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Measurement of scatter broadening for 27 pulsars at 327 MHz

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ABSTRACT

New measurements of scattering delay for 27 pulsars at 327 MHz are presented. These measurements significantly improve on the available set of measurements for pulsars with dispersion measures in the range 100 to 250 pc cm^{-3}. These measurements also sample an important section of the Galactic volume which should render better modelling of the electron density distribution. The dependence of the scatter broadening on the dispersion measure is discussed, and modelled based on the new data combined with similar, earlier, measurements.

Key words: scattering – pulsars: general.

1 INTRODUCTION

The density fluctuations in the interstellar plasma are responsible for the scattering of radio waves and this phenomenon has been studied extensively ever since the discovery of scintillations in early observations of pulsars (Scheuer 1968). The scattering of pulsar signals can be studied through many observable effects like the temporal broadening of pulse profiles, angular broadening and scintillation (see Rickett 1990 and references therein). By studying these different effects one can hope to study the density fluctuations in the interstellar medium (for example, Alurkar, Slee & Bobra 1986; Gwinn, Bartel & Cordes 1993).

Out of the 706 pulsars listed in the pulsar catalogue by Taylor, Manchester & Lyne (1993; updated version, 1995) the measured temporal broadening exists for only about 145 pulsars. Hence a systematic survey for measuring the scatter broadening in a large number of pulsar directions where such data are not available yet is undertaken using the Ooty Radio telescope (ORT). To help improve the detailed study of the distribution of the free electron density in the Galaxy it is desirable that such measurements should be available for a larger sample. For the first phase of the observations we selected 27 high dispersion-measure pulsars. The results from these observations are presented in this paper.

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2 OBSERVATIONS

Observations were conducted between 1996 January and April, with the ORT situated at a latitude of about 11°N in South India. ORT has an offset-parabolic cylindrical reflector, the dimensions of which are about 500 m in north–south and 30 m in east–west, and has an equatorial mount. The feed array consists of 1056 dipoles oriented along north–south, as the result of which it is not sensitive to the other (east–west) component of polarization. The telescope operates at a fixed centre frequency of 327 MHz.

The front-end electronics down-converts the signal to an intermediate frequency (IF) of 30 MHz. This IF signal is used as an input to a special purpose pulsar processor where it is passed through four filters with a width of 2.5 MHz each, spanning the band from 25 to 35 MHz. The signals from each of the filters are sampled using harmonic complex sampling at the Nyquist rate. Each of these sample trains is then Fourier transformed to obtain 256 spectral channels across each of the 2.5-MHz bands. Thus, each of the 1024 channels produced has a width of 10 kHz. The channel outputs are total-power detected and are digitally delayed to compensate for the interstellar dispersion, before adding them up to produce a single time series with a time resolution of 102.4 μs. These time series are then averaged synchronous with the apparent pulse period over blocks of every 2^{15} sample points separately to obtain an average profile over a specified number of bins across the pulsar period. The mean total power (in some arbitrary units) in each of these blocks is computed and subtracted from the average profile for that block. The subtracted means of all the blocks are stored separately and were used for flux calibration (for more details of this processor see McConnell et al. 1996).

2.1 Sample selection

We selected a set of candidates for which the expected pulse broadening due to scattering was greater than about 40 per cent of the effective pulse width, which included the dispersion smearing of the spectral resolution used and the intrinsic time resolution of the system in addition to the intrinsic pulse width (taken from the pulsar catalogue of Taylor et al. 1995). In cases in which the pulse widths at higher frequency were not available, an intrinsic duty cycle of 4 per cent was assumed. A nominal estimate of temporal broadening due to interstellar scattering was calculated at 327 MHz based on the electron density distribution model of Taylor & Cordes (1993). With the above-mentioned criterion, a set of 27 candidates was selected for observations.

3 ANALYSIS AND RESULTS

The sub-average profiles for a given pulsar were combined further to produce an observed average pulse profile. The scatter broadening was estimated using a least-squares-fit to the observed profile with the following well-known model. The observed pulse profile $y(t)$ is the convolution of intrinsic pulse shape $x(t)$ with (a) the impulse response characterizing the scatter broadening in the ISM, $s(t)$; (b) the dispersion measure across the narrow spectral channel, $d(t)$, and (c) the instrumental impulse response, $i(t)$. That is,

$$y(t)=x(t)\otimes s(T)\otimes d(t)\otimes i(t), \quad (1)$$

where $\otimes$ denotes convolution. In a simplistic picture, the scattering material is assumed to be concentrated in a region the thickness of which is very small compared with the distance between the pulsar and the observer (thin screen approximation). Then the impulse response function characterizing the interstellar scatter broadening can be written as

$$s(t)=\exp(-t/\tau_{sc}). \quad (2)$$

For the Kolmogorov power spectrum given by $P_{\delta n_e}(q)=C_n^2 q^{-11/3}$, the value of τ_{sc}, a measure of scatter broadening, depends on the frequency ν and the dispersion measure (DM) as $\nu^{-4.4}$ and $DM^{2.2}$ respectively (see Sutton 1971).

