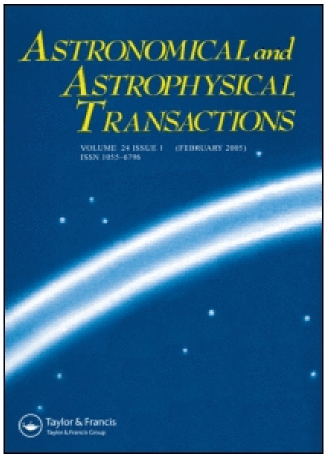

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FORMATION OF THE OBSERVED DOUBLE NEUTRON STAR SYSTEMS

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We investigate the properties of the immediate progenitors of the double neutron star (DNS) systems detected in the Galactic disc. An analysis of the effect of supernovae on orbital dynamics combined with recent results from the study of hypercritical accretion onto neutron stars shows that the observed systems could not have been formed had the explosion been symmetric. Their formation, however, can be explained if kick velocities are imparted to neutron stars at birth. For this case, we calculate the range of possible DNS progenitors as a function of the kick magnitude and of the time elapsed since the second supernova. For each of the observed systems, we derive a minimum kick magnitude needed for its formation, which, for the close ones, exceeds 200 km s^{-1}.

KEY WORDS Neutron stars, double systems, formation

1 INTRODUCTION

Since the discovery of PSR 1913+16 by Hulse and Taylor (1975) and its likely neutron star companion, three additional binary pulsars have been found in the Galactic disc with companions that are also likely to be neutron stars: PSR 2303+46, PSR 1534+12, and PSR 1518+4904.

Studies of radio pulsars and various types of X-ray binaries have revealed evidence for kicks imparted to neutron stars during their formation. For most of these systems, however, it is difficult to obtain direct information about the supernova kick because they have evolved considerably since the neutron-star formation due to binary and Galactic-motion effects. Such effects are often poorly constrained by models or observations. In contrast, the only type of evolution experienced by double neutron star (DNS) systems after the second supernova explosion is orbital shrinkage due to gravitational radiation (a well-understood phenomenon at the orbital separations relevant to the four observed binary pulsars).

By evolving the observed DNS systems backwards (accounting for the effects of gravitational wave emission) to the time of their formation (second supernova), we can obtain information about their helium-star/neutron-star binary progenitors. Such an analysis avoids any uncertainties due to binary evolution and provides a direct study of the supernova explosion (and possible neutron star kick). Here, we summarize an investigation of the four known galactic DNS systems by Fryer and Kalogera (1997; hereafter FK97). We find that such systems could not have formed in a symmetric explosion and that kick magnitudes in excess of 200 km s^{-1} are necessary for the formation of the two short-period DNS systems.

2 SYMMETRIC SUPERNOVA EXPLOSIONS

Regardless of the details of prior evolution, all mechanisms for DNS formation in the Galactic disc converge to the same configuration before the second supernova explosion: a binary consisting of a neutron star and a helium star in a circular orbit. The helium star collapses to form the degenerate companion to the observed radio pulsar. In this section, we assume that the explosion is symmetric and no natal kick is imparted to the second neutron star.

2.1 Orbital Dynamics

For a given set of post-SN binary characteristics, the binary parameters just prior to the explosion are uniquely defined (Blaauw, 1961; Boersma, 1961). Observations of DNS systems have yielded measurements of the pulsars and their companion masses, their orbital separations and eccentricities at the current epoch, as well as their radio pulsar characteristics (summarized in Table 1 of FK97). We evolve the binary parameters backwards in time, accounting for the orbital evolution due to gravitational radiation, and calculate the binary parameters *just after* the second SN explosion. The only uncertainty lies in the time, T_{SN}, that has elapsed since the explosion, typically assumed to be equal to the characteristic age of the pulsar. Knowing the immediate post-SN binary parameters for the four DNS systems, we then calculate the values of their helium-star masses, M_0, and orbital separations, A_0, *just before* the explosion.

