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Interstellar scattering of the largest sample of Galactic pulsars

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Abstract. We present the results of the multi-frequency scattering analysis of radio pulsar signals. For our study we used the data we gathered during various observing projects we conducted with the GMRT radio-telescope, as well as the 100-meter Effelsberg radio-telescope. We supplemented our data with the scatter time measurements from the literature, and constructed the largest multi-frequency scattering measurements database up to date. Our sample consists of about 100 pulsars, for which we were able to create the scatter time spectra, to check if the spectral indices conform with the theory predictions. We noticed that the scattering spectra for a lot of sources deviate from the predicted power-law with spectral index of −4.4, and the more distant the pulsar is the the more probable it is for the deviations to occur. We can not confirm however the sharp division in the behaviour of scattering between the low-DM and high-DM pulsars, that was proposed by Löhmer et al. (2001,2004).

Keywords : pulsars: scattering; interstellar medium: structure

1. Introduction: the basics of scattering

The existence of the ionized fraction of the Interstellar Medium (ISM) affects the observed pulsar radiation. Due to the turbulent nature of the interstellar medium and variations of the electron density along the line-of-sight, several phenomena may arise when observing pulsars. One of them is angular and temporal broadening, which are caused by the scattering of the radiation, so it reaches the observer after travelling along different geometrical paths. Even if one assumes that the signal (a pulse) leaves the pulsar at one instant, then due to the scattering by the ISM it will reach the observer along different geometrical paths, with different lengths, the pulse will arrive

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at the observer over a finite interval, i.e. the pulse will be smeared and will attain a "scattering tail". The length of the tail is characterised by the so called scatter time τ_d (or pulse broadening time, Scheuer 1968). This value will be strongly dependant of the observing frequency: $\tau_d \propto \nu^{-\alpha}$

To estimate the strength of scattering effects one has to assume a reasonable spectrum of electron density fluctuations. The most common way (following Rickett 1990) is to assume a homogeneous isotropic turbulence that within a range of fluctuation scales between an *inner scale* and the *outer scale*. In such case the spectrum simplifies to a power-law : $P_{n_e}(q) = C^2_{n_e} q^{-\beta}$, and if β is lower than 4 one can derive that the scatter time spectral index $\alpha = 2\beta/(\beta - 2)$. For a purely Kolmogorov spectrum of the density irregularities the spectral index $\beta = 11/3$ which yields the expected value of $\alpha = 4.4$.

It has to be mentioned however, that the simplification of the turbulence power spectrum to a power-law is valid only if the fluctuations affecting the observations at a given frequency are indeed much greater in size than the inner scale, otherwise the so called ''inner scale effects" may play their role and change the slope of the spectrum. The influence of the inner scale was discussed recently by Rickett et al. (2009).

Also, one has to remember, that the $\alpha = 4.4$ prediction is valid only for a single thin-screen model and with an assumption of isotropic and homogeneous ISM turbulence with a Kolmogorov spectrum. If any of those conditions is not fulfilled then the resulting scatter time spectral index may vary. There are other models of the turbulence spectrum (discussed by Romani et al. 1986) that may result in a different slope of the scatter time frequency dependence, but never lower than 4.0. Also we have evidence for the inhomogeneities in the ISM, and they may affect the observed slope causing it to drop below 4.0, as well as they may cause the scatter time to vary over time (see for example Brisken et al. 2010). Finally, the geometry such as the existence of multiple screens along the line-of-sight may influence the observed slope. We discussed all these potential causes in our recent paper (Lewandowski et al. 2013).

2. Multi-frequency scattering observations

The most recent analysis of the multi-frequency scattering observations was done by Lewandowski et al. (2013). In that paper we expanded on the work done a decade earlier by Löhmer et al (2001, 2004), who noted that while for the low-*DM* pulsars the measured spectral index of scatter time fits with the assumed theories (i.e. α is usually between 4.0 and 4.4), but for more distant objects ($DM > 300$ pc cm^{-3}) the observed spectral index is usually much lower than 4.0, with an average of 3.4 - a value that can not be explained by any single screen homogeneous turbulence theory (see the top panel of Fig.1 for a recreation of their α vs DM plot). In our paper we added the results obtained from our GMRT and Effelsberg observations, conducted for various projects over the last couple of years (see for example Kijak et al. 2007,

