The Mean Pulse Profile of PSR J0737−3039A

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ABSTRACT

General relativity predicts that the spin axes of the pulsars in the double-pulsar system (PSR J0737−3039A/B) will precess rapidly, in general leading to a change in the observed pulse profiles. We have observed this system over a one-year interval using the Parkes 64-m radio telescope at three frequencies: 680, 1390 and 3030 MHz. These data, combined with the short survey observation made two years earlier, show no evidence for significant changes in the pulse profile of PSR J0737−3039A, the 22-ms pulsar. The limit on variations of the profile 10% width is about $0\overset{\circ}{.}5$ per year. These results imply an angle δ between the pulsar spin axis and the orbit normal of $\lesssim 60^\circ$, consistent with recent evolutionary studies of the system. Although a wide range of system parameters remain consistent with the data, the model proposed by Jenet & Ransom (2004) can be ruled out. A non-zero ellipticity for the radiation beam gives slightly but not significantly improved fits to the data, so that a circular beam describes the data equally well within the uncertainties.

Subject headings: pulsars: general — pulsars: individual (J0737–3039A)

1. Introduction

The double-pulsar system PSR J0737−3039A/B (Burgay et al. 2003; Lyne et al. 2004) provides a wonderful laboratory for investigations of relativistic gravity (Kramer et al. 2004) as well as the physics of pulsar magnetospheres (e.g., McLaughlin et al. 2004). The system consists of a 22-ms pulsar, PSR J0737−3039A, in a 2.4-h binary orbit with PSR J0737−3039B, a younger pulsar with a spin period of 2.7 s. The system is mildly eccentric ($e \sim 0.088$) and is viewed nearly edge-on (orbit inclination $i \sim 88^\circ$). With mean orbital speeds $v \sim 0.001c$, the system is highly relativistic, allowing the detection of four "post-Keplerian" parameters in just six months of observation (Lyne et al. 2004). The post-Keplerian parameters, together with the mass ratio, uniquely measurable in this double-pulsar system, give accurate values for the masses of the two stars as well as stringent tests of general relativity (Kramer et al. 2004).

Within the framework of general relativity, the spin vectors of the two pulsars are expected to exhibit geodetic precession about the total angular momentum of the system (Damour & Ruffini 1974; Barker & O'Connell 1975). Since the total angular momentum is dominated by the or-

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bital motion, the pulsar spin vectors effectively precess about the orbit normal. The precession rate Ω depends on the Keplerian parameters and the masses of both pulsars, with predicted precessional periods of $\sim$ 75 yr and $\sim$ 71 yr for PSR J0737−3039A and PSR J0737−3039B respectively (Lyne et al. 2004). These are about a factor of four shorter than the value for PSR B1913+16, the Hulse-Taylor binary pulsar (Weisberg, Romani & Taylor 1989). In general, precession will result in a change of the width and shape of the observed profile as the angle of the line of sight with respect to the pulsar spin axis (ζ) changes during the precessional period. Long-term evolution of the mean pulse profile has been observed in PSR B1913+16 (Weisberg et al. 1989; Kramer 1998) and PSR B1534+12 (Stairs et al. 2004) and interpreted as evidence for geodetic precession. This gives the three-dimensional geometry (within a 180° ambiguity) of the system and, in the case of PSR B1913+16, a prediction that the pulsar will no longer be visible after the year 2025. Weisberg & Taylor (2002) have used the precessional motion to produce a two-dimensional image of the part of the PSR B1913+16 emission beam traversed so far, suggesting that the beam is elongated in the latitudinal direction.

If the magnetic-pole model (Radhakrishnan & Cooke 1969) is assumed, ζ and the inclination angle of the magnetic axis with respect to the spin axis (α) can be deduced from a fit of the model to the observed variations of polarization position-angle, at least for wide profiles (e.g., Lyne & Manchester 1988). Demorest et al. (2004) used such an analysis to conclude that PSR J0737−3039A is a nearly aligned system with $\alpha \sim 4°$, but the fit to the observed position angle variations is poor. The observer angle ζ is unconstrained by this fit. Jenet & Ransom (2004) determined possible geometries of the J0737−3039A/B system based on a model for the orbital modulation of the PSR J0737−3039B pulse intensity. Two solutions were obtained with (α, δ) of $(1.^{\circ}6 \pm 1.^{\circ}3, 167° \pm 10°)$ and $(14° \pm 2°, 90° \pm 10°)$ respectively. The first of these is consistent with the Demorest et al. (2004) solution. Both solutions predict a rapid evolution of the observed profile width of PSR J0737−3039A, with expected changes of $\sim 42°$ and $\sim 96°$ per year for the two models. Here we report on observations of the mean pulse profile of PSR J0737−3039A over a three-year interval, 2001 August to 2004 August.

