The formation of the double neutron star pulsar J0737 − 3039

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Abstract

We find that the orbital period (2.4 h), eccentricity (0.09), dipole magnetic field strength (6.9 \times 10^{9} G) and spin period (22 ms) of the new highly relativistic double neutron star system PSR J0737 − 3039 can all be consistently explained if this system originated from a close helium star plus neutron star (HeS–NS) binary in which at the onset of the evolution the helium star had a mass in the range 4.0–6.5 M⊙ and an orbital period in the range 0.1–0.2 d. Such systems are the post-common-envelope remnants of wide Be/X-ray binaries (orbital period \sim 100 to 1000 d) which consist of a normal hydrogen-rich star with a mass in the range 10–20 M⊙ and a neutron star. The close HeS–NS progenitor system went through a phase of mass transfer by Roche-lobe overflow at a high rate lasting a few times 10^4 yr; assuming Eddington-limited disc accretion on to the neutron star, this star was spun up to its present rapid spin rate. At the moment of the second supernova explosion the He star had a mass in the range 2.3–3.3 M⊙, and in order to obtain the present orbital parameters of PSR J0737 − 3039 a kick velocity in the range 70–230 km s^{-1} must have been imparted to the second neutron star at its birth.

Key words: binaries: general – stars: evolution – stars: neutron – pulsars: individual: J0737 − 3039 – supernovae: general.

1 INTRODUCTION

A new double neutron star (DNS) system, J0737 − 3039, was recently discovered (Burgay et al. 2003). This is the fifth Galactic DNS; all share the same characteristics of having eccentric orbits (e \gtrsim 0.08), short pulse periods (22–104 ms) and low period derivatives (\sim 10^{-18} s^{-1}). The two latter parameters imply a weak surface magnetic field (\sim 10^{10} G) which indicates that the pulsar has been recycled (Smarr & Blandford 1976; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982), and that the observed pulsar in each system is the older neutron star and has gone through a mass-transfer phase (Srinivasan & van den Heuvel 1982).

Dewi & Pols (2003) found that the wide-orbit DNSs J1518+4904 and J1811 – 1736 are produced from helium star–neutron star (HeS–NS) binaries that avoided Roche-lobe overflow (RLOF); while the close-orbit B1913+16 and B1534+12 can be formed either with or without a mass-transfer phase in the HeS–NS binary stage of evolution. Among the five Galactic DNSs, J0737 − 3039 has the shortest spin period (22 ms), shortest orbital period (0.102 d) and lowest eccentricity (0.088). In this paper we examine the possible formation history of J0737 – 3039. We will show that, unlike the other DNSs, J0737 – 3039 can only be formed from HeS–NS binaries that have gone through RLOF.

2 THE FORMATION OF J0737 − 3039

2.1 Possible progenitors

We examine the formation history of the system in terms of the so-called standard scenario (Bhattacharya & van den Heuvel 1991), in which DNSs were formed from Be/X-ray binaries. When the Be star leaves the main sequence and becomes a giant, a runaway mass transfer takes place due to the large mass ratio of the system. The neutron star is engulfed by the envelope of the giant, and a common-envelope (CE) phase ensues in which the neutron star spirals down to the helium core of the giant, ejecting its hydrogen-rich envelope in this process. The outcome of this spiral-in is a very close binary consisting of a helium star and a neutron star (HeS–NS). For companions less massive than about 5 M⊙, this mass transfer can still be stabilized such that the formation of a CE can be avoided (e.g. King & Ritter 1999; Podsiadlowski & Rappaport 2000; Tauris, van den Heuvel & Savonije 2000). However, for more massive companions such as the Be stars considered here, the formation of a CE cannot be avoided.

