GREEN BANK TELESCOPE MEASUREMENT OF THE SYSTEMIC VELOCITY OF THE DOUBLE PULSAR BINARY J0737–3039 AND IMPLICATIONS FOR ITS FORMATION

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ABSTRACT

We report on the measurement at 820 and 1400 MHz of the orbital modulation of the diffractive scintillation timescale from pulsar A in the double-pulsar system J0737–3039 using the Green Bank Telescope. With fits to this modulation, we determine the systemic velocity in the plane of the sky to be \( V_{\text{iss}} \approx 140.9 \pm 6.2\text{ km s}^{-1} \). The parallel and perpendicular components of this velocity with respect to the line of nodes of the pulsar’s orbit are \( V_{\text{iss}} \approx 96.0 \pm 3.7\text{ km s}^{-1} \) and \( V_{\text{iss}} \approx 103.1 \pm 7.7\text{ km s}^{-1} \), respectively. The large \( V_{\text{iss}} \) implies that pulsar B was born with a kick speed of \( \gtrsim 100\text{ km s}^{-1} \). Future Very Long Baseline Array determinations of the angular proper motion in conjunction with improved \( V_{\text{iss}} \) measurements should provide a precise distance to the system. Using high-precision timing data and the \( V_{\text{iss}} \) model, we estimate a best-fit orbital inclination of \( i \approx 88.7 \pm 0.9\text{°} \).

Subject headings: binaries: general — ISM: general — pulsars: general — pulsars: individual (PSR J0737–3039A, PSR J0737–3039B) — stars: kinematics

1. INTRODUCTION

Measurements of the decorrelation bandwidth \( \Delta f_{\text{D}} \) and scintillation timescale \( \Delta t_{\text{D}} \) of pulsars undergoing strong diffractive interstellar scintillation (DISS) can be used to estimate their velocity in the plane of the sky (Lyne & Smith 1982). Cordes & Rickett (1998) examined DISS-derived pulsar velocities in detail and found that they depend heavily on the observing frequency, the direction and distance to the pulsar, and the distribution of the scintillating medium. This last point causes various models for the electron distribution and its irregularities to produce differences in the “measured” scintillation velocities \( (V_{\text{iss}}) \) by factors of a few. However, for binary pulsars in compact orbits (orbital periods \( P_{\text{orb}} \leq 1\text{ day} \)), the pulsar-timing–derived orbital velocities can be used to calibrate \( V_{\text{iss}} \) measurements and remove many model-dependent and/or systematic effects. Unfortunately, suitable binary pulsars are rare, and successful measurements of this kind have only been made for two pulsars: PSR B0655+64 by Lyne (1984) and PSR J1141–6545 by Ord et al. (2002, hereafter OBvS).

PSR J0737–3039A and PSR J0737–3039B (hereafter A and B; Burgay et al. 2003; Lyne et al. 2004) comprise a fantastic double-pulsar binary (hereafter J0737) consisting of the 22.7 ms pulsar A and the 2.77 s pulsar B. It is nearby \( (D \sim 0.6\text{ kpc}) \), mildly eccentric \( (e \sim 0.088) \), compact \( (P_{\text{orb}} \sim 2.45\text{ hr}) \), highly inclined \( (i \sim 87^\circ) \), strongly relativistic, and displays eclipses of A and very large but systematic flux variations of B. Its proximity, relatively high flux density, and rapidly moving pulsars \( (\text{velocities} \sim 300\text{ km s}^{-1}) \) make it an ideal target for \( V_{\text{iss}} \) studies. In this Letter we report measurements of the orbital modulation of \( V_{\text{iss}} \) from A using data from the 100 m Green Bank Telescope (GBT).