2. Observations and Analysis

We have used the Parkes 64-m radio telescope to observe the PSR J0737−3039A/B system since 2003 May 1 (MJD 52670), shortly after its confirmation, to 2004 August 8 (MJD 53225). Observations were made in three frequency bands centered at 680, 1390 and 3030 MHz, with the 680-MHz (50cm) and 3030-MHz (10cm) observations commencing in 2003, December. Before 2003 October, the 1390 MHz observations were made using the center beam of the multibeam receiver, which has an equivalent system noise of approximately 29 Jy. In addition, we have the original survey pointing, a 4-min observation made at 1390 MHz on 2001 August 22 (Burgay et al. 2003). After 2003 October, the H-OH receiver with a system noise of about 42 Jy was used. Both the multibeam and H-OH systems were dual polarization and used a filterbank system consisting of $2 \times 512 \times 0.5$ MHz channels. After detection, the two polarizations for each channel were summed, sampled at either 80 μs or 125 μs intervals and recorded to tape for subsequent processing. The other two bands were observed using the dual-polarization coaxial 10cm/50cm receiver, with system noises of $\sim$ 48 Jy and $\sim$ 64 Jy at 10cm and 50cm respectively. A filterbank system with $2 \times 256 \times 0.25$ MHz channels was used with the 50cm receiver and at 10cm the filterbank system had $2 \times 192 \times 3$ MHz channels.

Over the 15-month interval, we obtained 59 observations at 1390 MHz, 17 observations at 680 MHz and 27 at 3030 MHz, all with durations ranging from 10 min to 5 hr. Data from each observation were folded at the apparent topocentric period of PSR J0737−3039A to form mean pulse profiles with 256 phase bins, which were then summed in frequency and time to form a single profile using the PSRCHIVE data analysis system (Hotan, van Straten & Manchester 2004). All observations for each frequency band were then summed to form grand-average profiles containing 116, 27 and 34 hrs of data, respectively. These profiles are shown in Figure 1.

The 1390-MHz observations over the 15 months from 2003 May were divided into eight chronologically-ordered groups and average profiles were formed

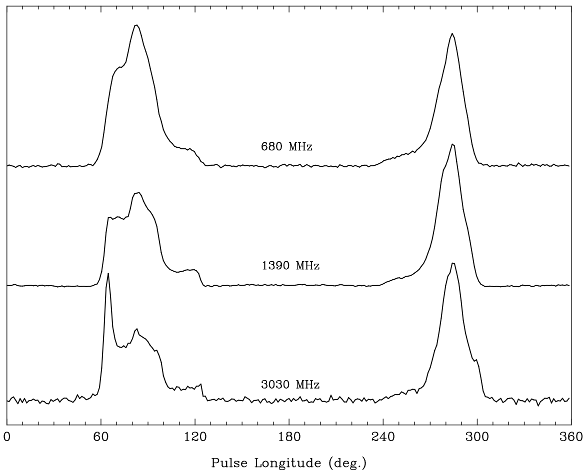

Fig. 1.— Mean pulse profiles for PSR J0737−3039A at three frequencies, where 360° of longitude corresponds to the pulse period. The 680-MHz and 3030-MHz profiles were aligned to give maximum cross-correlation with the 1390-MHz profile.

for each of these eight groups. Integration times ranged between 5 hrs (MJD 53068) and 20 hrs (MJD 53000). Examination of these average profiles showed little or no evidence for evolution of the mean pulse profile over the 15-month interval. The eight profiles were each aligned with the grand-average profile using a cross-correlation analysis and baselines subtracted, taking the longitude range 310° to 50° (Figure 1) as the baseline region. Each profile was scaled to have the same area as the grand-average profile, which was then subtracted from it to form the difference profiles shown in Figure 2. Also shown at the bottom of the figure is the difference profile corresponding to a stretched version of the grand-average profile, demonstrating the signature of a change in profile width. The adopted stretch factor (1.004) corresponds to an increase of about 1° in profile width, where the width is defined to be the separation of the steep outer edges of the profile (at roughly 60° and 300° in Figures 1 and 2) at 10% of the amplitude of the second (stronger) component.

