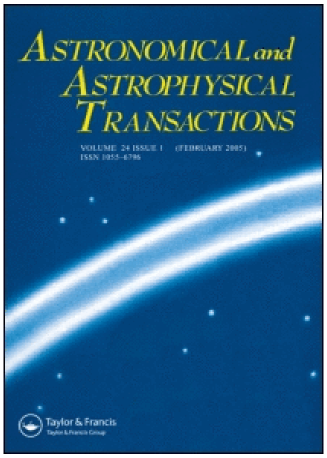

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B. Rickett [a]; B. Coles [a]; M. Mclaughlin [bc]; J. Bank [b]; A. Lyne [c]; I. Stairs [c]; R. Ferdman [c]; P. Freire [d]; F. Camilo [e]
[a] University of California, San Diego, USA
[b] West Virginia University, West Virginia, USA
[c] University of British Columbia, British Columbia, Canada
[d] NAIC Arecibo, Puerto Rico
[e] Columbia University, NY, USA

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Interstellar scintillation of the double pulsar J0737-3039: effects of anisotropy

B. RICKETT*†, B. COLES†, M. McLAUGHLIN‡§, J. BANK‡, A. LYNE§, I. STAIRS§, R. FERDMAN§, P. FREIRE¶ and F. CAMILO||

†University of California, San Diego, USA
‡West Virginia University, West Virginia, USA
§University of British Columbia, British Columbia, Canada
¶NAIC Arecibo, Puerto Rico
||Columbia University, NY, USA

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We describe a year-long series of interstellar scintillation (ISS) observations of the double pulsar using the Green Bank Telescope. The goal is to improve the estimates of the proper motion velocity of this interesting binary system relative to the interstellar plasma. The scintillation time scale varies remarkably over its orbital period but only provides three independent parameters per epoch. Extra information is found from repeating these observations over a year, as the Earth velocity changes, and also from cross-correlating the scintillations of the two pulsars. The latter gives clear evidence that the ISS is anisotropic with an axial ratio greater than 2.6. This reduces the proper motion velocity over that obtained assuming isotropic ISS. However, changes in the timing of the orbital windows when the slow pulsar is detectable have limited the usefulness of this technique. A progress report on the work is presented.

Keywords: Interstellar scintillation; Binary pulsar system; Anisotropy

1. Introduction

The double pulsar J0737-3039 [1] is unique in being the only binary neutron star system in which both stars are seen as radio pulsars. Thus it presents a number of fascinating features which provide a new and very accurate laboratory for testing theories of general relativity. However, we are here concerned with its interstellar scintillation (ISS), for which the following basic properties are important. Pulsars (neutron stars) A and B orbit each other in 2.45 h. The orbit is small (0.003 AU), it is 9% eccentric and its plane is nearly aligned with the Earth; orbital speeds are fast, $\sim$300 km s^{-1}. A is eclipsed by B for about 30 s each orbit [2]. Excellent timing observations have pinned down almost all of the orbital elements.

*Corresponding author. Email: rickett@ece.ucsd.edu

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Ransom *et al.* [3] published observations from the Green Bank Telescope (GBT) at 0.82 and 1.4 GHz from which they found that the scintillation time scale $t_{\rm iss}$ of pulsar A varies greatly during its orbit. Here $t_{\rm iss} = s_{\rm iss}/V_{\rm iss}$ and its variation is due to the the changing transverse velocity $V_{\rm iss}$ of A (relative to the ISM), since the spatial scale of the scintillation $s_{\rm iss}$ should be a constant. $V_{\rm iss}$ is the vector sum of A's orbital velocity and and the centre-of-mass velocity $\boldsymbol{V}_{\rm c}$, which can thus be determined as was done by Ord *et al.* [4] for PSR J1141-6545. Ransom *et al.* found $V_{\rm c} = 141 \pm 8.5$ km/s, which implied a large kick velocity and raised questions about the birth circumstances. We subsequently re-analysed the same data and found evidence [5] for a highly anisotropic ISS pattern, which lead to a lower $V_{\rm c} = 66 \pm 15$ km/s and in turn eased the difficulties in explaining the birth circumstances.