2. OBSERVATIONS AND DATA REDUCTION

In 2003 December, we were awarded 5 × 6 hr Exploratory Time tracks on J0737 with the GBT as part of the NRAO Rapid Science program. For three of the observations discussed here, we used the Berkeley-Caltech Pulsar Machine (BCPM; e.g., Kaspi et al. 2004) with summed intermediate frequencies (IFs) and 72 \( \mu \text{s} \) sampling, one at 1400 MHz with \( 96 \times 1\text{ MHz} \) channels and the other two at 820 MHz with \( 96 \times 0.5\text{ MHz} \) channels (Table 1). During one 820 MHz observation, we also used the GBT Spectrometer Spigot Card, a new pulsar back end developed at Caltech and NRAO. It processes autocorrelations from the GBT Digital Spectrometer using two custom digital logic cards that accumulate, sort, pack, and decimate the data before sending it to a PC for output to a multi-TB RAID array. The Spigot can handle one or two IFs with band- widths of 50, 200, or 800 MHz. We used a 50 MHz mode (44) to process 1024 lags from summed IFs that were 8 bit–sampled every 40.96 \( \mu \text{s} \).

We folded these data modulo the predicted pulse period from the Lyne et al. (2004) timing ephemeris, determined a local timing solution for A, and then created the dynamic spectra discussed below. For the timing analysis, we measured 300 times of arrival (TOAs) from each of the observations for individual integration times of \( \sim 1\text{ minute} \) by referencing the maximum of the cross-correlation between the folded profiles and a Spigot-derived template to the observation start time as determined from the observatory clock. Our initial timing fits using TEMPO8 showed approximately linear, frequency-dependent drifts in the TOAs of tens of microseconds during each of the 5–6 hr observations. Since A’s pulsations are significantly linearly polarized (Demorest et al. 2004), such drifts may be caused by changes in the total-intensity pulse profile with time due to the rotation of the receiver feed with respect to the sky and gain differences in the two orthogonal IFs. In order to make high-precision measurements of local effects like the Shapiro delay, we fitted for frequency jumps between the observations that effectively whit-

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8 See http://pulsar.princeton.edu/tempo.
en ed the residuals to provide a postfit rms of ~11 μs. Using a mass for B of 1.25 $M_\odot$ (Lyne et al. 2004), we determine the Shapiro “shape” parameter to be $i = 0.99962^{+0.00038}_{-0.00093}$, which corresponds to $i = 88.4^{+1.8}_{-1.4}$. The errors for $i$ and the other orbital parameters were determined using a bootstrap analysis (e.g., Efron & Tibshirani 1986) that showed that our results are consistent with those in Lyne et al. (2004) at the 1 σ level. Figure 1 shows residuals from the 820 MHz Spigot observation alone.

Assuming a uniform Kolmogorov scattering medium, Cordes & Rickett (1998) derived the velocity estimator

$$V_{\text{ISS}} = 2.53 \times 10^4 \frac{D \Delta \nu_p}{\nu \Delta t_d} \text{ km s}^{-1}, \quad (1)$$

where $D$ is the distance to the source in units of kiloparsecs, $\Delta \nu_p$ is the decorrelation bandwidth in units of megahertz, $\Delta t_d$ is the scintillation timescale in seconds, and $\nu$ is the observing frequency in units of gigahertz. Unlike $\Delta \nu_p$, which varies with the relative velocities of the Earth, scintillation screen, and pulsar, $\Delta t_d$ is a property of the screen itself and does not vary significantly during an observation. The initial constant differs by factors of ~1–3 depending on the structure function of the scattering medium/screen as well as its location and extent. The key point is that $V_{\text{ISS}} \propto \Delta t_d^{-1}$, with an overall scaling that can be measured by fitting the known orbital velocity of the pulsar to the observed changes in $\Delta t_d$.