The helium star evolves further through core-helium burning and further burning stages. During this evolution it transfers mass to the neutron star by RLOF and also loses mass by stellar wind. Fig. 1 depicts the parameters of these HeS–NS binaries at the end of this RLOF and wind mass loss, resulting from detailed evolutionary calculations (Dewi et al. 2002; Dewi & Pols 2003). The number indicated at each curve represents the initial mass of the helium star at the beginning of its evolution. The star symbols indicate the
outcome of the evolution of systems with a range of initial orbital periods (note that the lines connecting the stars are not evolutionary tracks). Also presented in the figure are the maximum and minimum possible orbital periods of the progenitor of J0737 – 3039 just prior to the supernova (SN) explosion. These lines are derived with the assumption that the pre-SN (circular) orbital separation, \( a_i \), lies between the periapsis and apapsis of the post-SN separation, i.e.

\[
a_i(1 - e_i) \leq a_i \leq a_i(1 + e_i)
\]  

(Flammary & van den Heuvel 1975), where \( a_i \) and \( e_i \) are the post-SN separation and eccentricity. Here \( a_i \) and \( e_i \) are the parameters at the time when it was born, which is assumed to be a characteristic time ago, \( \tau = P/2P \). These parameters were derived by integrating the effects of gravitational wave radiation on the observed \((a, e)\) over \( \tau \).

Dewi & Pols (2003) found that systems represented with the open star symbols undergo a CE phase due to the development of a helium convective envelope. The consequence of this is that, after the CE phase, these systems will have a lower mass \( (M_{\text{He,t}} \sim 1.4 \, M_\odot) \) and much shorter orbital period \( (P_1 \sim 0.01 \, \text{d}) \) than their original parameters shown in Fig. 1. Hence only the helium stars represented by solid star symbols (i.e. with initial masses in the range of \( 4-6.5 \, M_\odot \)) are possible progenitors of J0737 – 3039. This range of mass requires an initial progenitor main-sequence star of \( 14-20 \, M_\odot \).

The region of the possible pre-SN orbital period \( P_1 \) limited by the two thick lines in Fig. 1 does not cross the shaded area where the helium stars never fill their Roche lobes. This implies that J0737 – 3039 can only have been formed through Roche-lobe mass transfer from the helium star progenitor – as opposed to the other four Galactic DNSs which could be formed either via RLOF or without a mass-transfer phase (Dewi & Pols 2003).

Fig. 2 depicts an enlargement of the region of allowed final HeS–NS systems from Fig. 1 in an \( a_i \) versus \( M_{\text{He,t}} \) diagram (the stars are the same as the allowed systems in Fig. 1). For a given combination of pre-SN helium star mass \( M_{\text{He,t}} \) and orbital separation \( a_i \), we calculated the kick velocity required to produce the post-SN orbital period and eccentricity. Fig. 2 shows the ranges of the required kick velocities \( V_k \) limited by the curves of \( V_k = 70, 125, 175 \) and 230 km s\(^{-1}\). The region where the systems undergo a CE phase and evolve to extremely short orbital periods is to the left of the dash-dotted line in Fig. 2. Assuming that only systems which do not go through the CE phase are the possible progenitors of J0737 – 3039 (i.e. the systems on the right-hand side of the line), we find that to explain the orbital parameters of J0737 – 3039 when it was born \( (i.e. \, a = 1.688 \, R_\odot \) and \( e = 0.138; \) assuming that the age of the pulsar equals its characteristic age), a minimum kick velocity of 70 km s\(^{-1}\) is required at the birth of the companion of the pulsar.

The minimum separation, below which the mass-transfer phase from the helium star to a neutron star is dynamically unstable resulting in a merger of the two stars (Dewi et al. 2002), is marked by the dotted line in Fig. 2. This line gives a constraint on the maximum kick velocity, i.e. 230 km s\(^{-1}\).

### 2.2 Magnetic field and spin history of the pulsar

All five DNSs in eccentric orbits in the Galactic disc share the characteristic of a combination of a weak dipole magnetic field \( (\text{in the range } 10^7 \text{ to } 2 \times 10^{10} \text{ G}) \) and rapid spin, indicating that we are dealing here with recycled pulsars that have been spun up during an accretion phase (Smarr & Blandford 1976; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982; Srinivasan & van den Heuvel 1982). During such a phase with a non-degenerate donor companion the orbit will have been tidally circularized. Therefore the present
RLOF is highly super-Eddington, in the range $10^7$–$10^9$ G is thought somehow to be the result of the accretion, as there is an observed correlation between the amount of matter accreted and the field strength (Taam & van den Heuvel 1986). A simple relation for this case was derived semi-empirically, by Shibazaki et al. (1989):