The proper motion of the system has now been measured from nearly three years of timing observations [6], with the finding that the transverse velocity relative to the Sun is only $10 \pm 1\,{\rm km\,s^{-1}}$ – clearly incompatible with values derived from ISS. The implications for the birth of pulsar B have been explored by Stairs *et al.* [7]. In this paper we report on analysis of a year-long series of ISS observations aimed at understanding the ISS of this system.

In our earlier analysis [5] the ISS from pulsars A and B was found to be quite highly correlated near the time that A is eclipsed by B. The correlation depends on their projected transverse separation which changes quickly near the eclipse and so allowed us to estimate the spatial correlation as a function of the transverse baseline between the two pulsars. It also gave us an estimate of the orbital inclination at only $0.3 \pm 0.14°$ away from 90°. However, this disagrees with the recent measurement of the Shapiro delay [6] which gives an inclination 1.3° from 90° with asymmetric error bounds which only overlap the ISS error bounds at their 2σ levels.

2. Observations

We used the GBT to observe over 1600–2200 MHz for one or two orbits about every two months. Our goal was to observe any annual changes in the orbital modulation of $t_{\rm iss}$ and of the cross-correlation of the ISS between pulsars A and B. The 1024 channels from the auto-correlation spectrometer were dumped every 82 μ s using the 'SPIGOT' system at GBT. The spectra were then de-dispersed and folded according to the apparent periods of the two pulsars for integrations of 10 s. On-pulse and off-pulse windows were chosen and their difference were saved as a dynamic spectrum at each epoch for each pulsar.

Figure 1 shows examples for MJD 53560. The eclipse of A is marked by short vertical lines near 5 and 150 min. Near these times A's timescale ($t_{\rm iss}$) is short (and the 'scintles' are sloped); near times of 115 and 185 min the timescale is long which repeat at intervals of the orbital period 147 min. Also note that the slow scintles are curved alternately up and down. We believe this is due to refraction by a gradient in the plasma column density sampled over the pulsar orbit. We are investigating this and will include it in a future paper. Note also that

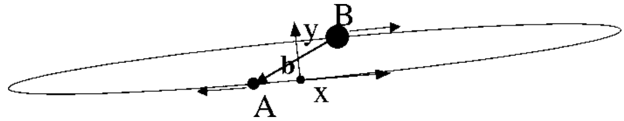

Figure 1. Dynamic spectra of pulsars A and B on modified Julian day 53560 observed with the GBT. Sample time is 10 s and channel bandwidths are 0.78 MHz. Orbits are 147 min each. The time of A's eclipse is shown by the short vertical lines near 5 and 150 min. Radio interference is visible especially at the lower frequencies.

ISS from B is only detectable in two narrow time windows per orbit and that the one near the eclipse time is centred just after the eclipse and is relatively weak.

3. Analysis of ISS time scale

From the observations an auto-correlation is estimated from short-time blocks of the dynamic spectrum by summing over frequency:

$$\rho(t_a, \tau) = \Sigma^{\nu}\delta S_a(t_a, \nu)\delta S_a(t_a + \tau, \nu)/[\Sigma^{\nu}\delta S_a(t_a, \nu)^2], \quad (1)$$

where δS is the deviation from the mean pulsar flux density. As the pulsars move, we define the *spatial* correlation function versus their transverse coordinates as defined in figure 2 $\rho(b_x, b_y)$. We equate this to the temporal acf at time lag t, by setting $b_x = V_{ax}t$ and $b_y = V_{ay}t$, and define $t_{\rm iss}$ where the correlation falls to 0.5.

