The Formation of the Double Pulsar PSR J0737–3039A/B

I. H. Stairs\textsuperscript{1}, S. E. Thorsett\textsuperscript{2}, R. J. Dewey\textsuperscript{2}, M. Kramer\textsuperscript{3}, C. A. McPhee\textsuperscript{1}

\textsuperscript{1}Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
\textsuperscript{2}Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, U.S.A.
\textsuperscript{3}University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, U.K.

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ABSTRACT
Recent timing observations of the double pulsar J0737–3039A/B have shown that its transverse velocity is extremely low, only 10 km/s, and nearly in the Plane of the Galaxy. With this new information, we rigorously re-examine the history and formation of this system, determining estimates of the pre-supernova companion mass, supernova kick and misalignment angle between the pre- and post-supernova orbital planes. We find that the progenitor to the recently formed 'B' pulsar was probably less than 2 $M_\odot$, lending credence to suggestions that this object may not have formed in a normal supernova involving the collapse of an iron core. At the same time, the supernova kick was likely non-zero. A comparison to the history of the double-neutron-star binary B1534+12 suggests a range of possible parameters for the progenitors of these systems, which should be taken into account in future binary population syntheses and in predictions of the rate and spatial distribution of short gamma-ray burst events.

Key words: pulsars: individual (PSR J0737–3039A/B)—supernovae:general

1 INTRODUCTION
The double pulsar PSR J0737–3039A/B\textsuperscript{1,2} (Burgay et al. 2003, Lyne et al. 2004) is an outstanding laboratory for tests of general relativity and of binary evolution and supernova theories. With its short orbital period, $P = 2.4$ hours, and moderate eccentricity, $e = 0.088$, the general-relativistic modifications to the Keplerian orbit are the largest known. Pulsars 'A' and 'B' have spin periods of 22.7 msec and 2.7 s, respectively; since both are observed as radio pulsars, the mass ratio is obtained directly from pulsar timing, leading to new theory-independent constraints on strong-field gravity (Lyne et al. 2003, Kramer et al. 2003).

Such double-neutron-star (DNS) systems are descended from high-mass X-ray binaries (HMXBs) in which both stars are massive enough to undergo supernova (SN) explosions (e.g., Tauris & van den Heuvel 2006, Dewi & Pols 2003). In brief, the J0737–3039A/B binary is thought to have begun as two main-sequence stars with masses of at least 8 $M_\odot$. After a first mass transfer stage, the primary formed a neutron star in a core-collapse SN. The secondary evolved, and matter was accreted by the neutron star in an HMXB phase. Eventually, the secondary's envelope enlarged to meet the neutron star, which spiraled in, ejecting the secondary's envelope. Angular momentum transferred to the neutron star spun it up to a period of a few tens of milliseconds; it is now observed as the A pulsar. Its envelope expelled, the helium core of the secondary remained in a circular orbit around the neutron star until a second supernova left the B pulsar. The radio lifetime of the recycled A pulsar is far longer than that of the high-magnetic-field B pulsar; this is the reason most double-neutron star systems are observed with only the recycled pulsar still active. We are fortunate to observe the double pulsar during its relative youth.

