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Dispersion measure variations observed in the direction of the millisecond pulsar PSR B1821-24

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Abstract. High-precision timing observations of the millisecond pulsar PSR B1821-24 have been conducted at the Nançay radiotelescope between 1.37 GHz and 1.7 GHz since January 22, 1992 until January 10, 1996. This dense and precise multi-frequency timing series has allowed secular variations of the dispersion measure as high as 0.005 pc.cm^{-3}/year in the direction of this pulsar to be determined. The index β of the power-law spatial spectrum of the electron density fluctuations has been determined for the first time in the direction of this pulsar and is 3.727 ± 0.211, a result consistent with a Kolmogorov turbulent medium. The diffractive time scale $\tau_{\rm d}$ is also determined to be $50 \pm^{183}_{40}$ s and is relatively consistent with the determination based on the space velocity of PSR B1821-24. We also provide a new proper motion for this pulsar for which the declination component is for the first time inconsistent with zero.

Key words: pulsars: general – pulsars: individual: PSR B1821-24 – ISM: general – stars: kinematics

1. Introduction

The variations of the column density of the free electrons in the interstellar medium (the dispersion measure DM in units of pc.cm^{-3}) can be measured by pulsar timing and used to characterize the spatial spectrum of the turbulence in the ionized interstellar medium (IIM). Turbulent processes are very important for the global dynamics of the interstellar medium and also for stellar formation or cosmic-rays transport, there is a considerable interest in determining this spectrum. The first variations of the dispersion measure were detected toward the Crab pulsar PSR B0531+21 (Rankin & Roberts 1970). On the same pulsar and over 15 years, Lyne, Pritchard & Smith (1988) reported variations of DM at the level of 0.003 pc.cm^{-3} per year. Rawley, Taylor & Davis (1988) have detected DM variations with the high-precision timing observations performed on PSR B1937+21 at Arecibo. Phillips & Wolszczan (1992) have also detected DM variations in slow pulsars by timing at decameters wavelengths.

The pulsar PSR B1821-24 in M28 is the first millisecond pulsar discovered in a globular cluster (Lyne et al. 1987). Using multi-frequency timing observations performed at Green Bank, Backer et al. (1993) first reported variations of the dispersion measure in the direction of this pulsar. At Nançay radiotelescope, we have acquired a high-precision and dense timing series on PSR B1821-24 since January 1989 at 1410 MHz and at multiple frequencies around 1.4 and 1.7 GHz since January 1992. In this paper, we present the determination of the DM variations toward PSR B1821-24 based on the Nançay data and use these variations to constrain the spatial spectrum of the IIM in this direction.

Rickett (1990) proposed that the electron density fluctuations of the IIM are described by a power-law spatial spectrum:

$$P(q) = C_n^2 q^{-\beta} \quad \frac{2\pi}{l_o} < q < \frac{2\pi}{l_i} \tag{1}$$

where q is the wavenumber $q = 2\pi/l$ and l the spatial scale of the perturbation. C_n^2 is a normalizing constant. l_i and l_o are the inner and outer cutoffs, respectively, and correspond to the length scales beyond which the power-law expression is not valid because of various damping mechanics. Usually, the exponent β is believed to be close to 11/3, the Kolmogorov value for turbulence in a neutral gas. It has been shown (Rickett 1988) that the structure function of the DM variations measured by pulsar timing is directly related to the structure function of the phase deviations affecting the propagation of the radio waves in the IIM. Since the structure function of the phase deviations depends directly on β, l_i and l_o, these parameters can be determined by such an analysis.

2. Observations

The timing observations have been conducted at the decimetric radiotelescope located near Nançay (France). The collecting area of the telescope is 7000 m^2 (equivalent to a 93 meter

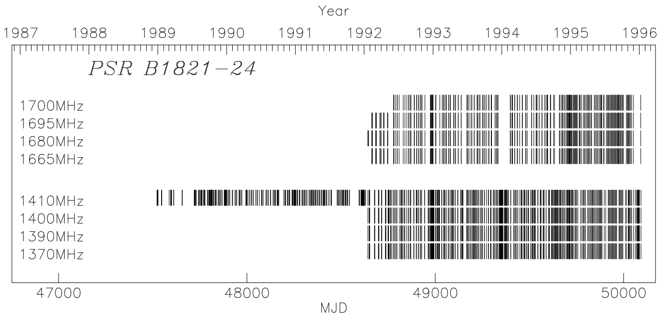

Fig. 1. Date of observations of the millisecond pulsar PSR B1821-24 at the radiotelescope of Nançay (1370, 1390, 1400, 1410 MHz in horizontal polarization and 1665, 1680, 1695 and 1700 MHz in vertical polarization).