As low-mass helium stars evolve, they expand beyond their main-sequence radii in a helium-star giant phase. Their radii may increase several orders of magnituded before slightly decreasing just before their impending supernova explosion. Based on such results of stellar evolution calculations (Habets, 1985; Woosley *et al.*, 1995, we use a fit (FK97) to the mass-radius relation of evolved helium stars and evaluate, for each DNS system, the ratio of A_0 to the maximum helium-star radius. For a range of T_{SN} values, we find this ratio to always be smaller than unity (Table 1 of FK97): it is 0.12–0.36 for PSR 1913+16, $\lesssim 0.01$ for PSR 1534+12, 0.3 for PSR 2303+46, and 0.025 for PSR 1518+4904. Therefore, it becomes clear that if the SN explosion were symmetric, then, in all four systems, the radio pulsar would lie within the envelope of its companion at the time of the explosion (see also Burrows and Woosley, 1986; Yamaoka *et al.*, 1993). Therefore, we must examine the fate of such a configuration, i.e. a neutron star that enters the envelope of a helium star.

Table 1. Neutron stars in helium common envelopes

	PSR 1913+16	*PSR 1534+12*	*PSR 2303+46*	*PSR 1518+4904*
		Evolution		
He-star mass	3.2–2.9$M_\odot$	2.0–2.2$M_\odot$	3.2–2.9$M_\odot$	2.0$M_\odot$
T_{ev}	10–1 × 10^3 yr	9 × 10^3 yr	1 × 10^3 yr	9 × 10^3 yr
		Accretion		
		No Angular Momentum[a]		
He-star mass	4.2–2.5$M_\odot$	2.0–2.25$M_\odot$	2.5$M_\odot$	2.0$M_\odot$
$\dot{M}$	370–1.5 × $10^3 M_\odot$ yr^{-1}	0.9–250$M_\odot$ yr^{-1}	2.5$M_\odot$ yr^{-1}	0.11$M_\odot$ yr^{-1}
T_{coll}	2.7 × 10^{-3}–6.5 × 10^{-4} yr	1.1–4.0 × 10^{-3} yr	1.4 yr	8.5 yr
		With Angular Momentum[b]		
He-star mass	4.2–2.5$M_\odot$	2.0–2.25$M_\odot$	2.5$M_\odot$	2.0$M_\odot$
$\dot{M}$	160–200$M_\odot$ yr^{-1}	0.01–75$M_\odot$ yr^{-1}	0.01$M_\odot$ yr^{-1}	$10^{-6} M_\odot$ yr^{-1}
T_{coll}	6.3 × 10^{-3}–5.0 × 10^{-3} yr	100–0.013 yr	110 yr	1.0 × 10^6 yr

Note. [a]We assume that the infalling material contains no angular momentum or is able to transport its angular momentum outward instantaneously. [b] We assume that there is no angular momentum transport. We are thus limited to accretion close to the poles where angular momentum is insufficient to halt the inflow of the material.

2.2 Neutron Stars in Common-Envelope Phases

Recent results from studies of the accretion process onto neutron stars (Chevalier, 1993, 1996; Brown, 1995; Fryer *et al.*, 1996) show that, for the conditions around a neutron star appropriate for many common envelope phases, neutrino emission becomes the dominant cooling mechanism and equilibrium accretion rates reach the Bondi–Hoyle rate (Bondi, 1952). Such rates exceed the photon-Eddington limit by many orders of magnitude and, in these cases, the neutron star collapses into a black hole in a short time.

Once a neutron star enters the envelope of its helium-giant companion, DNS formation is possible only if the helium star explodes before the neutron star collapses into a black hole. A common-envelope phase for these systems can occur at or before the helium star acquires its maximum radial extent. The interval between the time the helium star reaches maximum radius and the time it explodes as a supernova sets a lower limit on the evolution time, T_{ev}, that the neutron star remains in the common envelope accreting matter. Hence, the constraint for DNS formation is that T_{ev} is shorter than the time required for the neutron star to accrete one solar mass and collapse into a black hole (T_{coll}). However, if there is no neutron star kick, we find that the four galactic DNS systems all have collapse times shorter than the evolution time by orders of magnitude (see Table 1). Even if we include the maximum effects of angular momentum (see FK97 for details), three of the systems (with the exception of PSR 1518+4904) would not be able to avoid black hole formation.