The observed binary orbital elements and the space motion of the binary preserve important details of the evolution, including the mass lost in the second supernova (and hence the mass of the exploding helium star), the size of the pre-supernova orbit, and any asymmetry in the explosion itself. The lower limit on the mass of an exploding helium core is of particular interest; evolutionary models suggest it should be around 2.1 $M_\odot$ (Nomoto 1984, Habets 1984). Also of interest is the misalignment angle $\delta$ between the first-born NS's spin axis and the post-SN orbital angular momentum, equivalent to the tilt between the pre- and post-SN orbital planes (e.g., Wex et al. 2000). Constraints on all of the evolutionary parameters are important for estimating the detectability of DNS systems in pulsar surveys, and hence for estimates of the total DNS birthrate and population. These quantities are of wide interest for stellar evolution and nucleosynthesis, but particularly because of their importance to event rate estimates for gravitational-wave detectors (e.g.,...
Early attempts to constrain the pre-SN parameters and the kick velocity of J0737−3039A/B have led to ambiguous results. Shortly after the discovery, analyses based on the orbital elements alone (Devi & van den Heuvel 2004; Willems & Kalogera 2004) suggested that moderate kick velocities (of 60 km/s or more) were needed, and that the pre-SN helium star was likely low-mass and overflowing its Roche Lobe at the time of the explosion. Later analyses by Willems et al. (2004, 2006) used observational constraints on the transverse velocity of the system, first ~140 km/s from scintillation measurements (Ransom et al. 2004) and later <30 km/s from pulsar timing (Kramer et al. 2005), to trace the motion of the binary back through the gravitational potential of the Galaxy (Kuijken & Gilmore 1989) and derive probability density functions for the most likely kick velocity, pre-SN mass, and tilt angle. In the most recent paper (Willems et al. 2006), population synthesis models were also used to estimate the most likely radial velocity of the binary (which is not directly measurable); this helped to further restrict the allowed parameters. Overall, these authors favor the standard formation scenario, reasonably high kick velocities (70–180 km/s) and pre-SN mass $m_{2,i}$ of at least 2 $M_\odot$, but acknowledge that for very small transverse velocities (~10 km/s) lower-mass progenitors are allowed or even favored. Piran & Shaviv (2005a,b) have argued, based on the assumption that the system will oscillate vertically about the Plane of the Galaxy, that its current location close to the Plane implies that it must have a low transverse velocity and have experienced a very small or no kick at birth, indicating a pre-formation B mass less than 2 $M_\odot$ and possibly an entirely different formation mechanism, such as the electron-capture supernova proposed by Podsiadlowski et al. (2003).

### 2 NEW RESULTS

We are now in a position to reconcile these conflicting results. Our ongoing timing observations at the Parkes, Jodrell Bank Lovell and Green Bank Telescopes have yielded a well-measured proper motion, $\mu = 4.2 \pm 0.4$ mas/year, directed toward a celestial position angle (North through East) of 308.4 $\pm$ 6.5°, or a Galactic position angle of 247.9 $\pm$ 6.5° (Kramer et al. 2005) – that is, its transverse motion is nearly parallel to the Plane of the Galaxy. Our tentative detection of the timing parallax is consistent with the adopted distance estimate of 520 pc derived from the dispersion measure (Cordes & Lazio 2002). Our measurements thus yield an extremely low transverse velocity, only 10 km/s, allowing us to derive a better estimate of the history of the system’s motion in the Galaxy.

To determine not just the limits of the allowed progenitor mass and kick velocity, but also their most likely values, we adapt the analysis that we previously used for the DNS PSR B1534+12 (Thorsett et al. 2003, hereafter TDS05) to calculate posterior probability density functions (pdfs) for several choices of priors on observable or potentially observable parameters.

The unknown physical parameters are: the presupernova companion mass $m_{2,i}$, the presupernova orbital separation $a_i$, the 3-dimensional supernova kick vector $V_k$, the 3-dimensional centre-of-mass velocity of the post-supernova system $V_{cm}$, the ‘tilt’ angle $\delta$ between the pre- and post-supernova orbital planes, the angle $\Omega$ of the current binary’s line of nodes on the sky, and the sign of the cosine of the current system’s orbital inclination angle $i$ (note that $0^\circ < i < 180^\circ$ and that $\sin i$ is well measured through timing). Two components of the current 3-d velocity are now measured through timing. Two relations between $m_{2,i}$, $a_i$, and $V_k$ can be obtained through conservation of energy and momentum (e.g. Kalogera 1996; Wex et al. 2003; Willems et al. 2006). Willems et al. (2006) derive the set of possible solutions for $V_k$, weighting by a likelihood that assumes a uniform prior on the magnitude $V_k$ and an isotropic angular distribution. They then convolve this function with their pdfs for the system’s radial velocity $V_r$, $\Omega$ and probability that a given system will move to the pulsar’s current location.