$$B(t) = \frac{B_0}{1 + \Delta M/m_g},$$

where $B(t)$ and $B_0$ are the present and initial magnetic field strengths, respectively, $\Delta M$ is the amount of matter accreted and $m_g$ is a constant to be derived from the observations. Francischelli, Wijers & Brown (2002) found $m_g = 1.25 \times 10^{-3}$ M$_\odot$ to agree well with the observed data for low-mass X-ray binaries. Adopting this value and a duration of the RLOF phase of the helium star of $2 \times 10^4$ yr [this is about the average value for helium stars in the mass range $4.0$–$6.3$ M$_\odot$ (Dewi et al. 2002; Dewi & Pols 2003)], with accretion at an Eddington rate for helium ($3 \times 10^{-8}$ M$_\odot$ yr$^{-1}$), one finds that $B(t)$ can have decreased by a factor of about 50 during this phase alone. Furthermore, a $15$-M$_\odot$ Be star resides for 10$^7$ yr on the main sequence. Be/X-ray binaries tend to be transients (Rappaport & van den Heuvel 1982; van den Heuvel & Rappaport 1987; Ziółkowski 2002) and are ‘on’ as an X-ray source only part of the time, during which they often reach a luminosity close to the Eddington limit. Assuming them to be ‘on’ only 1 per cent of the time and then to reach the Eddington limit, the neutron star will during the Be/X-ray binary phase have accreted about $1.5 \times 10^{-3}$ M$_\odot$. With equation (2) this is already sufficient to reduce its magnetic field by a factor of about 100. So, adding the amount of matter accreted during the Be/X-ray binary phase and the RLOF of the helium star, one finds with equation (2) that these phases together provide enough accretion to reduce the magnetic field by a factor of about 200.

Magnetic fields of young pulsars on average typically have a dipole strength of a few times $10^{12}$ G, and after reduction by this factor will typically be around $10^9$ G, as observed in the five DNSs. As to the spin-up of the ‘old’ neutron star: during the RLOF from the helium star, accretion to the neutron star will have proceeded through a disc. The amount of angular momentum accreted during this phase can be calculated as follows. The mass-transfer rate during RLOF is highly super-Eddington, in the range $1$–$2 \times 10^{-7}$ M$_\odot$ yr$^{-1}$ for helium stars in the mass range $4.0$–$6.3$ M$_\odot$ (Dewi et al. 2002; Dewi & Pols 2003). Dewi et al. (2002) and Dewi & Pols (2003), in their calculations of the evolution of the systems during this phase, assumed the accretion rate on to the neutron star to be the Eddington rate ($3 \times 10^{-8}$ M$_\odot$ yr$^{-1}$) and the super-Eddington fraction of the transferred matter to be blown out of the system by the radiation pressure, carrying with it the specific angular momentum equal to the specific orbital angular momentum of the neutron star. Following this assumption of accretion at the Eddington rate – as radiation pressure will prevent accretion at a higher rate – and using the dipole strength of the magnetic field of J0737$-$3039 of $6.9 \times 10^9$ G, one can calculate the value of the Alfven radius $R_a$, where the matter becomes coupled to the magnetic field and starts to rotate with the neutron star magnetosphere. $R_a$ is given by (see e.g. Bhattacharya & van den Heuvel 1991):

$$R_a = \frac{(B_0 R_g^4)}{(M/M_{\text{Edd}})^2(M/M_{\text{Edd}})^{1/2}} \times 32.9 \text{ km},$$

where $B_0$ is the dipole field strength in units of $10^9$ G, $R_g$ is the neutron star radius in units of $10^6$ cm, $M$ and $M_{\text{Edd}}$ are the accretion rate and the Eddington accretion rate for hydrogen, respectively, and $M$ is the mass of the neutron star. With the dipole field strength of $6.9 \times 10^9$ G of PSR J0737$-$3039, the Eddington rate for helium accretion $M = M_{\text{Edd}} = 3 \times 10^{-8}$ M$_\odot$ yr$^{-1}$ and $M = 1.3$ M$_\odot$, one obtains $R_a = 78.4$ km.