The intrinsic pulse shape profile was assumed to be a Gaussian with half-power width w_0. The template of the scatter-broadened pulse profile can be produced by convolving the different responses with a Gaussian as given by equation (2). The dispersion smearing (due to the finite width of the frequency channels) is considered to correspond to a channel width of 10 kHz. However, in most cases the smearing can be ignored, as a dispersion measure as high as 425 pc cm^{-3} produces a smearing of only about 1 ms.

Many different combinations of τ_{sc} and w_0 were tried in a suitable grid search to look for the best match between the observed average pulse and the predicted pulse template. In some cases, where it is suspected that the intrinsic pulse profile may have two components, we have assumed an intrinsic pulse profile consisting of two Gaussians with an assumed separation while solving for the ratio of their heights and a common value for their widths. The best fit was produced by minimizing the normalized χ^2 value defined by

$$\chi^2=\frac{1}{N_{dof}\sigma_n^2}\sum_{i=1}^{N}[y_i^o(t)-y_i^m(t)]^2, \quad (3)$$

where σ_n is the root mean square noise value of the off-pulse, y^o is the observed pulse profile and y^m is the model pulse profile. The y^m profile is similar to $y(t)$ except for an amplitude scalefactor and a constant offset in phase and baseline that minimizes χ^2. N is the number of points used, and N_{dof} is the number of degrees of freedom.

Fig. 1 gives the observed pulse profile of PSR J1848 – 0123, and the best-fitting model (solid line). The best-fitting scatter broadening for this pulsar is 141.2 ms.

The results of the analysis are listed in Table 1. The table lists, against the name of each pulsar, its rotation period, dispersion measure, the observed average flux density at 327 MHz, the estimated scatter broadening (τ_{sc}) and its error bar, an estimate of the intrinsic width (w_i) and its error bar, the correlated error on ($\tau_{sc}+w_i$), the value of the minimum χ^2 obtained, number of degrees of freedom, and the expected scatter broadening according to the free electron density distribution model of Taylor & Cordes (1993). The error bars correspond to a 99.99 per cent confidence level.

3.1 Flux calibration

As mentioned in Section 2, the total-power estimate for each subaveraged profile was recorded. For simplicity, a mean of these estimates was computed for each observa-

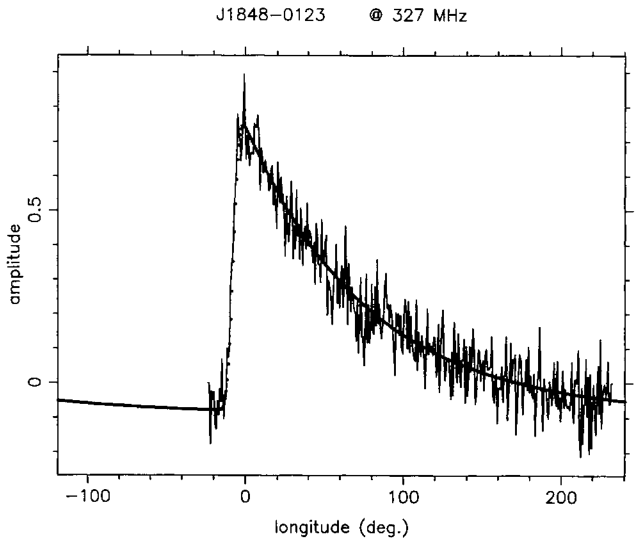

Figure 1. The portion of the observed pulse profile of PSR B1848 – 0123 at 327 MHz considered for model fitting. The solid line gives the best fitting model for the pulse, with a scattering delay of 141 ± 19 ms.

Table 1. Results. The table lists period, dispersion measure, flux at 327 MHz, best-fitting scatter broadening at 327 MHz and its error corresponding to 99.99 per cent confidence level, the best-fitting intrinsic width and its error corresponding to 99.99 per cent confidence level, the correlated error on $(\tau_{sc}+w_i)$, the normalized χ^2, the degrees of freedom, and the expected scatter broadening according to the electron density model of Taylor & Cordes (1993).