We formulate the problem slightly differently, using our insight from TDS05 that if $V_r$ (and hence $V_{cm}$), $\delta$, $\Omega$ and $\cos i$ are measured or specified, then at every potential birthsite in the Galaxy, the equations connecting the remaining variables reduce to a simple quadratic in $m_{2,i}$, with at most 2 possible real solutions. This allows us to assume prior distributions for $V_r$ and the potentially observable $\delta$ and $\Omega$. Our 3-d pdf may be written:

\[
p(V_r, \Omega, \delta | D, I) = p(V_r, \Omega, \delta, V_{pec}, \cos i | m_{1}, m_{2,f}, a_f, e_f, V_i, I)
\propto p(m_{1}, m_{2,f}, a_f, e_f, V_i | V_r, \Omega, \delta, V_{pec}, \cos i, I)
\times p(V_r, \Omega, \delta, V_{pec}, \cos i | I)
\]

where $m_1$ is the mass of pulsar A, $m_{2,f}$ is the mass of pulsar B, $a_f$ is the post-SN semi-major axis, and $e_f$ the post-SN orbital eccentricity. $V_{pec}$ represents the 3-dimensional peculiar velocity of the system before the second explosion, and is treated as a nuisance parameter along with $\cos i$. The likelihood $p(m_{1}, m_{2,f}, a_f, e_f, V_i | V_r, \Omega, \delta, V_{pec}, \cos i, I)$ is simply 1 for each acceptable real positive-mass solution of the quadratic equation for that choice of parameters, and 0 otherwise.

Our analysis proceeds as follows: For each of a large number of trials, we pick a radial velocity $V_r$ from a prior distribution. As discussed by Piran & Shaviv (2005a) and recognized by Willems et al. (2006), the choice of this prior has important effects on the final pdfs. For the purposes of illustration, we investigate two prior distributions: 1) a gaussian in $V_r$ with a dispersion 200 km/s (Willems et al. 2006), and 2) $V_r = V_i / \tan \theta$, where $\cos \theta$ is chosen uniformly between $-1$ and $+1$. The second prior is the one preferred by Piran & Shaviv and is arguably the more logical prior to use. We consider the first prior to be extremely conservative, in that its dispersion is much larger than the observed transverse velocities of DNS systems. We sample the proper motion from

1 The Willems et al. (2006) definition of $\Omega$ differs from ours, but as both studies assume uniform priors this is not very important.
2 We note that the expected radial velocity of the pulsar’s LSR to that of the Sun is very small, on the order of 5 km/s. Given the uncertainties in, for example, the gravitational potential of the Galaxy, we consider it appropriate to discuss radial velocities centred on 0 km/s.

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[References]
gau ssian distributions using the measured uncertainties on magnitude and direction, and the pulsar distance assuming a 20% gaussian uncertainty.

We then follow the motion of the binary system back in time through the Galaxy, similarly to the procedure in Willems et al. (2006) and TDS05, incorporating the Sun’s position and peculiar motion. We accept any position with |z| < 50 pc and galactocentric radius R < 15 kpc as a possible birth site for the B pulsar. We integrate back in time the orbital eccentricity and semi-major axis, according to the equations of Peters (1964), testing ages up to 100 Myr.

At each birth site, 1000 trial sets of parameters are selected. The peculiar velocity \( v_{\text{pec}} \) is assumed to be a Maxwellian with a 1-dimensional dispersion of 12 km/s, based on the proper motions of Be/X-ray binaries (Chevalier & Ilovaisky 1992; van den Heuvel et al. 2000), while the \( \cos i < 0 \) and \( \cos i > 0 \) cases are treated as equally likely. We draw each of \( \Omega \) and \( \delta \) from uniform distributions: \( 0^\circ < \Omega < 360^\circ \) and \( 0^\circ < \delta < 180^\circ \). The angle \( \delta \) is potentially observable but currently unknown, although the lack of profile shape changes in A (Manchester et al. 2002) implies that it is probably small. The angle \( \Omega \) can in principle be estimated from scintillation (Coles et al. 2003) but its value depends strongly on the modeling of the anisotropy of the interstellar medium and is not currently well constrained (Coles & Rickett, private communication). For each set of parameters, we construct the quadratic equation and determine whether there are solutions. We record progenitor and kick parameters and construct pdfs via histograms.

