CONSTRANTS ON THE FORMATION OF PSR J0737–3039: THE MOST PROBABLE ISOTROPIC KICK MAGNITUDE

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1. INTRODUCTION

The significance for relativistic astrophysics of close binaries with two neutron stars (NSs), one of which is detected as a recycled pulsar, has been recognized for many years, since the discovery of the first such system (Hulse & Taylor 1975). More than 10 years since the discovery of the second relativistic double neutron star (DNS) PSR B1534+12 (Wolszczan 1991), the discovery of the third system in the disk has been recently announced with important implications for the current expectations for the detection of DNS in-spiral by ground-based interferometers (Burgay et al. 2003; Kalogera et al. 2004). This new system has broken a number of barriers already: it harbors the fastest pulsar (spin period of 22 ms) in all DNSs, in the tightest orbit (orbital period of 2.4 hr) with the smallest eccentricity (0.09) of all DNSs. In addition, Lyne et al. (2004) recently reported the discovery of a 2.8 s pulsar companion to the millisecond pulsar, making this the first observed double pulsar system.

A number of earlier studies of DNS binaries (e.g., Fryer & Kalogera 1997 and references therein) have examined the evolutionary history of the previously known systems and have derived some constraints related to the formation of the second NSs in the binaries. In this Letter we consider the recent evolutionary history of PSR J0737–3039 and derive a set of necessary constraints on the supernova kick imparted to the second NS and on its progenitor characteristics. We compare our results to those obtained very recently by Dewi & van den Heuvel (2004, hereafter DvdH04), and we comment on the origin of their derived constraints.

2. ORBITAL EVOLUTION AND DYNAMICS

The orbital characteristics of the observed DNS systems are determined primarily by the effects of the supernova (SN) explosion leading to the birth of the second NS and by the subsequent loss of orbital energy and angular momentum via gravitational radiation. In the case of a symmetric SN explosion, the semimajor axis and eccentricity of the post-SN orbit are uniquely determined by the amount of mass lost from the system during the explosion. If, on the other hand, the SN explosion is asymmetric as currently thought, the post-SN orbital parameters also depend on the magnitude and direction of the kick imparted to the NS.

In agreement with the current understanding of DNS binaries (Tauris & van den Heuvel 2004) and as we show in what follows, the tight orbit essentially constrains the pre-SN orbital separation to such small values that the binary just before the explosion is expected to consist of a helium star (the progenitor of the second NS) and the first NS. This pre-SN orbit is expected to be circular because of Roche lobe overflow (RLOF) from the helium star progenitor during earlier evolutionary phases. We constrain the mass $M_H$ of the helium star, the pre-SN orbital separation $A_p$, and the magnitude $V_k$ of the kick velocity by considering (1) the orbital evolution of the DNS due to gravitational radiation and (2) the orbital dynamics of asymmetric SN explosions (see also Fryer & Kalogera 1997 and DvdH04).

We first determine the post-SN semimajor axis $A$ and orbital eccentricity $e$ from the currently observed values $A_{\text{obs}}$ and $e_{\text{obs}}$ by integrating the equations derived by Junker & Schäfer (1992) for the evolution of the orbit due to gravitational radiation backward in time. To this end, we use the values $A_{\text{inv}} = 1.26 R_\odot$ and $e_{\text{inv}} = 0.0878$ reported by Burgay et al. (2003). For the masses of the pulsar and its companion, we use the values $M_p = 1.34 M_\odot$ and $M_c = 1.25 M_\odot$ expected for an edge-on orbit (see Burgay et al. 2003). Since the characteristic age is derived under the assumption of a birth spin period much smaller than the current spin period, it may be quite unreliable as an estimate for the true age of a recycled pulsar. The characteristic age derived for the second (not recycled) pulsar in PSR J0737–3039 is equally uncertain because the spin evolution of the second-born NS is likely to be affected by torques exerted by its millisecond pulsar companion (Lyne et al. 2004). We therefore assume that the first-born NS was recycled to maximum spin-up for Eddington-limited accretion and use an estimate for the time $\tau_8$ since the pulsar left the spin-up line as an upper limit to the time $T_{\text{SN}}$ elapsed since the last SN explosion (see Arzoumanian, Cordes, & Wasserman 1999 for details). The post-SN orbital parameters at $T_{\text{SN}} = \tau_8 = 100$ Myr are calculated to be $A = 1.54 R_\odot$ and $e = 0.12$. We note that the orbital evolution due to gravitational radiation backward in time for this time is uncertain because of uncertainties in the post-SN orbital parameters.
radiation is relatively slow for this system, so that the values of $A$ and $e$ are not greatly sensitive to the adopted value of $T_{SN}$.