No.	Name	P (s)	DM (pc/cc)	S_{327} (mJy)	Delay (ms) τ_{sc}	$\Delta\tau_{sc}$	Width (ms) w_i	Δw_i	$\Delta(\tau_{sc}+w)$ (ms)	χ^2	N_{dof}	τ_c
1	0738–4042	0.3749	160.8	105	76	3	20	3	3	1.2	485	0.3
2	1209–5556	0.2798	174.0	3	4	2	2	2	2	1.0	55	10
3	1556–4258	0.3292	145	20	12	2	5	1	1	1.0	167	6
4	1604–4909	0.3274	140.8	16	2	2	5	3	1	1.3	55	11
5	1613–4714	0.3824	161.3	16	9	3	7	3	2	1.2	117	15
6	1615–3936	0.4073	152	7	5	5	8	5	3	0.9	75	6
7	1651–5222	0.6351	179.1	15	7	2	8	2	2	1.3	101	13
8	1705–3422	0.2554	145	18	29	7	16	6	5	1.1	488	11
9	1722–3207	0.4772	126.035	126	13	1	6	1	1	1.5	125	11
10	1732–4128	0.6280	195	12	28	9	13	11	8	1.0	197	18
11	1745–3040	0.3674	88.4	79	5	1	4	1	1	1.3	121	5
12	1750–3506	0.6840	195	11	54	52	99	45	30	1.0	113	20
13	1757–2421	0.2341	178.0	18	36	20	10	25	14	1.0	113	28
14	1759–2205	0.4610	177.3	50	10	2	4	2	1	1.2	90	27
15	1807–2715	0.8278	313.3	26	32	8	16	5	5	1.1	147	9
16	1823–0154	0.7600	135	7	10	3	5	4	2	1.1	70	9
17	1829–1751	0.3071	217.8	74	96	18	33	6	6	1.1	502	32
18	1833–0338	0.6867	235.8	132	51	2	19	2	2	1.2	207	40
19	1835–1106	0.1659	132	33	6	2	7	2	2	1.0	137	13
20	1836–1008	0.5627	318	32	83	61	112	63	33	1.3	98	152
21	1848–0123	0.6594	159.1	121	141	19	14	7	6	1.0	487	17
22	1848–1414	0.2978	134	7	8	10	12	12	5	1.1	37	8
23	1902+0556	0.7466	179.7	29	33	16	21	12	11	0.9	157	15
24	1903–0632	0.4319	195.7	45	18	1	9	2	1	1.2	317	12
25	1904+0004	0.1395	234	12	13	6	18	6	4	1.2	493	36
26	1905–0056	0.6432	225	18	11	3	11	3	2	1.0	107	26
27	2013+3845	0.2302	238.6	27	15	6	24	7	4	1.1	493	15

tion, assuming that the system parameters were constant within the 30-min integration. This mean is the sum of the contribution from the system temperature and the pulsar (C_s+C_p). The average pulse contribution was estimated from the average profile to estimate the contribution C_s proportional to the system temperature alone. The system temperature was estimated by assuming the receiver temperature to be 110 K (Selvanayagam et al. 1993), and by computing the sky background temperature at 327 MHz extrapolating from that given by the 408 MHz survey of Haslam et al. (1982) (using a frequency dependence of $\nu^{-2.5}$). The sensitivity of the ORT was estimated to be about $(2.5\ \mathrm{K\,Jy^{-1}})\cos\delta$, using a large number of continuum calibration sources, where δ is the declination of the source. This gave us the ability to calculate the average flux of the observed pulsars at 327 MHz. The flux values thus calculated are given in Table 1.

However, it should be remembered here that our typical observation time for each pulsar was only one session of about 30 min, which may not be enough to average out the variations of pulsar flux due to various systematic effects. This is particularly so if the pulsar signal is highly linearly polarized, and it should be remembered that ORT responds to only single linear polarization and that the observing bandwidth was only 10 MHz. Moreover, the explicit declination dependence of the gain variation of the ORT system is not well calibrated, especially at high declinations.

4 DISCUSSION AND CONCLUSION

Out of our 27 measurements, 26 are new measurements. The only pulsar in our sample for which a scattering delay measurement already exists is PSR J1848 – 0123. The measured scatter broadening at 430 MHz is 42 ms (Cordes, Weisberg & Boriakoff 1985). For an assumed dependence of $\lambda^{4.4}$ corresponding to the Kolmogorov spectrum for irregularities, the expected scattering delay is about 140 ms. As Table 1 shows, the measured value is 141 ± 19 ms, quite consistent with the measurement at the higher frequency. It may be worth mentioning here that for this pulsar, at 327 MHz, the scattering delay predicted by the electron density model of Taylor & Cordes (1993) is only 17 ms.