The rate at which angular momentum is accreted by the neutron star is then

$$J = M\Omega(r = R_g)R_g^2,$$

where $\Omega(r)$ is the Keplerian angular velocity of matter in the disc at distance $r$ from the centre of the neutron star. With $M = M_{\text{Edd}}$ and $M = 1.3$ M$_\odot$, one finds $J = 1.1 \times 10^{-1}$ M$_\odot$ km$^2$ s$^{-1}$ yr$^{-1}$. The present spin angular momentum of the neutron star is

$$J = M(2\pi/P)R^2r_g^2,$$

where $R$ and $P$ are the radius and spin period of the neutron star and $r_g$ is its radius of gyration, respectively. The value of $r_g$ is typically about 0.075 for a polytropic index $n = 3$ (e.g. Lattimer & Prakash 2001). With this value and $R = 10$ km and $P = 22$ ms, one obtains $J = 2.8 \times 10^{15}$ M$_\odot$ km$^2$ s$^{-1}$, which together with the above-mentioned rate of accretion of angular momentum results in a required time-scale for the spin-up of about $2.5 \times 10^4$ yr.

The duration of the phase of RLOF in the HeS–NS binaries with helium star masses between $4.0$ and $6.3$ M$_\odot$ ranges from $2.4$ to $0.7 \times 10^4$ yr, which is of the same order as the value of $2.5 \times 10^4$ yr required for the spin-up. It thus appears that the magnetic field strength and spin rate of PSR J0737$-$3039 fit quite well with the evolutionary model presented here in which the immediate progenitor system was a very close HeS–NS binary which evolved through a phase of RLOF with a duration of the order of $10^4$ yr. As mentioned above, the progenitor of this system was so close that it cannot have avoided the phase of mass transfer by RLOF from the helium star (Dewi & Pols 2003), so here this phase must absolutely have taken place in the history of PSR J0737$-$3039. This may be the reason why the pulsar has the shortest spin period of all. The progenitors of the other systems may, in principle, have avoided RLOF, although it can certainly not be excluded that also in (some of) them RLOF from the helium star may have taken place.

### 3 Discussion and Conclusions

We have examined the formation of J0737$-$3039. We find that this system must have gone through a mass-transfer phase from a helium star with initial mass in the range of $4$–$6.3$ M$_\odot$. We also find that an asymmetric SN explosion with a kick velocity of $70$–$230$ km s$^{-1}$ is necessary to explain the observed orbital parameters. However, these constraints may still be subject to some uncertainties. Whether the neutron stars in the systems that go through a CE phase (the open stars in Fig. 1) complete the spiral-in in the envelope of the helium star depends on the competition between the spiral-in time-scale and the time left before the explosion of the helium star (Dewi & Pols 2003). If the SN explosion in systems with open star symbols in Fig. 1 occurred before the neutron star completed the spiral-in process, a lower kick velocity or even a symmetric SN explosion (shown as the solid circle) would then be possible. Furthermore, the constraints on the maximum pre-SN mass and the maximum kick velocity depend somewhat on the assumed wind mass-loss rate and the loss of angular momentum during the RLOF. As the stability of a mass-transfer phase depends on the mass ratio of the system and the period at the onset of RLOF, applying a higher wind mass-loss rate results in a lower mass helium star in a wider orbit, and hence...
more stable mass transfer than by adopting wind mass loss with a lower rate.

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NOTES ADDED IN PROOF

1) In this Letter we restricted ourselves to kicks imparted in the plane of the orbit. After acceptance of this Letter we became aware of a letter on the origin of PSR JO737-3039 by Willems & Kalogera (2004) which took into account also kicks in directions outside the orbital plane. These authors find that for such kicks, velocities larger than our derived upper limit of 230 km s\(^{-1}\) are in principle possible for this system. They find the most likely kick velocity to be about 150 km s\(^{-1}\). They confirm our conclusion that the helium stars in the progenitor systems must have overflowed their Roche lobes: they find that detached helium star progenitors more massive than 25 M\(_{\odot}\) would theoretically be possible. However, it is likely that helium stars more massive than 25 M\(_{\odot}\) leave black holes instead of neutron stars as remnants and therefore cannot be real progenitors of the neutron star companion of PSR JO737-3039.

2) Very recently the companion of PSR JO737-3039 was discovered also to be a radio pulsar (Lyne et al. 2004). It is a strong magnetic field non-recycled radio pulsar with a pulse period of 2.8 s, which, together with the recycled nature of the first-discovered pulsar in this system, very nicely confirms the predictions of the ‘standard scenario’ for the formation of double neutron stars (e.g. Srinivasan & van den Heuvel 1982).

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