Next, we consider the orbital dynamics of asymmetric instantaneous SN explosions. As in the past we use the conservation laws of orbital energy and angular momentum to relate the pre-SN parameters ($A_o$, $M_o$, $M_p$) and the kick velocity $V_k$ to the post-SN parameters ($A$, $e$, $M_p$, $M_e$):

$$V_i^2 + V_f^2 + 2V_iV_f \cos \theta = G(M_p + M_e)(\frac{2}{A_o} - \frac{1}{A}), \quad (1)$$

$$A_o^2(V_i^2 \sin^2 \theta \cos^2 \phi) + [(V_i \cos \theta + V_f)^2] = G(M_p + M_e)A(1 - e^2), \quad (2)$$

where $G$ is the gravitational constant and $V_i = [G(M_p + M_e)/A_o]^{1/2}$ is the relative orbital velocity of the helium star just before its SN explosion (e.g., Hills 1983; Kalogera 1996). The angles $\theta$ and $\phi$ describe the direction of the kick velocity: $\theta \in [0, \pi]$ is the polar angle between the kick velocity and the relative orbital velocity of the helium star just before the SN explosion, and $\phi \in [0, 2\pi]$ is the corresponding azimuthal angle defined so that $\phi = 0$ represents a plane perpendicular to the line connecting the centers of mass of the binary components (see Kalogera 2000 for a graphic representation).

The requirements that the post-SN orbit must pass through the position of the two stars at the time of the explosion and that $\cos^2 \phi \leq 1$ limit the pre-SN orbital separation to the range $A(1 - e) \leq A_o \leq A(1 + e)$ (Plannery & van den Heuvel 1975). The range is independent of the helium star mass and the magnitude of the NS kick and is shown by the gray-shaded region in Figure 1.

From equations (1) and (2) it is clear that for a given pair of $(M_o, A_o)$ there is no unique solution for the kick magnitude $V_k$ consistent with the post-SN properties (cf. DvdH04). Instead, Fryer & Kalogera (1997) have shown that the absolute requirement $\cos^2 \phi \geq 0$ yields an upper limit for the mass $M_o$ of the helium star, for every pair of $(A_o, V_i)$ values:

$$M_o \leq -M_p + k^2(M_p + M_e)(A_o/A)[-2(A/A_o)(1 - e^2)^{1/2} \times [(A/A_o)^2(1 - e^2) - k]^{1/2} + 2(A/A_e)^2(1 - e^2) - k\}^{-1}, \quad (3)$$

where

$$k = 2 \frac{A_o}{V_i^2A_o} \left[ \frac{V_i^2A}{G(M_p + M_e)} + 1 \right]. \quad (4)$$

The equality in equation (3) is valid only if the kick is assumed to be restricted in the plane of the pre-SN orbit ($\cos^2 \phi = 0$), and it is only then that the value of $V_i$ can be viewed as an exact solution. For this reason, no strict upper limit on the magnitude of the kick velocity results from equation (3), which is in contrast to the conclusion obtained by DvdH04. As can be seen from the dotted lines in Figure 1, the upper limit on $M_o$ increases with increasing values of $V_i$.