Significant differences are seen, especially between MJDs of 53000 and 53103. In general, these differences do not have the signature of an increase or decrease in profile width, but rather appear to result from changes in the relative amplitude of the various pulse components, especially at the leading and trailing components of the profile. Polarization observations (e.g., Demorest et al. 2004) show that these components have high linear polarization. It is likely that the observed changes are an instrumental effect resulting from differences in receiver gain between the two polarization channels combined with parallactic angle variations.

These difference profiles confirm the lack of significant secular profile evolution. There is no evidence for a systematic change in the overall profile width to a level of much less than 1° and there is no evidence for any intrinsic changes in the width or shape of the leading and trailing pulse components considered separately. We have also reprocessed the original 4-min survey pointing to give a profile with signal-to-noise ratio of about 25. Again, this shows no evidence for any significant change in profile shape or width.

In order to quantify the profile stability, widths at 10% of the pulse peak were measured for each of the eight 1390-MHz profiles and the 2001 observation using a cross-correlation technique. The leading (50° − 130° in Figures 1 and 2) and trailing (240° − 310°) pulse components were separately cross-correlated with a standard profile derived from the grand-average profile containing just the relevant component, determining the phase of each component relative to a reference phase. The difference of these phases was then added to the 10% width of the grand-average profile to give the 10% width at each epoch. Errors from the cross-correlation analysis were increased in quadrature by 10 μs to allow for systematic effects. The derived 10% widths are plotted in Figure 3 along with the fitted trend line. Clearly, there is no significant trend, with the fitted slope being $-0.^\circ2 \pm 0.^\circ3$ per year. The 10% profile width at MJD 53000 (2003 December 27) from the fit is $238.^\circ45 \pm 0.^\circ12$. Quoted errors are $\pm 2\sigma$ for both the width and slope.

3. Discussion and Conclusions

Figure 1 confirms the overall bilateral symmetry of the PSR J0737−3039A pulse profile, consistent with its origin from magnetic field lines associated with a single magnetic pole (Burgay et al. 2003; Demorest et al. 2004). There are significant

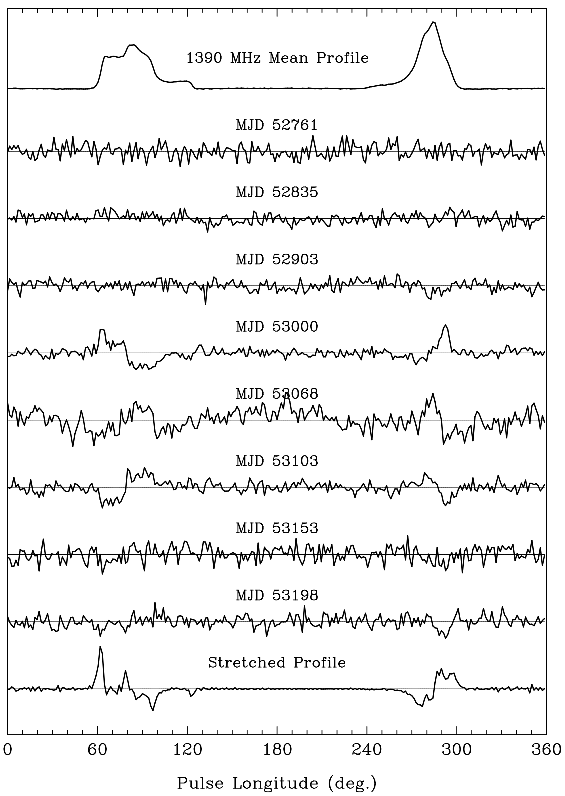

Fig. 2.— Difference profiles for PSR J0737−3039A at 1390 MHz relative to the grand-average pulse profile shown at the top of the figure for eight epochs, together with the difference profile corresponding to the grand-average profile stretched by 0.4%. The vertical scale of the difference profiles is a factor of ten larger than that of the grand-average profile.