An important point neglected by both Willems et al. and Piran & Shaviv is that a neutron star’s mass contains a large negative contribution from gravitational self-energy, meaning that the minimum progenitor mass must be equal to the current neutron-star mass plus the magnitude of the binding energy \( E_B \). This quantity can be estimated, to within about 20%, as \( E_B \approx 0.084(M/M_\odot)^2M_\odot \) (Lattimer & Yahil 1989; Lattimer & Prakash 2001). The majority of plausible equations of state predict a very slightly lower binding energy for a 1.25 \( M_\odot \) neutron star. The net implication is that a minimum (baryonic) mass of about 1.37 \( M_\odot \) is required for the progenitor of B, and we consider only solutions which yield progenitor masses above this limit.

To place the double pulsar in context, we compare it to the only other DNS with strong constraints on the progenitor, PSR B1534+12 (TDS05). (Recent proper motion measurements for PSR B1913+16 will necessitate a revised set of kick constraints for that pulsar.) For a fair comparison, we have revisited our analysis of B1534+12, calculating pdfs as for J0737−3039A/B, while allowing for progenitor masses down to 1.48 \( M_\odot \) and not using the scintillation constraint on \( \Omega \) (Bosdanov et al. 2002) in case anisotropy systematics also affect this measurement. Because of the strong misalignment angle constraint, fewer sets of trial parameters are tested per birth site, while more separate radial velocity trials are used.

3 DISCUSSION

Because of the constraint equations used, each point in the \((v_k, m_{2,ij}, a_i)\) parameter space corresponds to a point in the \((v_r, \delta, \Omega)\) parameter space. Thus we have effectively constructed the posterior pdfs for the \((v_k, m_{2,ij}, a_i)\) parameters as well, and may marginalize to derive confidence ranges on all the parameters. For both J0737−3039A/B and B1534+12, our pdfs for the physically interesting quantities are plotted in Figure 1 and confidence ranges are summarized in Table 1. We recognize, as pointed out by Willems et al. (2004), that projection effects are neglected in these 1-d pdfs. The most important such effect for J0737−3039 is the association of large-\( v_k \), large-\( m_{2,ij} \), and large-\( \delta \) solutions exclusively with the large \( v_r \) \((\sim 100 \text{ km/s})\) progenitors accessible only with the gaussian \( v_r \) prior. Because these imply that the current velocity makes a very small angle to our line of sight, we regard them as inherently less plausible.

We can draw several conclusions about the J0737−3039B progenitor and the supernova kick. First, the explosion was asymmetric, but not extremely so. The \( v_r \) pdf extends downward to 0 km/s for both \( v_r \) priors, but a nonzero kick is strongly favoured. That the supernova explosion was most likely asymmetric is bolstered by the B pulsar’s spin-orbit misalignment observed through long-term changes in the B profile (Burgay et al. 2005) and derived through modeling of the A eclipses (Lyutikov & Thompson 2003; Lyutikov 2004). For the gaussian \( v_r \) prior, the kick tends to be directed out of the plane of the pre-SN orbit and away from the pre-SN progenitor orbital velocity. For the uniform-direction \( v_r \) prior, the kick is directed
nearly randomly in the plane perpendicular to the pre-SN progenitor orbital velocity.

The only likely radial velocities are either slightly negative or else positive. This reflects the fact that large negative velocities (relative to our current reference frame) imply that the system must have been born in the outer reaches of the Galaxy, but there are far fewer potential birth sites at large Galactic radii.