For a given helium star mass $M_o$, the maximum stellar radius reached by the second-born NS’s direct progenitor sets an additional divide separating detached from Roche lobe–filling systems in the $(A_o, M_o)$-parameter space. The divide is represented by the thick dashed line in the left-hand panel of Figure 1. It follows that in order for the progenitor of PSR J0373−3039 to be detached just before the helium star’s SN explosion, the helium star must be more massive than $\approx 25 M_\odot$ and the kick magnitude must be in excess of $\approx 1200$ km s$^{-1}$. Although such high kick magnitudes have been discussed in the past (e.g., the Guitar nebula; Cordes, Romani, & Lundgren 1993), helium stars of such high mass are not very likely at the time of the SN explosion, given the strong wind mass loss associated with them (Woosley, Langer, & Weaver 1995). In addition, such high-mass helium stars are expected to end up as a black hole instead of an NS (e.g., Fryer & Kalogera 2001; Tauris & van den Heuvel 2004). Nevertheless, none of the above is a strict constraint, and therefore we conclude that although helium stars more massive than $\approx 25 M_\odot$ cannot be
Fig. 2.—Probability distribution function of kick velocity magnitudes \( V_k \) yielding viable progenitors for PSR J0737–3039 for different mass ranges of the second-born NS’s progenitor. The nonzero probabilities for kick velocities larger than \( \approx 1000 \text{ km s}^{-1} \) correspond to kicks for which the majority of the admissible solutions for \( \theta \) and \( \phi \) are directed opposite to the pre-SN orbital velocity and perpendicular to the line connecting the components’ centers of mass. For comparison, the kick velocity distribution for PSR 1534+12 is also shown. The mass range for the latter is \( 2.1 \leq M_0/M_\odot \leq 8.0 \).

excluded, they are most probably highly unlikely. Hence it appears more reasonable to consider that the helium star progenitor of the last-born NS was filling its Roche lobe and was transferring mass onto the first-born NS at the time of its SN explosion, in agreement with DvdH04.

The fate of NS and helium star binaries undergoing mass transfer from the helium star depends on the orbital period and the mass of the donor star at the onset of the mass transfer phase. Since our analysis yields orbital periods and helium star masses just before the helium star’s SN explosion, the derivation of exact constraints in principle requires detailed mass transfer calculations to map the pre-SN parameter space to the viable parameter space at the onset of RLOF. However, the details of mass transfer sequences and the exact mapping mentioned above depend on the assumptions in the stellar evolution code adopted (see comparison of results from three studies of this topic: Dewi & Pols 2003, Ivanova et al. 2003, and Dewi et al. 2002). Instead, we can use the qualitative effect of such a mass transfer phase to derive robust constraints on the NS progenitor properties. In agreement with other studies, Ivanova et al. (2003) found that mass transfer from a helium star that is more massive than the NS companion by a factor greater than 3.5 leads to a delayed dynamical instability that prevents the formation of a DNS. Since the pre-SN helium star mass is bound to be slightly smaller than the mass at the onset of RLOF, the condition \( M_0/M_\odot \leq 3.5 \) leads to a rather conservative upper limit of 4.7 \( M_\odot \) for the mass of the helium star that formed the companion to PSR J0737–3039. This upper limit is represented by a dashed horizontal line in Figure 1.

A lower limit on the mass \( M_0 \) of the helium star arises from the requirement that the helium star must be massive enough to evolve into an NS instead of a white dwarf. However, the value of this lower limit depends on the modeling of massive stars as well as on whether or not the star is affected by binary evolution processes. Current models of helium star evolution indicate that the minimum mass required to form an NS ranges from 2.1 to 2.8 \( M_\odot \) (Habets 1985; Tauris & van den Heuvel 2004). Here we adopt a conservative value of 2.1 \( M_\odot \). From Figure 1, it can be seen that the lower limit on \( M_0 \) imposes a lower limit of 60 km s\(^{-1}\) on the magnitude of the kick velocity imparted to the second NS. Any higher value for the minimum progenitor mass \( M_0 \) shifts the minimum kick velocity to higher values (as it is evident from Fig. 1). In particular, if the lower limit on \( M_0 \) would increase to 2.3 \( M_\odot \) as in DvdH04, the minimum required kick velocity is 78 km s\(^{-1}\). The small difference with the lower limit of 70 km s\(^{-1}\) obtained by DvdH04 is due to the different age (and thus different post-SN orbital parameters) adopted by these authors.