To determine $\Delta t_d$ and $\Delta \nu_p$, we closely followed the process described in OBvS. Briefly, we created calibrated dynamic spectra (see Fig. 2) by taking the on-pulse minus off-pulse flux during a duration $T_{\text{int}}$ divided by the average level in each frequency channel during the full observation. We computed the autocorrelation function (ACF) of nonoverlapping (and hence independent) blocks of the dynamic spectra of duration $T_{\text{meas}}$ to measure $\Delta t_d$ (the $1/e$ half-width of the central ACF peak in the time direction; Cordes 1986). We measured $\Delta \nu_p$ (the half-width at half-height of the central ACF peak in the frequency direction; Cordes 1986) and its errors by fitting Gaussians to the central ACF peaks from 15 subintegrations and examining their statistics. We determined the relative errors for the $\Delta t_d$ values similarly, by examining the statistics for $\Delta t_d$ fits made in six and three frequency sub-bands for the Spigot and BCPM data, respectively. Due to the small number of sub-bands, we added errors of 5 and 10 km s$^{-1}$ in quadrature to the measured errors for the Spigot and BCPM data, respectively, to guard against underestimates of $V_{\text{ISS}}$ errors.

We converted the $\Delta t_d$ values into $V_{\text{ISS}}$ estimates using equation (1), and we calculated the true anomaly $\Theta$ at the center of each $V_{\text{ISS}}$ measurement interval using the timing ephemeris from Lyne et al. (2004). We performed a weighted least-squares fit of these data to equation (7) in OBvS. $V_{\text{ISS}} = \rho (\ell''^2 + v'')^{1/2}$, where $\rho$, $\ell''$, and $v''$ are the total velocities (i.e., orbital + systemic) parallel to and perpendicular to the orbital line of nodes in the plane of the sky, respectively. In contrast to OBvS, we used the known angle of periastron $\omega$ from timing and fitted for four parameters: $i$, the systemic velocities parallel to ($V_{\text{plane}}$) and perpendicular to ($V_{\text{perp}}$) the line of nodes, and a scaling parameter ($\kappa$) to account for uncertainties in the nature of the scattering medium and the distance to the pulsar. Table 1 lists the fitted parameters and their 95% statistical confidence limits as determined from projections of the $\chi^2$ space. The known inclination ($i \sim 90^\circ$) of 0737 removes the twofold degeneracy seen by Lyne (1984) and OBvS and produces a single solution for each fit. The errors in the fitted parameters were calculated after scaling the $\Delta t_d$ errors such that $\chi^2/\text{dof} = 1$. Combining the fits and their errors from the independent BCPM and Spigot data provides best estimates of $V_{\text{plane}} \approx 96.0 \pm 3.7$ km s$^{-1}$ and $V_{\text{perp}} \approx 103.1 \pm 7.7$ km s$^{-1}$ for a total systemic velocity in the plane of the sky of $V_{\text{ISS}} \approx 140.9 \pm 6.2$ km s$^{-1}$. We note that $V_{\text{ISS}}$ fits can result in $i > 90^\circ$ if $V_{\text{perp}}$ is either aligned with the orbital angular momentum vector, if that is pointing slightly toward us, or antialigned if the angular momentum is pointing slightly away from.

### Table 1

**GBT Observations and Model Fits for J0737−3039A**

| $f_{\text{obs}}$ (MHz) | Start MJD | Freq. Res. (bands × MHz) | $T_{\text{int}}$ (s) | $T_{\text{meas}}$ (s) | $\Delta \nu_p$ (MHz) | $V_{\text{ISS}}$ (km s$^{-1}$) | $V_{\text{plane}}$ (km s$^{-1}$) | $V_{\text{perp}}$ (km s$^{-1}$) | $i$ (deg) | $\kappa$ | $\chi^2/\text{dof}$ |
|---------------------|----------|--------------------------|---------------------|---------------------|------------------|-----------------|-----------------|-----------------|-------|-------|-------|
| 820 MHz             | 52,997.214 | 1024 × 0.04883 | 5.00 | 10.0 | 320 | 0.096(4) | 139.0(4.5) | 95.1(3.8) | 101.4(8.0) | 91.0(1.1) | 0.631(11) | 0.64 |
| 1400 MHz            | 52,984.195 | 96 × 1.0 | 6.12 | 12.24 | 612 | 1.8(2) | 163(16) | 107(13) | 123(27) | 92.9(3.5) | 0.693(48) | 1.50 |

