FORMATION OF THE DOUBLE NEUTRON STAR SYSTEM PSR J1930–1852

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Received 2015 November 3; accepted 2015 December 6; published 2015 December 30

ABSTRACT

The spin period (185 ms) and period derivative (1.8 × 10^{-17} s^{-1}) of the recently discovered double neutron star (DNS) system PSR J1930–1852 indicate that the pulsar was mildly recycled through the process of Roche-lobe overflow. This system has the longest orbital period (45 days) of the known DNS systems, and can be formed from a helium star-NS binary if the initial mass of the helium star was \( \lesssim 4 M_\odot \); otherwise, the helium star would never fill its Roche-lobe. At the moment of the supernova explosion, the mass of the helium star was \( \lesssim 3 M_\odot \). We find that the probability distribution of the velocity kick imparted to the new-born neutron star has a maximum at about 30 km s^{-1} (and a tail up to 260 km s^{-1}), indicating that this NS probably received a low kick velocity at birth.

Key words: binaries: general – pulsars: individual (J1930–1852) – stars: evolution – stars: neutron

1. INTRODUCTION

The formation of double neutron star (DNS) systems is believed to be the endpoint of massive binary evolution (e.g., Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006). Generally a massive binary first evolves into a high-mass X-ray binary (following the formation of the first NS) and then evolves through a spiral-in (common-envelope) phase into a helium star plus NS binary (e.g., van den Heuvel & De Loore 1973). When the helium star explodes as a supernova (SN) to become the second NS, the final binary may be a DNS system. Most DNS systems share the characteristics of relatively short spin periods (22.7–104 ms), short orbital periods (0.1–18.8 days), and eccentric orbits. However, PSR J1930–1852, a DNS system recently discovered by Swiggum et al. (2015), has an orbital period as long as 45 days and a relatively long spin period of 185 ms. In this paper, we will discuss the formation history of this system from helium star-NS binaries.

2. FORMATION OF PSR J1930–1852

2.1. Constraints on the Parameter Space of the Helium Star-NS Binaries

Evolutionary calculations of helium star-NS binaries have been performed by many authors (e.g., Dewi et al. 2002; Dewi & Pols 2003; Ivanova et al. 2003; Tauris et al. 2015). During core helium burning and further burning phases, the helium star loses mass through stellar winds (Hamann et al. 1995). Of particular interest are low-mass (\( \lesssim 3.5 M_\odot \)) helium stars since they swell up to large radii during their late evolution (Paczynski 1971; Nomoto 1984; Habets 1986). The expansion of the helium star may finally result in the occurrence of Roche-lobe overflow (RLOF) and mass transfer. The NS can be recycled by the accretion of mass and angular momentum from the helium star companion. If the binary orbit is very wide or the helium star is too massive, mass transfer via RLOF will not occur prior to the SN explosion. For PSR J1930–1852, the measured spin period and period derivative give a relatively weak surface magnetic field of \( 6 \times 10^{10} \) G, implying that the pulsar was mildly recycled during the previous mass transfer phase (Tauris et al. 2015).

In Figure 1 we show the plausible distribution of the helium star-NS binary in the final mass (\( M_{\text{He},\text{f}} \)) of the pre-SN helium star versus the pre-SN orbital separation (\( a_0 \)) plane. The pre-SN orbital separation \( a_0 \) should lie between the periastron and apastron of the post-SN orbit with a separation of \( a \) (Flannery & van den Heuvel 1975), i.e.,

\[
\alpha (1 - e) \leq a_0 \leq \alpha (1 + e),
\]

where \( e \) is the post-SN eccentricity. In Figure 1 we indicate the maximum and minimum pre-SN orbital separations with the two black solid lines by adopting \( a = 73 R_\odot \) and \( e = 0.4 \).

The fact that PSR J1930–1852 has experienced mass transfer in a wide orbit indicates that \( M_{\text{He},\text{f}} \lesssim 3 M_\odot \), as indicated by the blue dashed line in Figure 1, which distinguishes whether the helium star can evolve to fill its RL. For a system with a wide orbit at the time of the SN explosion, the preceding mass transfer should have decreased the orbital separation, so the initial separation could have been wider, as indicated by the blue dotted line in Figure 1. The calculated results of Tauris et al. (2015, see their Table 1) were used to plot these two lines. From this figure we can estimate that the initial mass of the helium star is \( \lesssim 4 M_\odot \).

2.2. Asymmetric SN Explosions and NS Kicks

When the helium star exploded as an SN, a kick velocity \( V_k \) was imparted to the second NS. The orientation of the kick velocity is controlled by the angles \( \theta \) and \( \phi \), as shown in Figure 2. Here \( \theta \) is the angle between the kick velocity and the pre-SN orbital velocity \( V_0 \), and \( \phi \) is the positional angle of the kick velocity with respect to the orbital plane. Thus the relation between \( a_0 \) and \( a \) is given by (Hills 1983; Dewi & Pols 2003),

\[
\frac{a_0}{a} = 2 - \frac{M_0}{M} (1 + \nu^2 + 2 \nu \cos \theta),
\]

where \( M_0 = M_1 + M_{\text{He},\text{f}} \), \( M = M_1 + M_2 \), \( \nu = V_k/V_0 \), and \( V_0 = (GM_0/a_0)^{1/2} \); \( M_1 \) and \( M_2 \) are the pulsar mass and the second NS mass, respectively. We assume \( M_1 = M_2 = 1.3 M_\odot \) in the following calculation. The eccentricity of the post-SN