Finally, an upper limit on the magnitude of the kick velocity imparted to the last-born NS may be derived from the condition that the binary must remain bound after the SN explosion. The upper limit depends on the pre-SN helium star mass and orbital separation range and is given by \( V_0/V_1 = 1 + [2(M_\odot + M_0)/(M_\odot + M_1)]^{1/2} \) (e.g., Brandt & Podsiadlowski 1995; Kalogera & Lorimer 2000). For the mass and orbital separation constraints \( 2.1 \leq M_0/M_\odot \leq 4.7 \) and \( 1.36 \leq A_0/R_\odot \leq 1.72 \) derived above, the largest possible kick velocity is \( \approx 1560 \text{ km s}^{-1} \).

3. KICK VELOCITY DISTRIBUTIONS

For a given kick magnitude \( V_k \) and a given set of post-SN orbital parameters \((A, e)\), equations (1) and (2) form a set of two algebraic equations relating the pre-SN orbital separation \( A_0 \) and the NS progenitor mass \( M_0 \) to the polar angle \( \theta \) and the azimuthal angle \( \phi \) that define the kick direction with respect to the helium star’s pre-SN orbital velocity. Here we use the constraints on \( A_0 \) and \( M_0 \) to derive constraints on the kick direction that must be satisfied for a given \( V_k \) value. It follows that for kick velocities between 60 and 1560 km s\(^{-1}\), the polar angle \( \theta \) is restricted to the range \( 113^\circ \leq \theta \leq 180^\circ \), so that the kick is generally directed opposite to the orbital motion.

We point out that assuming an isotropic kick distribution, the constraints on \( \theta \) and \( \phi \) can be used to derive the likelihood of the kick magnitude \( V_k \): the more restricted the kick direction is, for a given \( V_k \) value, the lower the likelihood is. Formally, this kick-magnitude likelihood \( \Lambda (V_k) \) is obtained by

\[
\Lambda (V_k) = \frac{1}{4\pi} \int_{\theta_1}^{\theta_2} \sin \theta \, d\theta \int_{\phi_1}^{\phi_2} \, d\phi,
\]

where the boundaries \( \theta_1, \theta_2, \phi_1, \) and \( \phi_2 \) of the admissible region are functions of the kick velocity magnitude \( V_k \) and the boundaries \( \phi_1 \) and \( \phi_2 \) are usually also functions of the polar angle \( \theta \). Under the assumption that the kick velocity magnitude is independent of the direction of the kick, the probability \( P (V_k) \) that the second-born NS received a kick of magnitude \( V_k \) is then obtained by normalizing the likelihood so that the integral over all allowed kick velocities is equal to unity.

The probability distribution function \( P (V_k) \) for PSR J0737–3039 is plotted in Figure 2 (thick solid line). The curve has a clear maximum at \( \approx 150 \text{ km s}^{-1} \) that represents the most probable kick magnitude imparted to the pulsar companion at birth. In order to assess the sensitivity of the distribution to our helium star mass constraints, we also show curves corresponding to different lower and upper limits on the mass of the helium star progenitor of the second-born NS. As can be seen from the figure, the distribution is not very sensitive to changes in the upper limit on the allowed helium star mass range. In the particular case of a slightly higher lower limit of 2.3 \( M_\odot \) on the mass of the helium star, the peak in the distribution shifts to \( \approx 165 \text{ km s}^{-1} \). For comparison, the kick velocity distribution for PSR 1534+12 is also shown in Figure 2.
4. DISCUSSION