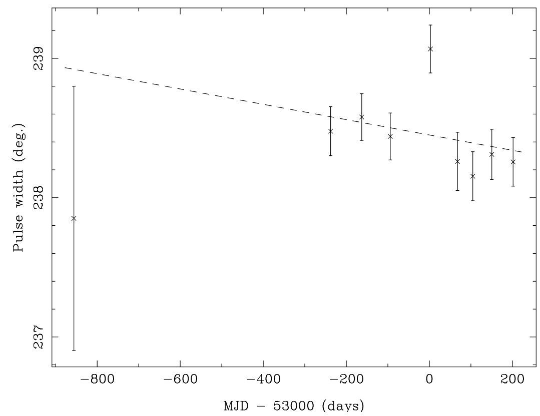

Fig. 3.— Profile widths at 10% of the peak amplitude for PSR J0737−3039A at 1390 MHz as a function of MJD relative to 53000. Error bars are $\pm 1\sigma$. The dashed line is a formal weighted least-squares fit of a linear trend to these data.

differences in the spectral indices of the various pulse components. The most striking of these is the relatively flat spectrum of the component at the extreme leading edge of the profile which is relatively much stronger at 3030 MHz. The 3030-MHz profile also shows a matching flat-spectrum component at the extreme trailing edge of the profile, reinforcing the idea that both components of the observed profile originate on field lines associated with a single magnetic pole. We assume this in the following discussion.

The main result of this paper is the extraordinary stability of the PSR J0737−3039A pulse profile over more than three years, a significant fraction of the expected geodetic precessional period of 75 years. Provided the angle between the spin axis of the pulsar and the orbital angular momentum (δ) is non-zero, we would expect to see a variation in profile width as a function of time. In particular, the system geometries proposed by Jenet & Ransom (2004) predict changes of many tens of degrees per year in the observed profile width. Clearly, these are not observed, ruling out this model in its present form.

One possible explanation for the observed lack of variation in profile width is that the spin axis of PSR J0737−3039A is aligned with the orbital angular momentum, i.e., $\delta \sim 0$. Since we view the orbit nearly edge-on, even for an orthogonal magnetic axis ($\alpha \sim 90^\circ$), this would require an effective beam radius $\rho > 90^\circ$, which seems unlikely. Furthermore, given that PSR J0737−3039B probably suffered a significant natal kick, an aligned rotation axis for PSR J0737−3039A is possible but unlikely (Willems, Kalogera & Henninger 2004).

We have investigated the limits which can be placed on the geometry of the system by modeling the observed profile width as a function of time (cf. Kramer 1998). An inclination angle $i = 88^\circ$ is assumed[1]. For a circular emission beam, four parameters are sufficient to model the expected profile changes: α, δ, ρ and an epoch T_0 describing the

[1] Since only $\sin i$ is determined at present, equivalent solutions are possible with $i = 92^\circ$ and $\alpha \to 180^\circ - \alpha$, etc.

precession phase. We fitted a circular beam model with $\rho < 90^\circ$ to the data and derive a χ^2-sphere plot for α and δ as shown in Figure 4. This figure shows that solutions with misalignment angle $\delta \lesssim 60^\circ$ are preferred, consistent with the conclusions of Willems et al. (2004) based on the observed velocity of the system.

The formal best-fit solution (reduced $\chi^2 = 2.88$) is located at $\alpha \sim 19^\circ$ and $\delta \sim 14^\circ$ (and at a corresponding mirror-solution of $\alpha \sim 161^\circ$ and $\delta \sim 166^\circ$). The predicted time variation for the observed profile width for this configuration is shown in Figure 4(a); pulses would be detected over the whole precessional period with an approximately sinusodial variation in the profile width. However, the χ^2-sphere is rather flat, and a statistically satisfactory solution is possible over a wide range of angles. Figure 4(b) shows a solution with small α and δ which is consistent with the preferred solution of Demorest et al. (2004) based on the observed position angle variations. Both of these solutions have a beam radius of very close to 90° corresponding to a fan beam. In case (b) however, the pulse is visible for a limited period only, roughly 1984 to 2023. Figure 4(c) shows a solution with intermediate α and δ for which the beam radius is smaller, about 65°. In all solutions, the observed pulse is emitted from field lines associated with a single magnetic pole as indicated by the observed profile symmetry.