Table 1. Pulsar parameters determined from the Nançay data at 1410 MHz (October 1989 - January 1996) and constant DM. The corresponding TOA residuals are shown at the bottom of Fig. 2. These parameters were used to produce TOA residuals at several frequencies around 1.4 and 1.7 GHz in order to determine the DM variations of PSR B1821-24 shown in Fig. 3

Parameter	Value
Period (s)	0.003054314803592100(24)
$\dot{P}$ (s.s^{-1})	$161.87717(8) \times 10^{-20}$
$\ddot{P}$ (s.s^{-2})	$-8.7(3) \times 10^{-31}$
$P^{(3)}$ (s.s^{-3})	$-3.1(1) \times 10^{-38}$
α (J2000)	$18^h\ 24^m\ 32.005713(12)s$
δ (J2000)	$-24^\circ\ 52'\ 10.709(3)''$
Time origin (JD)	2449200.0
μ_α (mas/yr)	$-0.9(1)$
μ_δ (mas/yr)	$-4.6(18)$
Parallax π (mas)	0.2^a
DM (pc.cm^{-3})	119.573
rms (μs)	3.21

[a] From Alcaino (1981).

dish) and the system temperature is typically $\sim$ 45 K. The integration time with this transit telescope is 70 minutes at the declination of PSR B1821-24. Usually, we conduct timing observations of this pulsar on $\sim$ 12 individual dates per month. As shown in Fig. 1, since January 1992 these observations are conducted alternately between the 21cm receiver (1370, 1390, 1400 and 1410 MHz, horizontal polarization) and the 18cm receiver (1665, 1680, 1695 and 1700 MHz, vertical polarization). This corresponds to the full scale operation of the 4-channel de-dispersion instrumentation built at Nançay for pulsar timing. The observations were conducted at a single linear polarization because PSR B1821-24 is $\gtrsim 90\%$ linearly polarized as measured at Nançay (Cognard et al. 1996). This scheme, rather than observations at both senses of circular polarization, optimises the signal-to-noise ratio at Nançay. However, a source of systematic error in our data comes from the single linear polarization TOA's used in the analysis. Cognard et al. (1996) estimated that, with a plausible daily variation of the ionospheric Rotation Measure of 1 rad/m^2, seen as annual by the meridian Nançay radiotelescope, and a maximum position angle swing of $\pm\pi$ for PSR B1821-24, the systematic timing error is at the level of $\sim$ 1 μs, roughly half of the estimated mean uncertainty. The major effect for the fit is to bias the pulsar position at the level of $\sim$ 0.5 milliarcsecond. The timing data acquired around Christmas each year, when the solar corona intervenes between PSR B1821-24 and the Earth, have been removed since there is an additional delay of several tens of microseconds that is not related to the IIM.

At Nançay, the pulsar signal is coherently de-dispersed prior to detection by using a swept frequency local oscillator (at 80 MHz) in the IF chain. The pulse spectra are produced by the station digital autocorrelator. The frequency of arrival for the start time of the observation (TOA) is determined by cross-correlation of the daily integrated pulse with a pulse template as described by Taylor (1992).

The data have been analysed by our software AnTiOPE using the Jet Propulsion Laboratory Ephemerides DE202 (Standish 1982; Newhall, Standish & Williams 1983) for the Earth orbital motion and for the celestial reference frame and the conventional UTC time scale for the time reference. More delails on the instrumentation and the analysis can be found in a previous paper (Cognard et al. 1995).

3. Dispersion measure variations

Multi-frequency timing measurements are needed to derive the DM variations in the direction of a pulsar. As shown in Fig. 1, four years of observations conducted at Nançay from January 1992 to January 1996 are available to determine the DM variations in the direction of PSR B1821-24.