We derived constraints on the pre-SN progenitor of the newly discovered relativistic binary pulsar PSR J0737−3039. For an assumed age of 100 Myr, the tight limits on the pre-SN orbital separation (1.36 \( \leq A_0/R_0 \leq 1.72 \)) imply that the progenitor consists of the first-formed NS in orbit around a helium star (and not its hydrogen-rich progenitor, since the system would then be in a common-envelope phase with a spiral-in timescale that is much shorter than the evolutionary timescale leading to the SN explosion). We found that the helium star is most likely overflowing its Roche lobe and constrained its mass to be between 2.1 and 4.7 \( M_\odot \). The lower limit of 2.1 \( M_\odot \) implies that a birth kick with a velocity of at least 60 km s\(^{-1}\) was imparted to the second-born NS, in agreement with the minimum kick velocity derived by DvdH04. From the condition that the binary must remain bound after the second SN explosion, we derived an upper limit for the kick velocity of 1560 km s\(^{-1}\). We found that the helium star is most likely overflowing its Roche lobe and constrained its mass to be between 2.1 and 4.7 \( M_\odot \). The lower limit of 2.1 \( M_\odot \) implies that a birth kick with a velocity of at least 60 km s\(^{-1}\) was imparted to the second-born NS, in agreement with the minimum kick velocity derived by DvdH04. From the condition that the binary must remain bound after the second SN explosion, we derived an upper limit for the kick velocity of 1560 km s\(^{-1}\). This is in contrast to the upper limit of 230 km s\(^{-1}\) derived by DvdH04, which is valid only if the kick is restricted to the pre-SN orbital plane. These results are fairly insensitive to the adopted age: if the system were only 50 Myr old, the progenitor and kick constraints are 1.27 \( R_\odot \leq A_0 \leq 1.57 \ R_\odot \) and 65 km s\(^{-1}\) \( \leq V_\odot \leq 1610 \) km s\(^{-1}\). The allowed helium star mass range is independent of the adopted age.

We furthermore extended the constraints on NS formation and, for the first time, derived a probability distribution for the kick magnitude imparted to the second-born NS in a DNS binary (PSR J0737−3039). The distribution exhibits a clear maximum at 150 km s\(^{-1}\) that is fairly independent of the adopted age: if the system were only 50 Myr old, the progenitor and kick constraints are 1.27 \( R_\odot \leq A_0 \leq 1.57 \ R_\odot \) and 65 km s\(^{-1}\) \( \leq V_\odot \leq 1610 \) km s\(^{-1}\). The allowed helium star mass range is independent of the adopted age. In addition, a small secondary peak was found for kick velocities larger than \( \approx 1000 \) km s\(^{-1}\) that correspond mainly to kicks directed opposite to the pre-SN orbital velocity and perpendicular to the line connecting the components’ centers of mass.

We also applied the analysis described above to the other two relativistic DNS systems known in the Galactic disk. These systems may arise from detached as well as semidetached pre-SN progenitors. An upper limit for the mass of the helium star in these progenitors is therefore given by the largest possible helium star mass forming an NS instead of a black hole. If we set this upper limit at 8 \( M_\odot \), the most likely kick velocity imparted to the second-born NS in PSR 1913+16 is 240 km s\(^{-1}\). In addition, it turns out that kicks smaller than 170 km s\(^{-1}\) are allowed but have a vanishingly small probability. This is in contrast to the findings of Fryer & Kalogera (1997) and Dewi & Pols (2003), who found minimum kick velocities of 260 and 70 km s\(^{-1}\), respectively. Note, however, that in the derivation of the kick velocity distribution for PSR 1913+16, we did not yet take into account the measured space velocity as was done by Wex, Kalogera, & Kramer (2000). We will include this in a forthcoming investigation on the spin-orbit misalignment of PSR J0737−3039A, in which we will also present a more detailed comparison between the possible kick velocities and kick directions imparted to the last-born NS in PSR 1913+16 and PSR J0737−3039. Finally, for PSR 1534+12, we find that the most likely kick velocity imparted to the second-born NS is 130 km s\(^{-1}\) and that kick velocities below 100 km s\(^{-1}\) have a vanishingly small probability.

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