For anisotropic scintillation ρ can be written as a function of the elliptical quadratic form $Q = [ab_x^2 + bb_y^2 + cb_xb_y]^2$, where the axial ratio $A(>1)$ and orientation angle θ define $a = \cos^2\theta/A + A\sin^2\theta$; $b = \sin^2\theta/A + A\cos^2\theta$; and $c = 2\sin\theta\cos\theta(1/A - A)$. Here the projected velocity of pulsar A is the sum of its known orbital velocity about the centre of mass and the unknown V_c (which includes a term due to the Earth's velocity and is relative to a scaled ISM velocity as discussed in section 5):

$$V_{ax} = V_{oax} + V_{cx};\ \ V_{ay} = V_{oay} + V_{cy} \quad (2)$$

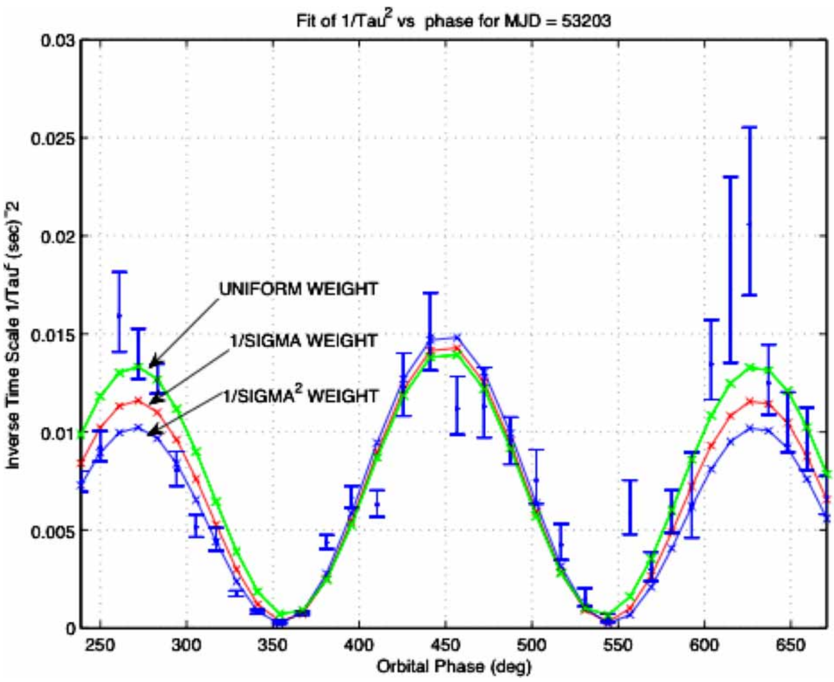

Figure 2. x, y-coordinate system for projected positions of pulsars A and B near the eclipse of A. The origin is defined by A's position at eclipse and the x-axis is parallel to B's velocity (shown by an arrow).

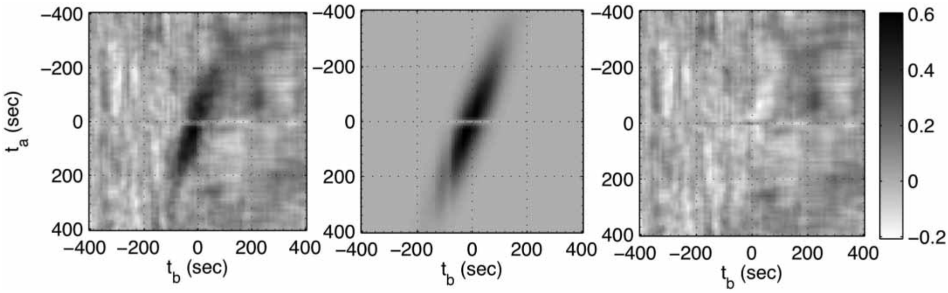

Figure 3. The error bars plot the observed $t_{\rm iss}$ from pulsar A versus ϕ over two full orbits. Three curves are fitted models with various weighting schemes.

From these definitions we find

$$(1/t_{\rm iss})^2 = (aV_{ax}^2 + bV_{ay}^2 + cV_{ax}V_{ay})/s_{\rm iss}^2 \tag{3}$$

$$= K_0 + K_S \sin\phi + K_C \cos\phi + K_{S2}\sin 2\phi + K_{C2}\cos 2\phi, \tag{4}$$

where ϕ is A's known orbital phase angle (relative to the line of nodes).