Note.—All confidence intervals are 95% statistical. The number of degrees of freedom for the model fits are $\text{dof}_{\text{sys}} = 56 - 4 = 52$ and $\text{dof}_{\text{iss}} = 36 - 4 = 32$. For these measurements, $i$ can range from 0 to 180° (see § 2). The errors on the fitted parameters were determined from projections of the $\chi^2$ space after adjusting the errors of the $V_{\text{ISS}}$ measurements such that $\chi^2/\text{dof} = 1$.

* Spigot data.

**B** CPM data.

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**Fig. 1.—Timing results from the 820 MHz GBT+Spigot observation listed in Table 1. Top:** Residuals from a Keplerian orbit fit to the data. Systematic deviations corresponding to the unmodeled Shapiro delay (shown as the line) are obvious in each orbit. **Bottom:** Residuals from a fit using the “DD” timing model that includes the Shapiro delay for a 1.25 $M_\odot$ pulsar B at an orbital inclination $i = 88.4^\circ$. The postfit rms residuals for the Spigot data alone are <7 μs.
us. Combining the timing- and scintillation-based measurements gives $i = 88.7\pm0.9$, if we use the more standard notation $i \leq 90^\circ$.

While the “self-calibrating” nature of binary pulsar $V_{\text{iss}}$ measurements eliminates many of the uncertainties found in $V_{\text{iss}}$ studies of isolated pulsars (e.g., Cordes 1986), the motion of the Earth and the rotation of the Galaxy can both bias the measured $V_{\text{iss}}$. A flat, 220 km s$^{-1}$ Galactic rotation curve implies a velocity component in the plane of the sky of $v_{\parallel} \approx 14(D/0.6\text{ kpc})$ km s$^{-1}$ because of the differential Galactic rotation in the direction of 0737 ($l = 245^\circ.2$, $b = -4^\circ.5$). However, as Cordes & Rickett (1998) point out, the interstellar medium rotates along with the Galaxy, implying that the effective transverse velocity is less than 1 km s$^{-1}$ for all reasonable distances to 0737. Earth’s orbital motion projected onto the sky toward 0737 contributes a doubly periodic velocity component $\Delta v_{\parallel,1}$ to the measured $V_{\text{iss}}$ with minimum and maximum values of 23 and 30 km s$^{-1}$, respectively. During these observations, $\Delta v_{\parallel,1} \sim 29$ km s$^{-1}$. Since the orientation of the measured $V_{\text{iss}}$ in the plane of the sky is currently unknown, we cannot remove these biases from our data. However, measurement of an annual variation in $V_{\text{iss}}$ will allow us to remove $\Delta v_{\parallel,1}$, while a Very Long Baseline Array (VLBA) proper-motion determination will allow us to remove both biases directly.

3. DISCUSSION

0737’s large measured $V_{\text{iss}} \approx 140$ km s$^{-1}$ has important implications for its formation. We assume that 0737 followed the standard formation scenario for double neutron stars (DNSs) in the Galactic disk (e.g., Bhattacharya & van den Heuvel 1991). In this picture, the first NS (A) forms in orbit about a massive ($\geq 8 M_\odot$) stellar companion. The binary acquires some velocity because of impulsive mass loss in the supernova explosion and a possible natal kick to the NS. At this stage, the system resembles a high-mass X-ray binary (HMXB). Detailed studies (e.g., Pfahl et al. 2002) find expected HMXB systemic speeds of $\lesssim 30$ km s$^{-1}$, because the NS kick is distributed over the large total mass of the binary. It is unlikely that the first supernova provided the high systemic velocity implied by the measured $V_{\text{iss}}$.