We conclude that the pulsar cannot survive a common-envelope phase with its helium star companion, which it is, nevertheless, forced to experience if the explosion were symmetric. Therefore, we must consider the case of asymmetric supernovae.

3 ASYMMETRIC EXPLOSIONS

Asymmetries in supernova explosions, either in neutrino emission, mass ejection, or fall-back, can impart kick velocities to newborn neutron stars. For a given kick magnitude and direction relative to the pre-SN orbital velocity, we can use conservation of orbital angular momentum and energy (e.g., Hills, 1983; Kalogera, 1996) to derive progenitor masses, M_0, and orbital separations, A_0, for the four observed systems, given their post-SN characteristics.

For an isotropic kick of a specific magnitude, V_k, we calculate the limits imposed on the parameter space of M_0 and A_0. One constraint we must impose is that at a given helium star mass, the pre-SN orbital separation is large enough to accommodate its radius expansion. Two other limits have their origin in the details of orbital dynamics (bound post-SN orbit and relistic angle orientation of the kick; see FK97). The parameter space available to the progenitors of PSR 1913+16 and PSR 1534+12 are shown in Figure 1, for three kick magnitudes and T_{SN} equal to the pulsar characteristic age. As the magnitude of the kick velocity increases, the relative orbital velocity of allowed DNS progenitors also increases and systems with shorter separations and more massive helium stars are included in the progenitor parameter space. For the two wider DNS systems, the progenitor masses are $\sim 3M_\odot$ and the orbital separations are in the range $\sim$ 20–50$R_\odot$. The progenitor parameters also depend on the time elapsed since the SN explosion; as this gets longer the allowed ranges become wider by a factor of a few (FK97).

The constraints imposed on the DNS progenitors act in such a way that orbits wide enough to accommodate the helium-star expansion will become small enough after the explosion to agree with the currently observed parameters, *only* if the kick magnitude exceeds a specific minimum value: 260 and 220 km s^{-1} for the two close systems, PSR 1913+16 and 1534+12, while for the two wider, PSR 2303+46 and PSR 1518+4904, the minimum kick magnitudes are lower, 70 and 50 km s^{-1}, respectively.

4 DISCUSSION

A careful account of the change in orbital characteristics of binary systems experiencing symmetric supernova explosions and orbital evolution due to gravitational radiation, of the sizes of helium stars approaching collapse into a neutron star, and of recent results concerning the fate of neutron stars within helium-star envelopes, lead us to conclude that the observed double neutron stars in the Galactic disc could not have been formed if the SN explosions forming the second neutron stars