As Fig. 1 shows, the profile has a distinctly sharp rise and then an exponential fall-off, indicating that the scatter broadening is dominated by a single scatterer along the line of sight. The measured distance of 3.8 kpc to this pulsar and its direction ($l=31\overset{\circ}{.}339$, $b=0\overset{\circ}{.}039$) indicate that it lies behind the Sagittarius arm, which may explain the enhanced scattering.

One of the conventional methods of examining the scattering properties along various lines of sight is to plot the dispersion measure (DM) versus the measured scatter broadening. What is plotted in Fig. 2 is τ_{sc} (at 400 MHz) versus DM for 167 pulsars, after including our 26 new measurements. The open circles indicate the scatter broadening

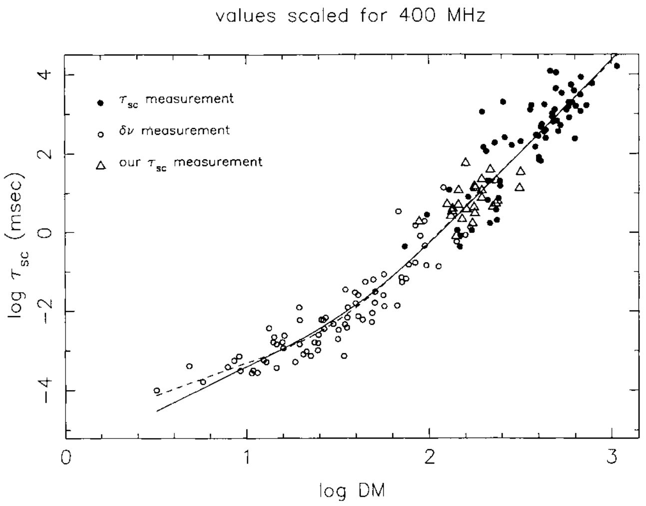

Figure 2. Observed scatter broadening as a function of dispersion measure, for 167 pulsars. Triangles represent our scattering delay measurements; open circles represent the scattering delay calculated from the decorrelation bandwidth measurement with the relation $2\pi\nu\tau_{sc}=1$; filled circles represent the directly measured scatter broadening. The values corresponding to open and filled circles are taken from the Princeton pulsar catalogue of Taylor et al. (1995). The best-fitting models of the form $\tau_{sc}=A\mathrm{DM}^{\alpha}(1+B\mathrm{DM}^{\gamma})$, with values of $\alpha=2.2$ and $\alpha=1.47$, are shown as continuous and broken lines (see the text for more details).

estimates based on the decorrelation bandwidth measurements, open triangles represent our scatter broadening measurements with the ORT, and filled circles indicate earlier direct measurements of scatter broadening. The τ_{sc} values were scaled to 400 mHz assuming a frequency dependence of $\nu^{-4.4}$. A line-fit for the direct τ_{sc} measurements (filled circles and triangles) shows a slope of 4.3 ± 0.4, and the corresponding slope for τ_{sc} measurements estimated through the decorrelation bandwidth measurements is 2.7 ± 0.3. It is interesting that similar results will be obtained when the DM dependence is considered in two separate DM ranges. The decorrelation bandwidth measurements available for pulsars with DM > 100 pc cm^{-3} seem to suggest that the steepening of the τ_{sc} dependence with DM is real and is not related to the coincidence that the dependence appears to change with the kind of measurement used.

Sutton (1971) and Rickett (1977) have noted that for DM $\lesssim 20$ pc cm^{-3} the measured scattering delay increases roughly as DM^2, but for $20\lesssim$ DM $\lesssim 400$ pc cm^{-3} the relationship steepens considerably, to give a slope of about 4. This is essentially what is seen in Fig. 2. For DM less than about 100 pc cm^{-3}, τ_{sc} (derived mainly from the decorrelation bandwidth measurements) values fit best for a power-law index of 2.7 ± 0.3. This is not significantly different from the expected slope of 2.2 for a Kolmogorov spectrum. However, for DM greater than about 100 pc cm^{-3} the observed slope is significantly higher (4.3 ± 0.4) than 2.2.