At the end of the HMXB phase, the companion star evolves and fills its Roche lobe. The extreme mass ratio leads to dynamically unstable mass transfer and a common-envelope phase. If coalescence is avoided, the NS emerges in a tight orbit with the hydrogen-exhausted core of its companion. The stellar core continues to evolve and may transfer matter stably to the NS via Roche lobe overflow—the likely mechanism for spinning up and reducing the dipole magnetic field strength of A (Dewi & van den Heuvel 2004). Subsequently, the stellar core explodes and produces the second NS (B). In 0737, the pre-supernova mass of the stellar core was likely $M_1 = 2.0–3.5 M_\odot$ (Dewi & van den Heuvel 2004; Willems & Kalogera 2004). The combination of supernova mass loss and a kick to B could easily have given 0737 a speed $\approx 140$ km s$^{-1}$. We now use the large component ($V_{\text{torp}} \approx 103$ km s$^{-1}$) of the systemic velocity perpendicular to the orbital plane to constrain the magnitude of the kick imparted to B.

The masses of A and B are $M_A \approx 1.34 M_\odot$ and $M_B \approx 1.25 M_\odot$, respectively, giving a total binary mass of $M = 2.59 M_\odot$ (Lyne et al. 2004). We assume that the pre-supernova orbit was circular, and we denote by $\mathbf{V}$, $\mathbf{V} = \mathbf{V} + \dot{\mathbf{V}}$, and $\mathbf{H} = \mathbf{R} \times \mathbf{V}$ the position, velocity, and orbital angular momentum of the precollapse progenitor of B relative to A, respectively. If B receives an impulsive natal kick velocity of $\dot{\mathbf{V}}$, the post-supernova relative orbital velocity and angular momentum are given, respectively, by $V = \mathbf{V} + \dot{\mathbf{V}}$ and $H = H + \mathbf{R} \times \dot{\mathbf{V}}$. The velocity added to the binary center of mass after the supernova is

$$V_{\text{cm}} = - \frac{M_A (M_C - M_B)}{M (M_C + M_A)} V + \frac{M_B}{M} \dot{\mathbf{V}}.$$  

If $V = 0$, then $V_{\text{cm}}$ is in the orbital plane. Therefore, the large
measured \( v_{\text{perp}} \) may require a significant kick velocity for B at birth. If we assume that \( v_{\text{CM}} \) and \( v_{\text{perp}} \) are entirely due to the second supernova (and have not been significantly affected by acceleration in the Galactic gravitational potential), then \( v_{\text{perp}} \) is related to \( v_i \) by (see also Wex et al. 2000)
\[
|H' \cdot V_{\text{CM}}| = |H \cdot V_i|(1 + \frac{M_b}{M_f})^{-1} \approx H' v_{\text{perp}},
\]
(3)

since 0737 is viewed nearly edge-on. For specified masses and orbital parameters before and after the supernova, \( v_i \) is minimized when \( v_i \) is parallel or antiparallel to \( H \) (i.e., perpendicular to the pre-supernova orbital plane). The minimum kick speed is then
\[
v_{\text{k, min}} = \frac{v_{\text{perp}} H'}{H} \left(1 + \frac{M_a}{M_f}\right).
\]
(4)

Note that
\[
\frac{H'}{H} = \left(\frac{M_f}{M_f + M_b}\right) \left(\frac{a'}{a}(1 - e'^2)^{1/2},
\right)
\]
where \( a' \) and \( e' \) are the immediate post-supernova semimajor axis and eccentricity, respectively, which evolved to their observed values because of gravitational wave emission. Dewi & van den Heuvel (2004) and Willems & Kalogera (2004) each find that \( e' \approx 0.14 \), which implies that \((a'/a)(1 - e'^2) \approx 1\). Finally, we obtain
\[
v_{\text{k, min}} \approx \frac{v_{\text{perp}}}{\sqrt{\left(\frac{M_f}{M_b}\right)} \left(1 + \frac{M_a}{M_f}\right)^{1/2}}.
\]
(6)