Our software AnTiOPE has been used to produce TOA residuals assuming a constant DM of 119.573 pc.cm^{-3} and with the fixed pulsar parameters of Table 1 for all frequencies. These residuals are used to determine the variations of DM following a standard least squares procedure based on the equation:

$$\delta DM = \frac{\delta t_{\nu_1} - \delta t_{\nu_2}}{k} \frac{\nu_1^2 \nu_2^2}{\nu_2^2 - \nu_1^2} \tag{2}$$

where the two TOA residuals $\delta t_{\nu 1}$ and $\delta t_{\nu 2}$ are observed at the two frequencies ν_1 and ν_2 and k is the dispersion constant. The usually adopted value of k is 4148.808(3) pc^{-1}.cm^3.MHz^2.s which has an uncertainty of 3 in the last digit owing to the combined uncertainties in the values for the charge of the electron and the rest mass of the electron (Backer et al. 1993; Cohen & Taylor 1989).

The δt_{ν_i} used in the fit are the mean TOA residuals at the frequency ν_i over 50 day wide boxes. The variation δDM and uncertainty are determined from the above equation with a least squares fit. We have made several tests to check that the chromatic signature in these residuals due to δDM are independant of the set of pulsar parameters used to produce the residuals

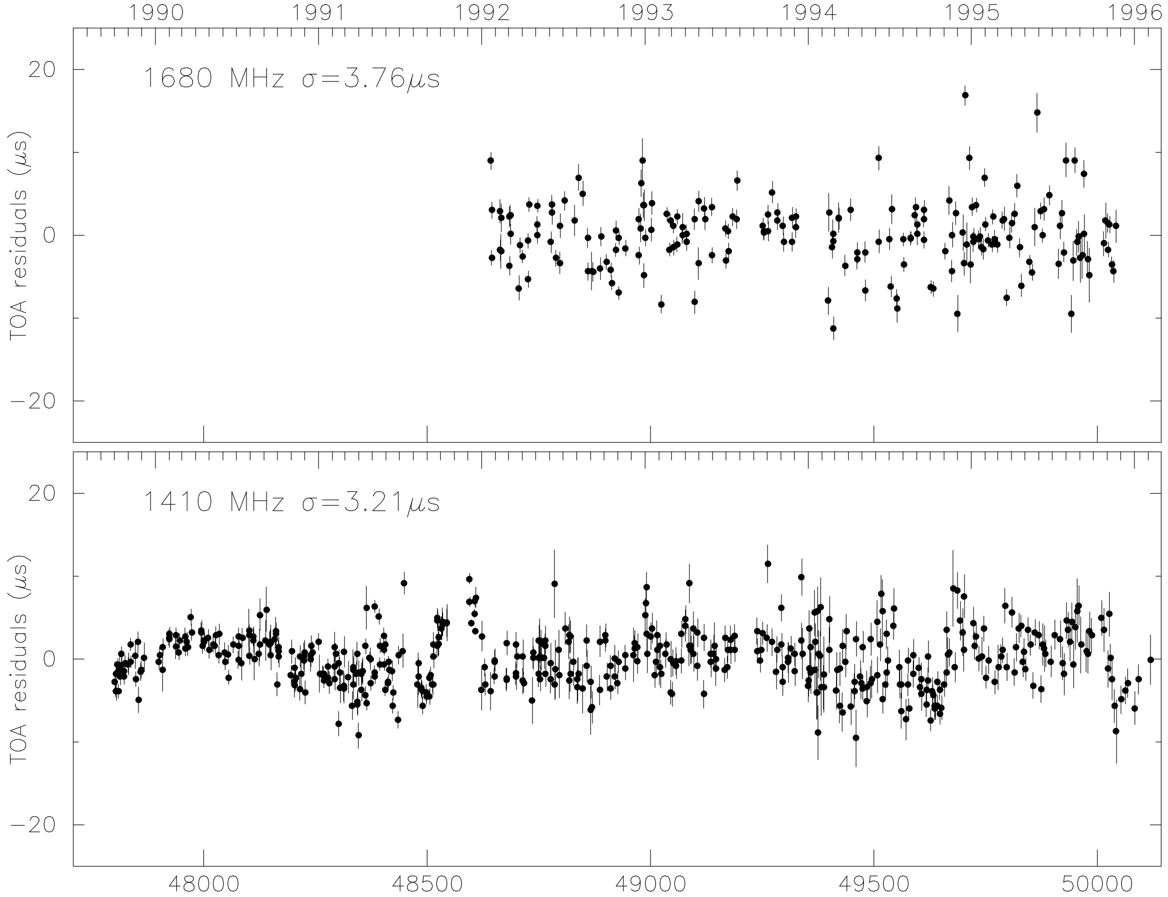

Fig. 2. TOA residuals of the timing data obtained on the millisecond pulsar PSR B1821-24 at the Nançay radiotelescope. (bottom) Residuals from timing observations at 1410 MHz characterized by a post-fit rms of 3.21μs. (top) Residuals from 1680 MHz data characterized by a rms of 3.76μs. Parameters solved are P, $\dot{\mathrm{P}}$, $\ddot{\mathrm{P}}$, $\mathrm{P}^{(3)}$, α, δ, μ_α and μ_δ.

δt_{ν_1} and δt_{ν_2}. The daily uncertainty for two TOA residuals, at 1400 and 1700 MHz, is generally ~ 2 μs which yields an uncertainty of $\sim 5 \times 10^{-3}$ pc.cm^{-3} for the daily determination of the DM variation with Eq. (2). There are generally 20 differences of TOA residuals used to derive δDM over 50 days and the resulting uncertainty of DM is therefore $\sim 10^{-3}$ pc.cm^{-3} in Fig. 3.