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\text{The Astrophysical Journal, 816:45 (3pp), 2016 January 1} 
\text{doi:10.3847/0004-637X/816/1/45} 
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orbit can be written as (Hills 1983; Dewi & Pols 2003)

\[
1 - e^2 = \frac{a_0 M_0}{a M \left[ 1 + 2\nu \cos \theta + \nu^2 (\cos^2 \theta + \sin^2 \theta \sin^2 \phi) \right]}
\]  

In Equations (2) and (3) there are five variables: \(V_k\), \(M_{\text{He,f}}\), \(a_0\), \(\theta\), and \(\phi\). We can derive useful information on the distribution of \(V_k\) if the values of \(M_{\text{He,f}}\) and \(a_0\) are reasonably constrained.

From Equations (2) and (3) the condition of \(\sin^2 \phi = 1\) always gives the solution \(a_0 = a (1 \pm e)\), independent of the magnitude of the \(V_k\). This result corresponds to the lower and upper limits of the orbital separation, as given by Equation (1). For the case of \(\sin^2 \phi = 0\), we can derive two boundary lines for any specific value of \(V_k\). In Figure 1, the orange and green lines correspond to \(V_k = 30\) and \(50\) km s\(^{-1}\), respectively. In a special situation in which a new born NS has no kick \((V_k = 0)\), there are two solutions with \(M_{\text{He,f}} = 2.34M_\odot, a_0 = 43.8R_\odot\), and \(M_{\text{He,f}} = 0.26M_\odot, a_0 = 102.2R_\odot\).

For any fixed value of \(V_k\), the possible values of \(M_{\text{He,f}}\) and \(a_0\) are confined by the conditions of \(\sin^2 \phi = 0\) and \(\sin^2 \phi = 1\). As an illustration, Figure 3 shows the allowed distribution of \(M_{\text{He,f}}\) and \(a_0\) with \(V_k = 40\) km s\(^{-1}\). The thick green and red lines show the solutions in the limits of \(\sin^2 \phi = 0\) and 1, respectively. We set 1000 random values for both \(\theta\) and \(\phi\) in the interval of \(0 \rightarrow \pi\), and plot the solutions in Figure 3 as triangles.

Habets (1986) suggested that the threshold mass for a single helium star to produce an NS is \(\sim 2.2M_\odot\). If the helium star is in a binary, the threshold mass is determined by the CO or ONeMg core mass (Nomoto 1984). Here we assume that the minimal mass of a pre-SN helium star is \(1.4M_\odot\), which is compatible with the calculated results of Tauris et al. (2015), while the pre-SN maximal mass is \(\sim 3M_\odot\) (see Section 2.1). We ran millions of numerical calculations with randomly distributed angles \(\theta\) and \(\phi\). Using the limits of \(1.4M_\odot \leq M_{\text{He,f}} \leq 3M_\odot\) and Equation (1), we derived the distribution of the kick velocities. Figure 4 shows the normalized and accumulated distributions of \(V_k\) with the black and red curves, respectively. We find that the \(V_k\)-distribution
has a peak at \( \sim 30 \text{ km s}^{-1} \) with a maximum value of \( \sim 260 \text{ km s}^{-1} \). For \( V_k \leq 50 \) and \( 100 \text{ km s}^{-1} \), the generated probabilities in our calculations are 0.63 and 0.77, respectively. In order to reproduce the observed parameters of PSR J1930–1852, the higher the value of \( V_k \), the more restricted the orientation of the NS kick. We therefore see that the most likely value of \( V_k \) was low, of the order of \( 30 \text{ km s}^{-1} \).

3. SUMMARY

Our analysis reveals the following results.

(i) To satisfy the condition that there was RLOF-mass transfer in the progenitor helium star-NS binary with a wide orbit, the mass of the pre-SN helium star \( M_{\text{He,f}} \) should be \( \lesssim 3.0M_\odot \) and correspondingly the initial mass should be \( \lesssim 4M_\odot \).

(ii) For randomly orientated NS kicks, the most likely values of the kick velocities are low, with a peak at \( \sim 30 \text{ km s}^{-1} \).

Recently, Beniamini & Piran (2015) demonstrated that the second collapse in the majority of DNS systems involved small mass ejection (\( \Delta M \lesssim 0.5M_\odot \)) and a low kick velocity (\( V_k \lesssim 30 \text{ km s}^{-1} \)), which may be related to the electron-capture SNe as suggested by Podsiadlowski et al. (2004) and van den Heuvel et al. (2004). For the helium star-NS progenitor of PSR J1930–1852, both the helium star’s mass and the kick velocity are relative low, which are indeed likely to correspond with the second NS having originated from an electron-capture SN. Still the formation channel of core-collapse SN cannot be excluded, and further observations can help settle this problem.

This work was supported by the Natural Science Foundation of China under grant numbers 11133001, 11203009, and 11333004, the Strategic Priority Research Program of CAS (under grant number XDB09000000).

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