At this point, it may be worth recalling the assumptions which have gone into expecting the dependence of scatter broadening on various physical parameters. If one assumed that (i) $\delta n_e \propto n_e$, (ii) DM $\propto$ distance, (iii) the scattering along the line of sight can be assumed to be confined to a thin screen half way down the line of sight, and (iv) the spectrum of wave numbers follows a power law of index 11/3 (Kolmogorov spectrum), then we get a relation (Romani, Narayan & Blandford, 1986),

$$\tau_{sc}\propto C_{-4}^{11.2}\lambda^{4.4}\mathrm{DM}^{2.2} \quad (4)$$

where $C_{-4}=10^4C_n^2$, λ is the wavelength of observation. For DM > 100 pc cm^{-3} it is clear that some of the assumptions become invalid. The existence of isolated regions of enhanced scattering along sight lines to many pulsars, and the consequent probable failure of the assumption that the scatterer is half-way down the line of sight, can very well explain the large deviation of the observed scattering from the mean trends, in both of the DM ranges. However, a very systematic change in the DM dependence needs to be understood differently. Rickett (1977) argued that the steep dependence of τ_{sc} on DM is the manifestation of large-scale variation of C_n^2 in the Galaxy. However, Hall (1980) argued that it is due to the large-scale variation of the mean electron density. Cordes et al. (1985) analysed various possibilities, and came to a conclusion which agrees with that of Rickett (1977).

One should keep in mind that, at higher DM, one is essentially looking in the central regions of the Galaxy. Instead of the assumption that the density fluctuation $\delta n_e \propto n_e$, it is more appropriate to assume a galactocentric radius (R) dependence of $\delta n_e \propto n_e \times f(R)$, where $f(R)$ is a suitable function of R, in order to explain the observed enhanced scattering for higher DMs. Such a dependence in some sense is already incorporated in the electron density distribution model of Taylor & Cordes (1993). Our new measurements sample a useful volume of the inner Galaxy and hence should help in refinement of this model. As can be seen from Table 1, in more than half of the directions the broadening observed differs from that predicted from the model by significant factors. These deviations are unlikely to be due to the lack of local enhancements (other than the Gum region) being incorporated in the model. This is because most of our pulsars have DM > 100 pc cm^{-3} and hence are somewhat too distant to see an appreciable contribution from the locall H II region.

For the purpose of many statistical studies of the pulsar population, it is useful if the mean dependence of τ_{sc} on DM can be modelled in a simple manner, spanning the entire range of DMs observed. Although similar attempts have been made earlier, the sample available then was much smaller in size (see for example Bhattacharya et al. 1992). We have considered a functional form given by

$$\tau_{sc}=A\mathrm{DM}^{\alpha}(1+B\mathrm{DM}^{\gamma})\lambda^{4.4} \quad (5)$$

and sought values for (A,α,B,γ) that fit the observed mean dependence of $\log\tau_{sc}$ on log DM shown in Fig. 2. The best-fitting model of the above form is found to be

$$\tau_{sc}(\mathrm{ms})=4.2\times10^{-5}\mathrm{DM}^{1.6}\times(1+3.1\times10^{-5}\mathrm{DM}^{3})\lambda^{4.4} \quad (6)$$

and is shown in Fig. 2 (as a dashed curve). Here, λ is substituted in metres. We have also attempted similar modelling with the value of α fixed to 2.2 (corresponding to the dependence expected from a Kolmogorov spectrum for electron density fluctuation). This gives us the relation

$$\tau_{sc}(\mathrm{ms}) = 8.4 \times 10^{-6} \mathrm{DM}^{2.2} \times (1 + 8.3 \times 10^{-5} \mathrm{DM}^{2.5}) \lambda^{4.4}, \quad (7)$$

where the term $(1 + B\,\mathrm{DM}^{\gamma})$ should provide a useful description of the apparent mean dependence of the turbulence level on DM. Equation (7) has been shown in Fig. 2 as a solid curve.

We also model the distribution of the observed deviation from this mean dependence (see equation 7). Bhattacharya et al. (1992), for similar modelling, used a functional form given by

$$P(\delta \log \tau_{sc}) = \left[1 + \exp\left(\frac{\theta - \delta \log \tau_{sc}}{\phi} \right) \right]^{-1}, \quad (8)$$

where $P(\delta \log \tau_{sc})$ is the cumulative distribution of the deviations and θ and ϕ are constants. While it is possible to find a better functional form, we have used the above functional form as it is found to provide an adequate description even in the present case. However, we obtain the values of θ and ϕ to be 0.106 and 0.313 respectively, compared with the values 0.04 and 0.342 as obtained by Bhattacharya et al. The positive deviations are probably due to the existence of regions of enhanced turbulence while the negative deviations may be attributed to the posibility that the scatterer location may be much closer to the pulsar or to the observer.

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