The variations of DM from the Nançay data are in good agreement with the determinations of Backer et al. (1993) at the radiotelescope of Green Bank for an earlier period. A global trend of $\sim$ 0.005 pc.cm^{-3}/year is seen in the two independant data sets. For our observations, the rms of the variations of DM when we removed the general trend is 0.002 pc.cm^{-3} and is comparable with the results of Backer et al. (1993) in their Fig. 4b. A plot of the combined determination at Green Bank until early 1992 (from observations at 800 and 1330 MHz) and at Nançay is shown in Fig. 3. In this plot, the Nançay and Green Bank DM series have not been shifted to align the short common period around January 1992. The residual offset at this epoch is smaller than 0.002 pc.cm^{-3} as seen on the plot. This is suprisingly small since systematic biases are expected from differential propagation delay in backends used at Green Bank and Nançay, in fiducial points chosen on the pulse shape, in the analysis procedures or even in the intrinsically variable pulse shape over such a large frequency interval.

4. Structure function analysis

The dispersion measure variations of PSR B1821-24 plotted in Fig. 3 can be used to constrain the spatial spectrum of the electron density fluctuations of the interstellar medium. The presence of scattering by a turbulent medium introduces random phase fluctuations into the wavefront. To describe these fluctuations, it is useful to consider the structure function of phase deviations (Rickett 1988). This function represents the mean square phase difference between two points separated by the distance r and is defined as a function of the spatial lag r :

$$D_\phi(r) = < [\phi(x+r) - \phi(x)]^2 > \tag{3}$$

Under the assumption that the turbulence is "frozen" all the observed variations are due to the relative motion between the Earth and the pulsar. Thus, $r = V\tau$ where V is the relative velocity of the pulsar and τ is the time lag. We can consider the velocity V as constant and write the phase structure function