Hence in general there are five harmonic coefficients to be determined from fitting to $t_{\rm iss}$ versus ϕ. These depend on the following five unknown parameters: $V_{cmx}, V_{cmy}, s_{\rm iss}, A, \theta$ and the system parameters already known from the timing solution. For PSR J0737-3039 the orbital inclination i is so close to 90°, that coefficients K_{S2} and K_C are essentially zero. Consequently there are only three coefficients that can be determined from a fit, an example of which is shown in figure 3. Hence a unique physical solution cannot be found. It turns out that the three coefficients depend on the following four combinations: ab/c^2, V_{cx}, $(c/a)V_{cy}$ and $s_{\rm iss}$, so extra information is needed.

4. Correlation of ISS between A and B

The correlation of the ISS between the two pulsars can provide the extra information. Our analysis [5] of earlier data showed a high degree of correlation, evaluated from the ISS from the two pulsars sampled at times t_a and t_b relative to the eclipse and averaged over the bandwidth as follows:

$$\rho(t_a, t_b) = \Sigma^{\nu}\delta S_a(t_a,\nu)\,\delta S_b(t_b,\nu)/[\Sigma^{\nu}\delta S_a(t_a,\nu)^2\Sigma^{\nu}\delta S_b(t_b,\nu)^2]^{0.5}, \tag{5}$$

The best example is shown in figure 4, in which we have now refined the model to include the estimated variation in signal to noise due to changing mean amplitudes due to A's eclipse and B's emission profile versus ϕ. This proceedure gives better estimates for the times t_{apk} and t_{bpk} for the peak in the ISS correlation function, which give independent information as follows:

$$V_{cx} = V_{oax}\frac{t_{apk}/t_{bpk} - m_a/m_b}{1 - t_{apk}/t_{bpk}} \tag{6}$$

$$y_{b0}/V_{cy} = t_{apk} - t_{bpk}, \tag{7}$$

where the mass ratio is known to be 1.07 and y_{b0} is the projected separation of A and B at eclipse and so depends on inclination i.

Unfortunately, our GBT observations July 2004–July 2005 showed that the window of B's visibility near the eclipse has migrated later, so when the AB baseline is small (near eclipse)

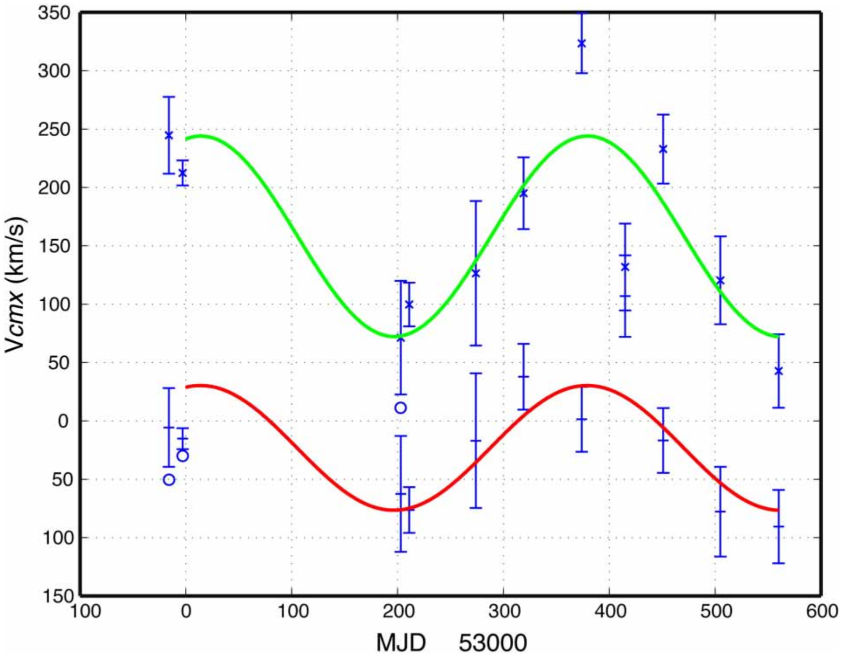

Figure 4. Correlation of the ISS from A and B versus time offsets t_a and t_b relative to the time of A's eclipse. *Left* Observation on MJD 52984 at 1.4 GHz; *Centre* Fitted model; *Right* Residual.