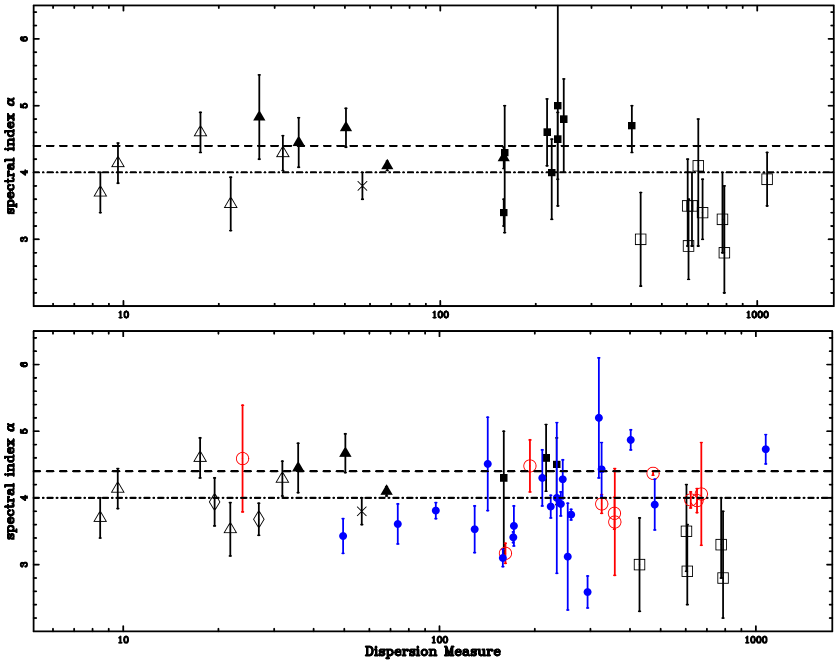

Figure 1. A comparison of the scatter time spectral index α databases available for Löhmer et al. (2001, 2004) (top) and using our data (bottom): the red empty circles were published in Lewandowski et al. (2013) and the the data represented by blue filled circles is currently being prepared for publication (Lewandowski et al. 2014).The plot also includes the α estimates from our interstellar scintillation studies (diamonds, see Lewandowski et al. 2011; Daszuta et al. 2013).

2011). We recalculated the scatter time spectral indices, and found out that while the deviation for high-*DM* pulsar is still present it is not as strong as Löhmer et al. (2001, 2004) suggested.

Following on that we decided to look for any scatter time measurements available in the literature and added the results from our newest GMRT observing projects. As a result we gathered a sample of ca. 100 pulsars that had scatter time measured at more than a single frequency. Then we excluded the sources that had been measured at only only two frequencies - while these allow to calculate scatter time spectral index it is impossible to give proper error estimates. We also added the α spectral indices derived from our interstellar scintillation observations for PSR B0329+54 (Lewandowski et al. 2011) and PSR B0823+26 (Daszuta et al. 2013).

The results for 50 objects are shown in the bottom panel of Fig.1, and this represents the largest database of multi-frequency scattering measurements analysed so far. In the figure the various black markers represent pulsars measured earlier, the red empty circles are our results published in Lewandowski et al. (2013, see that paper for the full reference list) and the blue full circles are the new or corrected α estimates (Lewandowski et al. 2014, in preparation). As one can see from the plot there is definitely no sharp division between the low-DM pulsars and high-DM ones that was proposed byLöhmer et al. (2001, 2004), it looks more likely that with an increasing dispersion measure the probability of deviation from the model prediction increases, as well as the scale of the deviation. But still, even amongst the highest-DM pulsars there are some that seem to follow simple model predictions reasonably well (showing scattering spectral indices between 4.0 and 4.4).

3. Summary

We analysed much bigger sample of scatter time observations pulsars than Löhmer et al. (2001, 2004) and we see no sharp DM-dependent division in the α values. One of the explanations may be that we added new measurements for some of the pulsars used in those papers and recalculated the spectral indices. The updated values usually agree better with the theory than it was reported – especially for very high-DM objects – by Löhmer et al. (2001). This can be noticed in Fig.1, as some of the empty squares from the upper panel (points based on that paper) got replaced by blue and red circles in the lower panel. In our sample we also had more pulsars with DM in range between 50 and 150 pc cm^{-3}, and as one can see these do not follow the theory predictions as well. One has to note that this DM range requires improvement, as even in our database in that range the number of pulsars with multi-frequency scattering measurements is still limited. The same holds true for very high-DM pulsars. Regardless, we believe that our results show that the connection between the dispersion measure and scattering properties is not so straightforward as it was previously presumed and in reality the scattering is probably much more line-of-sight dependant.

Additionally we would like to point out after Lewandowski et al. (2013) that one should plan any future multi-frequency scattering observations in a way that would help to avoid any malicious influence of the ISM inhomogeneity effects on the measured α values. These effects may vary scattering properties over time, hence may affect the spectral indices derived from multi-epoch data. Therefore it is crucial to perform any multi-frequency observations in at least quasi-simultaneous manner - i.e. within a few days (up to one week), since the time-scale of the inhomogeneity effects is presumed to be of order of a few weeks (Brisken et al. 2010).

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