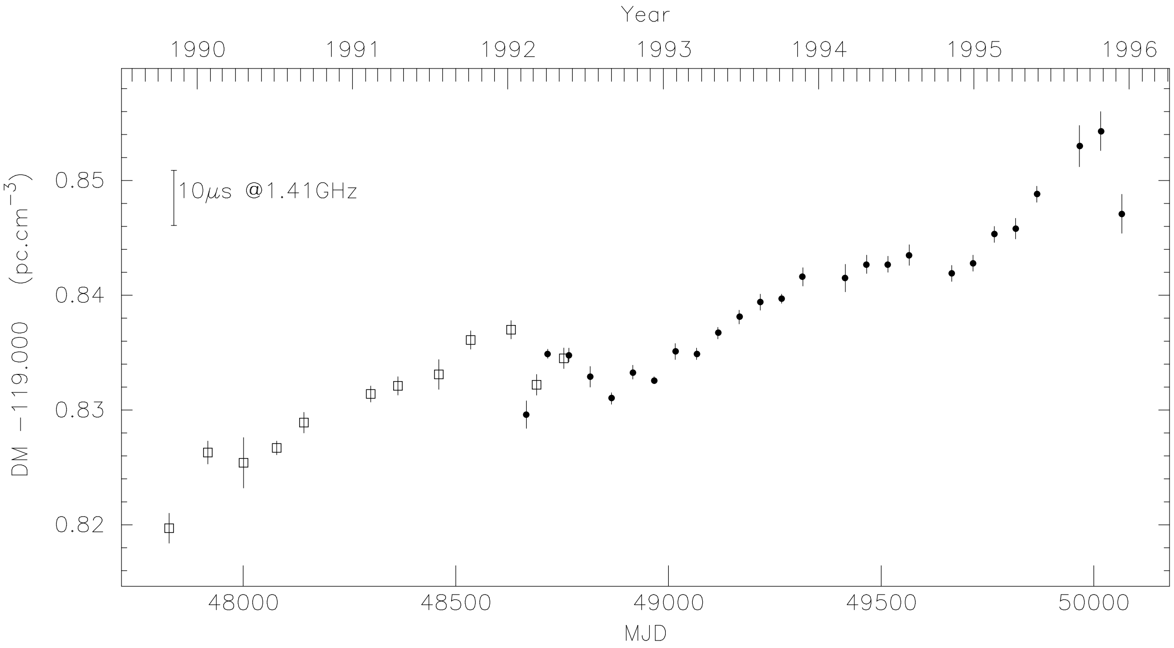

Fig. 3. Dispersion measure variations of the millisecond pulsar PSR B1821-24 from Green Bank observations (performed by Backer et al. (1993), empty squares) and from Nançay observations (this paper, filled circles). The DM determined at Nançay comes from the data acquired at 1370, 1390, 1400, 1410, 1665, 1680, 1695 and 1700 MHz with the TOA residuals averaged over 50 days boxes. The vertical bar indicates the dispersive delay at 1410 MHz due to the corresponding DM variation.

as a function of the time lag. For fluctuations described by a power-law for the spatial spectrum at a scale between an inner and an outer scale, the structure function D_ϕ can be written as:

$$D_\phi(\tau) = (\tau/\tau_\mathrm{d})^{\beta-2} \tag{4}$$

where τ_d is the diffractive time scale which corresponds to the transverse separation over which the phase fluctuations is coherent to within 1 rad. Rickett (1988) and Cordes et al. (1990) have shown that the phase structure function is related to the structure function D_{DM} of the DM variations and an unbiased estimator of D_ϕ is :

$$D_\phi(\tau) = (\frac{2\pi}{\nu}k)^2(D_{DM}(\tau) - 2\sigma^2) \tag{5}$$

where ν is the frequency of observation, k the dispersion constant and σ the mean measurement uncertainty in ΔDM (Cordes et al. 1990, Eq. (6) ; Phillips & Wolszczan 1991, Eq. (25)). The structure function of the DM variations $D_{DM}(\tau)$ can be estimated by :

$$D_{DM}(\tau) = \frac{1}{N}\sum_i(\Delta DM(t_i+\tau) - \Delta DM(t_i))^2 \tag{6}$$

where N is the number of pairs used to calculate the sum.

The slope of the phase structure function on a log-log plot provides the value of the index β, the diffractive time scale τ_d and information about the range over which the power-law expression of the spatial spectrum of the fluctuations $P(q)$ is valid.

The structure function of phase of Eq. (5) was calculated following the procedure described above for the Nançay DM variations available for the millisecond pulsar PSR B1821-24 (see Fig. 3). We kept the estimate of the structure function only when the number N of pairs was larger than 10. Uncertainties on D_ϕ were calculated from the ΔDM uncertainties with appropriate coefficients and summation. The resulting structure function is plotted in Fig. 4. A Levenberg-Marquardt method (Press et al., 1986) minimizing the χ^2 merit function was used to fit the function