B's amplitude is too small to be useful; see also [8]. As a result we cannot use this method to estimate V_{cx} for all of our data. Consequently, we proceed by using the estimate from the data of figure 4 of $ab/c^2 = 0.38(\pm 0.7)$, and assuming that it is constant in the $t_{\rm iss}$–ϕ fits. This gives two solutions for V_{cx} at each epoch. It also constrains the axial ratio of the ISS to be greater than 2.6 with an unknown orientation.

5. Correcting for the Earth's motion

The changing (tansverse projected) velocity of the Earth ($\boldsymbol{V}_{\bf E}$) makes $\boldsymbol{V}_{\bf c}$ change with epoch. Since our velocities are defined at the pulsars the relations are:

$$\boldsymbol{V}_{\bf c} = \boldsymbol{V}_{\bf cm} + \boldsymbol{V}_{\bf E}\, s/(1-s) = \boldsymbol{V}_{\bf ism}/(1-s). \tag{8}$$

Here $\boldsymbol{V}_{\bf cm}$ is the pulsar system proper motion relative to the Sun and $\boldsymbol{V}_{\bf ism}$ is the velocity relative to the Sun of the scattering plasma in the interstellar medium which is presumed to be confined to a relatively narrow region at distance sL from the pulsar, which is L from the Earth. The equation shows how to correct the scintillation velocity $V_{{\rm c},x}$ for the changing Earth velocity, even though it introduces two further unknowns: s and the position angle β of the orbital plane relative to celestial north.

Figure 5 shows the two estimates for V_{cx} at each epoch and the best model fits to the upper and lower values. In view of the low-measured system proper motion we adopt the lower model fit and can obtain s and β. This fit has a mean at $-22\,{\rm km\,s^{-1}}$ which is an estimate of the quantity $V_{cmx} - V_{{\rm ism},x}/(1-s)$. The next step is to use β to project the known proper motion velocity parallel to the orbit plane to give V_{cmx} and so estimate $V_{{\rm ism},x}$.