Low, even very low (< 10^6), misalignment angles are predicted between A’s spin axis and the orbital angular momentum, in excellent agreement with the observed lack of profile variations (Manchester et al. 2003; Kramer et al. 2006).

The immediate B progenitor was probably less than about 2 M_⊙. Since the pre-SN orbital period was comparable to the current 0.1-day value, the low mass is likely due to significant mass loss accompanying the orbital shrinkage (Dewi et al. 2002) and Dewi & Pols (2003) trace the histories of He-star/NS binaries, showing that suitable parameters can be obtained from a range of starting points. A difficulty is that the lowest-mass systems are expected to undergo common-envelope evolution and spiral-in, resulting in extremely tightly-bound or even merged systems (Dewi & Pols 2003, but see Ivanova et al. 2003). Dewi & Pols note, however, that the relative time-scales of the spiral-in and supernova explosion are not well known, and an explosion might occur before the spiral-in is complete.

The low-mass B progenitor is consistent with either an electron-capture collapse of the ONeMg core of a low-mass He-star (Podsiadlowski et al. 2003) or the collapse of a low-mass iron core. Either might occur sufficiently fast to prevent the development of large asymmetries, resulting in the small kick (Pfahl et al. 2002; Podsiadlowski et al. 2004). Estimates of the time-scales for the onset of the two types of explosions are similar (Dewi & Pols 2004) and appear too long relative to the spiral-in time. Better modeling of the two types of explosions may ultimately allow us to distinguish between the two on the basis of the required short time-scale.

PSR B1534+12 presents an interesting contrast. Our derived pdfs are fully compatible with the parameter space allowed in TDS05; in particular the kick velocity is likely in the range 200–270 km/s while the progenitor companion mass was in the range 2.0–3.35 M_⊙. We report the confidence intervals only for the gaussian (dispersion 200 km/s) V_r prior in Table 1; the uniform-in-cos prior gives similar results. We note that the most important constraint in this case is the measured misalignment angle (25 ± 4°; Stairs et al. 2004), whose only model-dependence is on the reasonable assumption that the rotating vector model (Radhakrishnan & Cooke 1969) describes the linear polarization position-angle swing of this pulsar (c.f. Dewi et al. 2003). Overall, the parameters of the B1534+12 progenitor fit quite well with a more ‘standard’ evolutionary picture that involves He-star Roche-lobe overflow but not a late spiral-in phase. It is possible that the longer orbital period and/or higher mass of the B1534+12 progenitor permitted a larger core to develop before the SN explosion, leading to a larger kick; we note that the second-formed NS in B1534+12 is 0.1 M_⊙ more massive than J0737–3039B. Also of interest is that Ihm et al. (2006) find PSR B1913+16, with the largest known second-formed NS mass, cannot be formed in population syntheses with small kick velocities.

The contrast between these systems urges caution in discussing expectations based on low kicks. In the last several years, small (σ ~ 50 km/s) kicks have been proposed to be nearly universal for nascent neutron stars processed in relatively close binary systems, due to the early loss of the NS progenitor’s envelope and subsequent formation of a low-mass core which in turn provides a small kick upon collapse (e.g., Podsiadlowski et al. 2004). This hypothesis has been used to explain the existence of long-period, low-eccentricity high-mass X-ray binaries (Pfahl et al. 2002), the retention of large numbers of neutron stars in globular clusters (Pfahl et al. 2004; Podsiadlowski et al. 2004); the apparent correlation between the orbital eccentricity and the recycled pulsar spin period in DNS systems (Faulkner et al. 2003; Dewi et al. 2003) and the apparent dearth of isolated mildly recycled pulsars (‘failed DNSs’) ejected from unbinding second SN explosions (Dewi et al. 2003), as well as to predict larger numbers of DNS mergers than are inferred from the observed set of objects (Pfahl et al. 2002). Our derived progenitor parameters for J0737–3039A/B certainly imply that some fraction of DNS progenitors will be low-mass and experience small kicks, and hence that each of these explanations is plausible at some level. However, the much larger kick needed for B1534+12, which is also a short-period (10h) binary, indicates that a range of parameters must be considered in all of these arguments. Noting the additional rough correlation between the orbital eccentricity and the mass of the second-formed compact object in the six systems for which the masses are well-determined (PSRs J1756−2251, J0737−3039, J1141−6545, B2303+46, B1534+12 and B1913+16; see also Faulkner 2004), we speculate that the magnitude of the kick may depend quite sensitively on the size of the collapsing core. This speculation is not supported by the most recent 2-D numerical simulations of hydrodynamic instabilities during SN explosions.