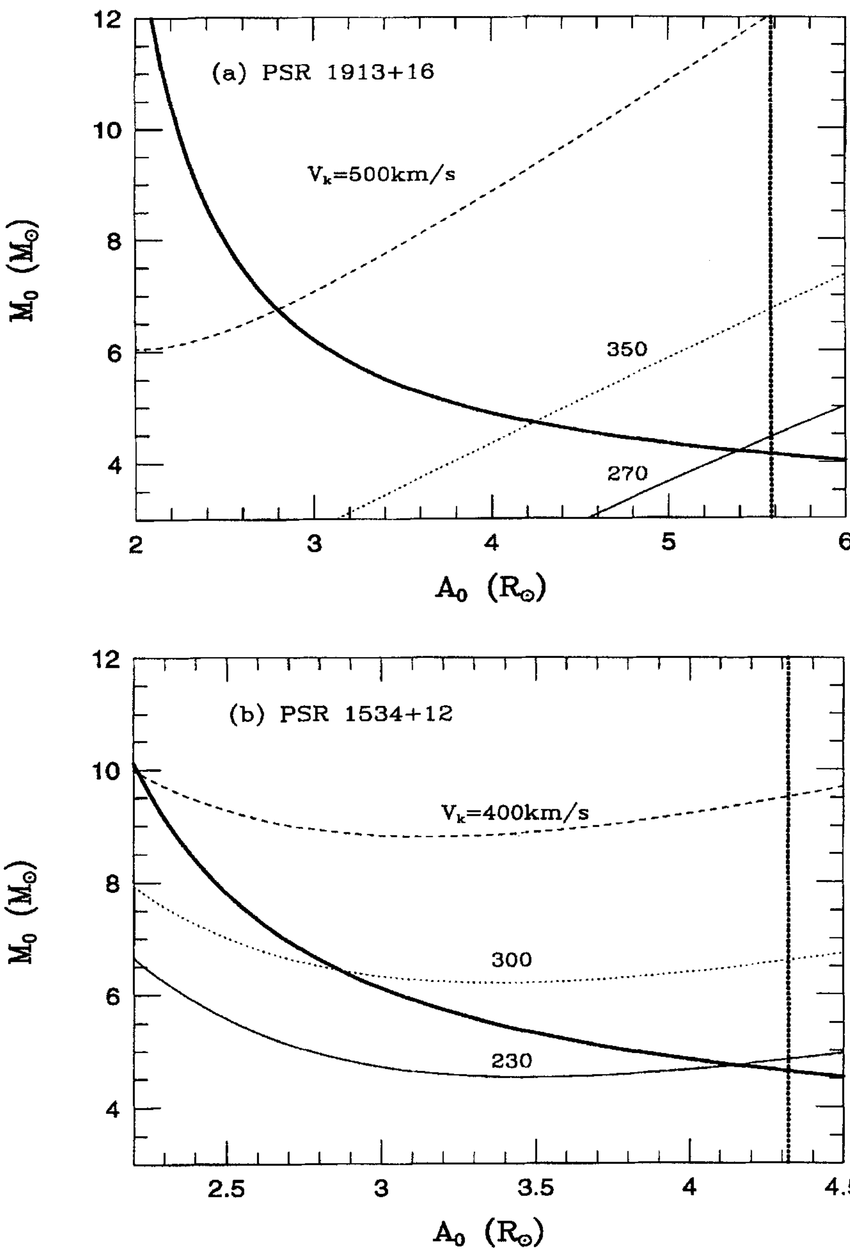

Figure 1 Limits on the pre-supernova orbital separation, A_0, and mass of the helium star, M_0 of (*a*) PSR 1913+16 and (*b*) PSR 1534+12, for three different magnitudes of the kick velocity, V_k. The vertical thick dotted line corresponds to the maximum orbital separation for a bound post-SN orbit; the thick solid line corresponds to the minimum helium-star mass that can be accommodated in the orbit; thin lines correspond to the maximum possible pre-supernova helium-star mass, for a realistic kick orientation and their position depends on the kick magnitude. Limits are calculated for circular pre-supernova orbits and for T_{SN} equal to the characteristic pulsar age.

were symmetric. Instead, we find that natal kicks of a minimum magnitude (exceeding 200 km s^{-1} for the close systems) are required to explain the observed DNS parameters.

We have further used the limits on kick magnitude and progenitor characteristics to derive corresponding limits on the centre-of-mass velocities for the known double neutron stars (Kalogera, 1996). For the two systems in close orbits (PSR 1913+16 and 1534+12), we find minimum centre-of-mass velocities of 200 km s^{-1} and 225 km s^{-1}, while for the two wider systems, the minimum values are considerably lower, $\sim$ 50 km s^{-1}. Since simulations of DNS formation favour low kick magnitudes (Fryer *et al.*, 1998), these minimum centre-of-mass velocities are also the most probable. Values of T_{SN} longer than the characteristic pulsar age decrease these by a factor of a few. These results are consistent with current proper-motion measurements and upper limits (see FK97 for details).

Because the short-period systems will merge via gravitational wave emission within a Hubble time, they are important both as gravitational wave sources for observatories such as LIGO and VIRGO, but also as progenitors of gamma-ray bursts. The fact that these systems must have systemic velocities greater than $\sim$ 200 km s^{-1} means that by the time these systems merge, they will not only be far from their formation site, but, for small galaxies, DNS systems may not even reside in their host galaxy!

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