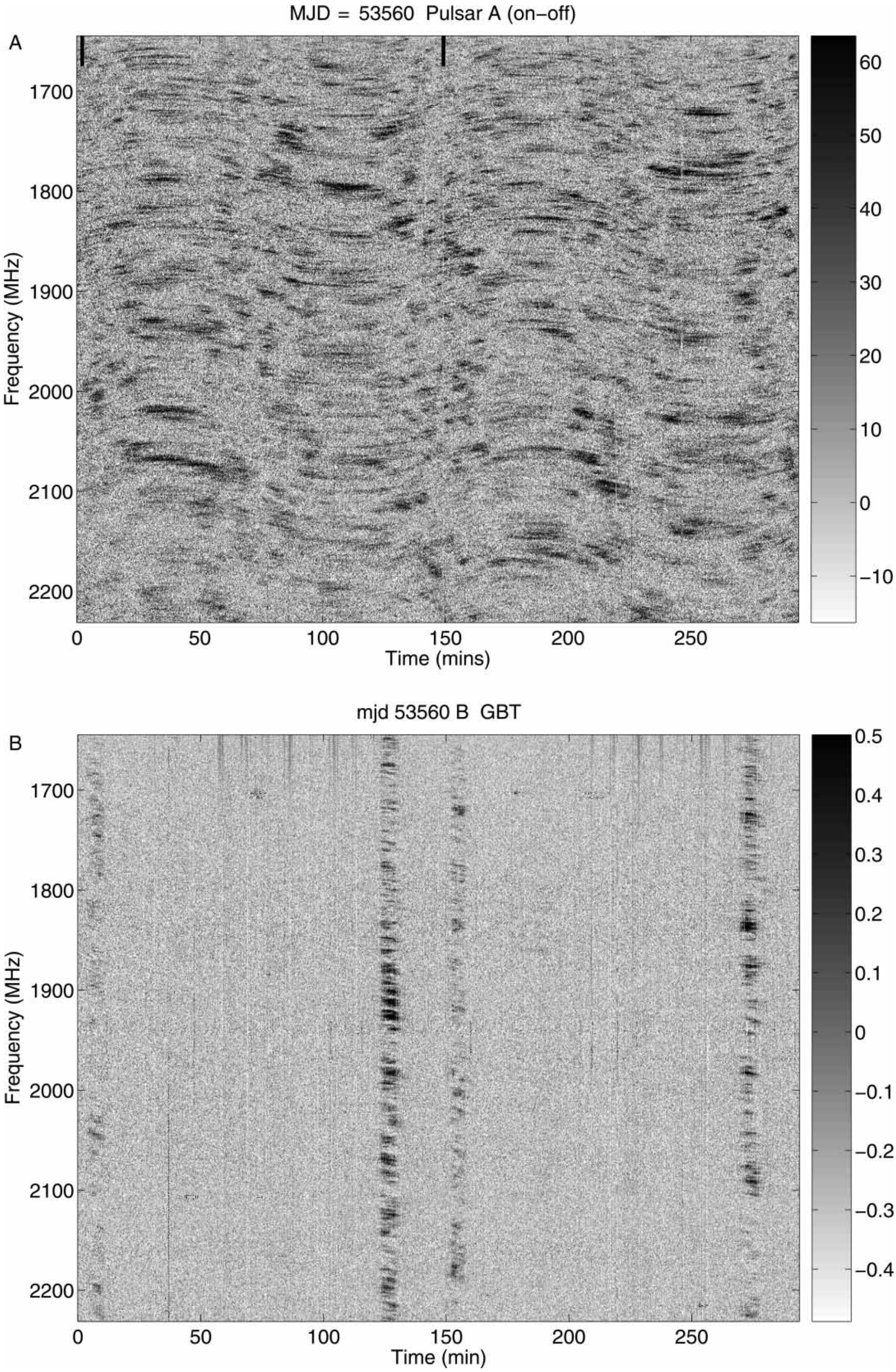

Figure 5. Estimates of V_{cx} from 11 epochs found by assuming a fixed value for the anisotropy parameterized by $ab/c^2 = 0.38$. The circles are estimates from data for which the A–B correlation gave a useful estimate.

Then we will use $(c/a)V_{cy}$ estimates from the 11 epochs and combine with the A–B correlation to extract V_{cy} and do an annual fit to find the velocity components perpendicular to the orbit plane. By applying the model in both coordinates we will obtain estimates of the parameters of the ISM $(s, \boldsymbol{V}_{\mathbf{ism}})$ and the orbital position angle. We will also obtain new estimates of the impact parameter at eclipse and so revisit our measurement of the inclination. However, there are some signs that our model may not be sufficient, in that the parameter s_{iss} appears to vary unexpectedly with epoch. Thus our analysis is not complete and full results will be published in a future paper.

6. Conclusions

- The ISS timescale for PSR J0737-3039A has been measured near 2 GHz versus orbital phase at 11 epochs over more than a year. Three harmonic coefficients of this variation have been estimated at each epoch.
- We present theoretical analysis of the harmonic coefficients in the presence of anisotropic ISS and how they vary with the Earths velocity. Anisotropy has a strong influence on the apparent centre-of-mass velocity.
- Since the Earth lies very close to the orbit plane of PSR J0737-3039 there are only three degrees of freedom in fitting the changing ISS time scale over the orbit–insufficient to determine the centre-of-mass velocity from one epoch.
- Correlation in the ISS between the A and B pulsars provides strong evidence for an axial ratio ($A > 2.6$) and can allow an independent estimate of V_{cx}. However, the drift in the on-times for B have reduced the A–B correlation after January 2004.
- By fixing the anisotropy parameter ab/c^2, we have estimated the component of the centre of mass velocity parallel to the orbit plane in 11 epochs over more than one year. After correcting these for the Earth's velocity, we hope to determine the celestial position angle of the orbital plane, the distance to the scattering region of the ISM and the transverse velocity of the plasma that causes the ISS.

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