### Table 1. Confidence ranges on progenitor parameters

| V_r prior | Median likelihood value | 68% confidence interval | 95% confidence interval |
|-----------|-------------------------|-------------------------|-------------------------|
|           | V_k (km/s) m_2,i (M_⊙) δ (°) V_k (km/s) m_2,i (M_⊙) δ (°) V_k (km/s) m_2,i (M_⊙) δ (°) |           |                      |
| J0737−3039A/B | 165 | 1.80 | 12.0 | 80−305 | 1.50−2.40 | 3.0−24.5 | 45−1005 | 1.37−4.00 | 1.0−102.5 |
| Uniform-in-cos | 60 | 1.45 | 3.5 | 40−80 | 1.37−1.55 | 1.5−5.5 | 20−140 | 1.37−1.80 | 0.5−11.0 |
| B1534+12 | 235 | 2.45 | 24.5 | 200−270 | 2.00−3.35 | 20.5−28.5 | 175−305 | 1.60−3.90 | 16.5−32.5 |
which suggest that core mass and NS velocity are not correlated, but more work will be required on 3-D simulations and on other kick models. At the same time, careful population synthesis, incorporating initial mass functions and preferably an improved understanding of the supernova vs. orbital-evolution time-scales, will be required to determine whether this correlation or the (likely related) spin-period–eccentricity relation can truly be reproduced by a mass-dependent kick.

As pointed out by Podsiadlowski et al. (2005), the low space velocity of J0737–3039 may provide a further probe of its long-term evolutionary history. A competing model to the ‘standard’ DNS evolutionary model outlined in Section 1 is the ‘double-core’ scenario (Brown 1993; Bethe & Brown 1995) in which the He cores of two main-sequence stars of nearly equal mass undergo a spiral-in through the envelopes of both stars simultaneously. Thus at the time of the first SN, the secondary star is a (low-mass) He star rather than a massive main-sequence star, and the systemic velocity after the first supernova explosion would be expected to be higher than in the standard model. The observed low space velocity therefore makes the double-core scenario less likely. If SN kicks are in fact lower in He stars processed in binaries, this argument is slightly weakened; however we note that under the mass-dependent kick hypothesis, since $A$’s mass is close to that of the companion in B1534+12, its kick velocity might well have been large.

Finally, our low-velocity progenitor for J0737–3039A/B may have implications for the nature of short GRBs. In the popular DNS inspiral models (Paczyński 1986), a poor correlation between active star formation and GRB activity can be a natural consequence of the time delay between birth and inspiral and the space velocity of the post-supernova binary. The few detected counterparts to short GRBs place these objects in the outskirts of a broad variety of galaxies without active current star formation (e.g., Prochaska et al. 2006). Allowing for large DNS kicks, this is consistent with the production of the progenitors during normal galactic star formation (Belczynski et al. 2006). However, if smaller DNS kicks are assumed, then it may also be necessary to produce a significant fraction of the progenitors in globular clusters in the galaxy halo (Grindlay et al. 2006). Our low velocity for J0737–3039A/B tends to support the latter scenario, but also suggests that similar systems could be a source of GRBs near the Earth, with possible implications for our terrestrial environment (Thorsett 1995; Thomas et al. 2001).

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