$$\log(D_\phi(\tau)) = \log(S + (\tau/\tau_\mathrm{d})^{\beta-2}) \tag{7}$$

where S accounts for the measurements errors and includes the noise offset σ. The uncertainties were estimated from confidence regions delimited by constant χ^2 boundaries. More precisely, the uncertainty on a given parameter was the change of this parameter corresponding to a $\Delta\chi^2$ equal to unity when the rest of the parameters were adjusted to minimize the χ^2. This fit yields $\beta = 3.727 \pm 0.211$. The value of the lag τ where the structure function is unity is the diffractive time scale and is also provided by the fit: $\tau_\mathrm{d} = 50 \pm^{183}_{40}$ s. We should note that we have scaled down by a factor 4 the D_ϕ uncertainties estimated from the DM uncertainties and Eq. (6) in order to make the minimum χ^2 consistent with the number of degrees of freedom (14-3=11). Indeed, due to the rough procedure adopted for the determination of uncertainties on D_ϕ, an overestimation is very likely. Note that the D_ϕ uncertainties plotted in Fig. 4 are the renormalized ones.

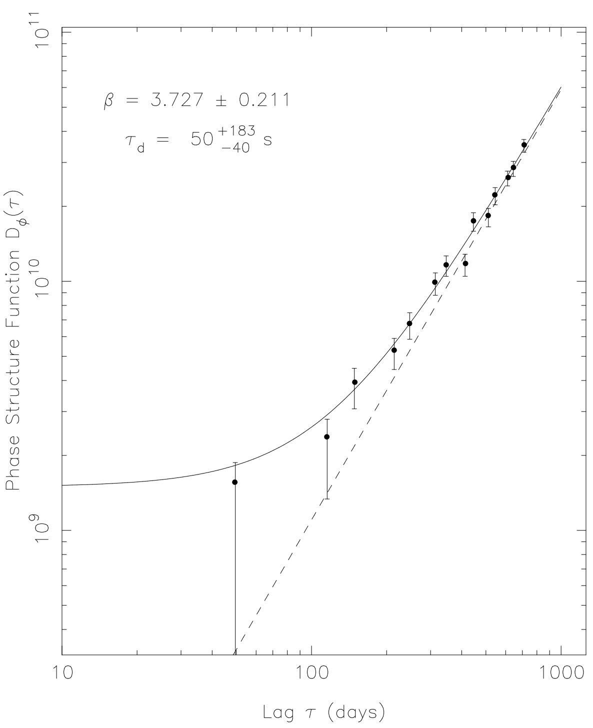

Fig. 4. Estimates of the phase structure function at 1.4 GHz based on DM variations for the millisecond pulsar PSR B1821-24. A fit of Eq. (7) was performed to deduce the parameters β, $\tau_{\rm d}$ and S. The solid line corresponds to Eq. (7) and the dashed line corresponds to the same relation without the noise term S.

5. Discussion

The value of the power-law index β = 3.727 ± 0.211 is in agreement with the Kolmogorov value ($\beta = 11/3$) of a turbulent medium. The large uncertainty on β is due to the limited number of data points for the structure function $D_\phi(\tau)$ in Fig. 4. Various efforts have been conducted to determine the power-law index β. For instance, in the direction of the millisecond pulsar PSR B1937+21, Kaspi, Taylor & Ryba (1994) found β = 3.874 ± 0.011 with a similar method to analyse DM variations in the direction of this pulsar. A different value was found by Cordes et al. (1990), β = 3.55 ± 0.11, using the scaling of diffractive scintillation bandwidths measured between 430 and 1400 MHz for PSR B1937+21. Phillips & Wolszczan (1991) found a mean value of β = 3.84 ± 0.02 along three lines of sight toward three distinct pulsars. From published data about the local interstellar medium ($\lesssim$ 1 kpc), Armstrong, Rickett & Spangler (1995) found an averaged $\beta \sim 3.7$. Kaspi, Taylor & Ryba (1994) mention that the uncertainty accounts only for random effects, and the discrepancy found by various authors may be due to systematic errors. The relatively large uncertainty on our value of β makes it consistent with these previous determinations.