For the range of precollapse core masses given above, and \( v_{\text{perp}} \approx 100 \text{ km s}^{-1} \), we find that \( v_{\text{k, min}} \approx 100 - 150 \text{ km s}^{-1} \), where the upper limit corresponds to \( M_f = 2 M_c \). If the pre-supernova core mass takes its smallest possible value of \( M_f = M_b \), then \( v_{\text{k, min}} \approx 210 \text{ km s}^{-1} \).

Piran & Shaviv (2004) note that for \( D \approx 0.6 \text{ kpc}, 0737 \) is only \( \approx 50 \text{ pc} \) from the Galactic plane. They suggest that finding 0737 so close to the plane implies that \( v_{\text{perp}} \) is small \( \approx 15 \text{ km s}^{-1} \) or \( \approx 150 \text{ km s}^{-1} \) at 68% or 95% confidence, respectively) and that the supernova mass loss and kick to B must also have been small. The measurement of a large \( v_{\text{perp}} \) implies that (1) either the velocity direction is largely in the Galactic plane or we happen to see it as it passes through the plane, and (2) moderate precollapse core masses and NS kicks are permitted if not required.

VLBA observations will soon determine the magnitude and direction of 0737’s proper motion, \( \mu = 0.056 \text{ yr}^{-1}(v_{\text{iss}}/140 \text{ km s}^{-1})(D/0.6 \text{ kpc})^{-1} \). When combined with the known transverse velocity \( v_{\text{iss}} \approx v_{\text{CM}} \), this will provide a unique geometric distance to the pulsar \( (D = v_{\text{CM}}/\mu) \). For long-term timing observations, the large \( v_i \) will cause an apparent acceleration (Shklovskii 1970) that will bias the measured spin- and orbital-period derivatives. For 0737, \( P'P = \frac{v_{\text{CM}}}{H}(Dc) = \frac{v_{\text{CM}}}{H}c = 3.5 \times 10^{-10} \text{ s}^{-1} \), which amounts to \( \lesssim 5\% \) of A’s measured spin-down and \( \approx 2.5\% \) of the predicted orbital decay rate due to gravitational wave emission. Future bias-corrected measurements of \( v_{\text{iss}} \) should help us determine \( v_i \) to a few percent, and VLBA observations will likely measure \( \mu \) to even better precision. Therefore, the “Shklovskii effect” should be measurable to \( \lesssim 5\% \) precision, and consequently its error will contaminate the measurement of the orbital period-derivative \( P'_{\text{orb}} \) due to gravitational wave emission by \( \lesssim 0.2\% \).

4. CONCLUSIONS

We have measured the systemic velocity and inclination of 0737 using the self-calibrating method of binary scintillation velocity measurements. The inferred high-velocity \( v_{\text{iss}} \approx 140 \text{ km s}^{-1} \) strongly suggests that a substantial \( \approx 100 \text{ km s}^{-1} \) kick was imparted to pulsar B at its birth. The large \( v_{\text{iss}} \) will impact long-term timing of the system and will allow us to make a precise geometric distance measurement when combined with a VLBA proper motion.

Future observations using the GBT+Spigot will allow us to make substantially improved measurements of \( v_{\text{iss}} \) at 1400 MHz and even at 2200 MHz where we have already detected the orbital modulation of A in BCPM data. These measurements should also allow us to remove the biases due to the Earth’s motion and the differential Galactic rotation. Finally, while we have already detected scintillation from B during the bright portions of its orbit, future observations may allow us to make “snapshot” \( v_{\text{iss}} \) calibrations based on simultaneous measurements of \( \Delta t_d \) from A and B and the known relative orbital velocities of the pulsars. Such measurements will demand far less telescope time.

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