Unless $\delta \sim 0$, the essentially constant profile width observed so far implies that the system is at or close to precessional phase zero (or 180°). At these times is $\mathrm{d}W/\mathrm{d}t \sim 0$.[2] This is possible – a similar situation evidently applies for PSR B1913+16 (Kramer 1998) – but statistically unlikely. A possible way of relaxing this constraint is to allow a non-circular beam. Biggs (1990) and Kapoor & Shukre (1998) have shown that, under certain assumptions, the polar emission beam is compressed in the latitudinal direction for $\alpha > 0^\circ$. On the other hand, polarization observations of young and millisecond pulsars (e.g., Narayan & Vivekanand 1983; Manchester & Han 2004) suggest beams effectively elongated in the latitude direction. First, we took the model of Kapoor & Shukre (1998) in which the beam compression is a function of α only and recomputed the χ^2-sphere. The results were only marginally different to those shown in Figure 4. We then took the beam ellipticity as a free parameter, first doing a grid search in ellipticity at each point on the (α,δ) plane and then searching for a global χ^2 minimum in (ρ_m, T_0, ϵ) space, where ρ_m is the beam major axis, T_0 is the time of precessional phase zero and ϵ is the beam ellipticity. Latitudinally compressed beams with axial ratio $\rho_{\rm lat}/\rho_{\rm long} \lesssim 0.5$ are restricted to a fairly small range of α and δ around 45°. On the other hand, fan-like beams with large axial ratio allow a much larger range of α and δ with values $\lesssim 30^\circ$ preferred. However, in none of these cases was the χ^2 value significantly better than those found in the circular-beam case.

In conclusion, we find that the pulse-width variations (or lack of them) observed so far allow a wide range of configurations for the PSR J0737−3039A/B system. Models with non-circular beams give somewhat better fits to the data but are statistically indistinguishable from fits with a circular beam. Misalignment angles $\delta \lesssim 60^\circ$ are generally preferred, consistent with the conclusions of Willems et al. (2004), and the configurations discussed by Jenet & Ransom (2004) can be ruled out. Solutions in which the pulse never disappears from view are possible, as are solutions where it does, in the most extreme cases about 15 years from now. Clearly, a longer time baseline, even one more year, will help to constrain the models, as will a more realistic interpretation of the observed position-angle variations.

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[2]There is a special case with $\cos\rho\sin\delta\cos\Phi = \cos\alpha$, where Φ is the precessional phase, which results in $\mathrm{d}W/\mathrm{d}t = 0$, but this requires an improbable fine-tuning of the system parameters.

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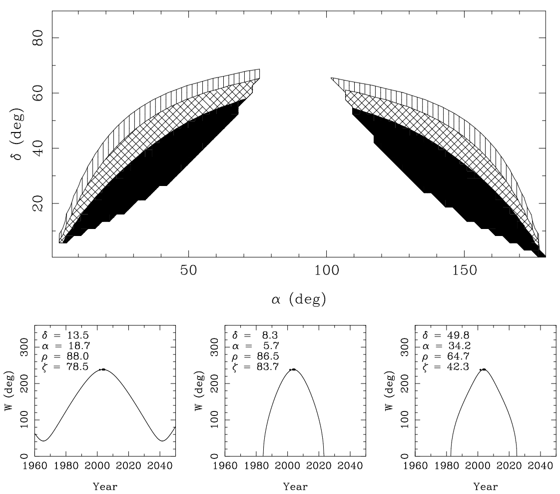

Fig. 4.— Results of fits to the observed profile widths of a model for geodetic precession of the pulsar spin axis, inclined by an angle δ to the orbit normal, with a circular beam of radius ρ inclined at an angle α to the pulsar spin axis. The upper part shows contours of χ^2 at 1-σ intervals, relative to the minimum value, with the darker regions having lower χ^2. The lower cutoff to the allowed regions represents the locus of points where the beam radius $\rho = 90^\circ$. These contours are mirrored for $90^\circ < \delta < 180^\circ$ with (α, δ) corresponding to $(180^\circ - \alpha, 180^\circ - \delta)$. In the lower part of the figure, the variation of profile width is shown as a function of time for three cases: (a) a point near the global minimum for χ^2, (b) a small α, small δ case, and (c) a solution with intermediate α and δ. The angle ζ is the minimum value of the inclination of the line of sight to the pulsar spin axis which occurs at precessional phase zero (or 180°) when the pulsar spin axis is in the plane defined by the orbit normal and the line of sight.