The diffractive time scale $\tau_{\rm d}$ = 50 $\pm^{183}_{40}$ s determined with Eq. (4) and the structure function D_ϕ of Fig. 4 for PSR B1821-24 can be compared to other determinations. The diffractive time scale $\tau_{\rm d}$ is linked to the scintillation pattern speed V_{iss} (assumed to be dominated by the velocity of the pulsar) and the characteristic spatial scale of the scintillation pattern s_d (geometricaly related to the decorrelation bandwidth $\Delta\nu$ for the diffractive scintillations) by $V_{iss} = s_d/\tau_{\rm d}$. In order to have an estimation of the diffractive time scale $\tau_{\rm d}$, we need estimations both on the velocity of the pulsar and on the diffractive scintillation bandwidth $\Delta\nu$. First, we use the space velocity for PSR B1821-24 that lies between 80 and 180 km/s when based on the proper motion newly given in Table 1 ($\mu_\alpha = -0.9 \pm 0.1$ mas/yr and $\mu_\delta = -4.6 \pm 1.8$ mas/yr) by timing at Nançay and the distance 5.8 kpc from Alcaino (1981). The proper motion previously given in Cognard et al. (1996) ($\mu_\alpha = -1.27 \pm 0.17$ mas/yr and $\mu_\delta = 3 \pm 3$ mas/yr) were based on significantly less data. Second, we can set an upper limit on the diffractive scintillation bandwidth $\Delta\nu$ from the width ($\sim$ 150 μs) of the pulse observed at 400 MHz (Taylor, Manchester & Lyne, 1993 ; Lyne et al. 1987). Indeed, with a deduced upper limit for the pulse broadening $\tau_{\rm b} \lesssim 100$ μs at 400 MHz converted to a pulse broadening less than 0.5 μs at 1.4 GHz, we determine a limit of $\Delta\nu = 1/2\pi\tau_{\rm b} \gtrsim 0.35$ MHz. Using the recent derivation of Gupta, Rickett & Lyne (1994) for the scintillation velocity (Eq. C14), a mid-placed screen and a space velocity v=130 km/s, we found a diffractive time scale $\tau_{\rm d} \sim 300$ s ($\tau_{\rm d} \sim 217$ s for v=180 km/s and $\tau_{\rm d} \sim 490$ s for v=80 km/s). For a high velocity, this determination is just consistent with the upper limit of our determination. However, as pointed out by Gupta, Rickett & Lyne (1994), an asymmetrically placed screen between the Earth and the pulsar will change the estimated value for $\tau_{\rm d}$ by a factor $\sqrt{L_o/L_p}$, where L_o is the distance from the screen to the observer and L_p is to the pulsar. For the pulsar PSR B1821-24 which lies in the globular cluster M28, we can question whether the scattering turbulence extends all the way to the pulsar. The effect to take a screen closer to the Earth is to decrease the value of $\tau_{\rm d}$ and improve the consistency. To be complete, we should mention that an other estimate for $\Delta\nu$ could be obtain from the temporal broadening listed in Table 4 of Taylor, Manchester & Lyne (1993). Following the $\nu^{-4.4}$ law, this predicts a broadening of 56 μs at 1.4 GHz inconsistent with observations made at Nançay. Indeed, Fig. 1 of Cognard et al. (1996) can be used to put the limit $\tau_{\rm b} \lesssim 10$ μs due to the lack of scattering tail. We should note that the various values for $\tau_{\rm b}$ found in the literature makes the comparison not very reliable.

A lower limit can be set on the outer scale. The outer scale must be greater than the spatial lag corresponding to our greatest lag without deviations from the expected behavior of the theoretical phase structure function. With a temporal lag of $\sim$ 700 days ($\sim$ 2 years, half of our data span), the lower limit is $l_o \geq 6 \times 10^{14}$ cm. This outer scale is compatible with measurements done along other line of sights (Kaspi, Taylor & Ryba 1994).

The determination of a spectral index lower than 4 indicates that at least on average there is no strong focusing by large discrete structures in the interstellar medium. However, a few strong refractive events might have been seen in the direction of PSR B1821-24 (Cognard & Lestrade 1996). These events are characterized by a depressed flux density and an increased delay in the timing measurements. They are interpretated as refractive scintillation of radio waves caused by discrete ionized structures as also tracked daily on the millisecond pulsar PSR B1937+21 in October 1989 (Cognard et al. 1993). These different observations might be explained by a wide distribution of plasma structures with more refractive power than that in the Kolmogorov spectrum at scales within a decade of 1 AU as proposed by Rickett (1996).

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