in the range $\kappa \sim 10^{-6}$ m^{-1} to ~ 10^{-11} m^{-1}, with *excess* power at $\kappa \sim 10^{-12} - 10^{-13}$ m^{-1} for the overall nature of the spectrum in the LISM (see Bhat et al. 1999b for details).

3.3 Refractive scintillation in the interestellar medium

Ever since its discovery in early 1980's, RISS has been playing an important role in radio astronomy, and it is thought to be the cause of a variety of phenomena seen with pulsars and other compact radio sources (Rickett 1990). Over the past 10 years, there have been a number of observational attempts supporting several basic consequences of RISS, but the quantitative predictions from theories have not been thoroughly tested.

Data from the present observations have been used to test the theoretical predictions. The observations allow simultaneous measurements of several observable (ν_d, τ_d, $dt/d\nu$ and F), spanning many cycles of refractive fluctuations. An extensive correlation analysis is carried to examine the relation between the fluctuations. The theory predicts a strong correlation between the fluctuations of ν_d & τ_d and strong anti-correlations between those of ν_d & F and τ_d & F (Romani et al. 1986). For 5 pulsars, there is a reasonable agreement with the predictions, but for the rest of the pulsars, results are too complex to comprehend in terms of simple models of RISS (see Bhat et al. 1999c for details).

The correlated variations of observables and the qualitative agreement with the predictions seen for some pulsars confirm that the basic picture is correct. However, discrepancies in the form of reduced correlations and absence of one or more predicted correlations seen with several pulsars suggest that the existing models are too simplistic. A more comprehensive theory incorporating realistic scenarios – such as extended and/or inhomogeneous scattering media and *non-power-law* forms of density spectra – needs to be evolved for explaining the observational results.

4. Summary and conclusions

Data from long-term pulsar observations using the Ooty Radio Telescope have been used for studying the ISS phenomena and properties of the LISM. The important findings from the present study are :

- The distribution of radio wave scattering material in the LISM is not uniform. A 3-component model, where the Solar neighborhood is surrounded by an ellipsoidal shell of enhanced scattering, is proposed for the LISM. The morphology of the scattering structure is found to be strikingly similar to the Local Bubble.
- The spectrum of plasma density fluctuations in the LISM has a *Kolmogorov-like* form ($\alpha \approx 11/3$) in the spatial scale range $\sim 10^6$ m to $\sim 10^{11}$ m. At larger spatial scales ($\sim 10^{12} - 10^{13}$ m), there is evidence for *excess* power. Also, the accumulated data suggest the presence of localized density structures along some lines of sight.
- The existing models for refractive interstellar scintillation are too simplistic, and more comprehensive theories are necessary for explaining the observational results on the refractive fluctuations of observables and their cross-correlations.

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