High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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The masses of 18 pairs of double neutron stars and implications for their origin

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Abstract. For the observed 18 pairs of double neutron star (DNS) systems, we find that DNS mass distribution is very narrow and its mean value (about 1.34 solar mass) is less than the mean of all measured pulsars of about 1.4 solar mass. To interpret the special DNS mass characteristics, we analyze the DNS formation process, via the phases of HMXBs, by investigating the evolution of massive binary stars. Moreover, in DNSs, two classes of NSs are taken into account, formed by supernova (SN) and electron capture (EC), respectively, and generally the NS mass by SN is bigger than that by EC. Quantitatively, with various initial conditions of binary stars, the observed special DNS distribution can be satisfactorily explained.

Keywords. pulsar, double neutron star, binary system, mass

1. Introduction

The DNS masses are important parameters to constrain the gravitational wave by the NS merge, which has been detected by LIGO (e.g., Abbott *et al.* 2017), so the statistics of DNS masses not only infers the DNS formation process and the DNS birth rate but also implies the message of gravitational wave background in the universe. Until now, more than 80 NS masses have been measured in binary pulsar systems. However, the masses of DNSs (mean of 1.34 solar mass) are systematically lower than the mean (1.4 solar mass) of all pulsars, and show a very narrow distribution with a deviation of **0.3** solar mass (see Fig. 1 and Fig. 2) (e.g., Zhang *et al.* 2011; Miller & Miller 2015; Özel & Freire 2016; Tauris *et al.* 2017). So, this special DNS mass distribution should be involved in their formation process.

In this short paper, we propose a schematic phenomenon model to interpret the DNS mass by considering the massive binary star evolution process. It is usually believed that the first massive star in binary system will experience a SN to form a NS, then the second massive star has two choices to form a NS, experiencing a SN explosion if its mass over 10 solar masses or an electron capture if its mass ranges 8-10 solar masses (e.g., Podsiadlowski *et al.* 2004). Generally, a NS by SN should has a big kick, arising a big eccentricity system (e.g. Hulse-Taylor pulsar system: PSR B1913+16 (e.g., Hulse & Taylor 1975; Weisberg & Huang 2016)), while a NS by EC (e.g., Nomoto 1984) has a null kick, arising a circular orbit (van den Heuvel 2004; Yang *et al.* 2017) (e.g. double pulsar system: PSR J0737-3039 (e.g., Lyne *et al.* 2004; Kramer *et al.* 2006)).

2. DNS mass formation

For simplicity, we discuss a presentive case of massive binary star system, where the masses of both progenitor stars are much more massive than 10 solar masses and they

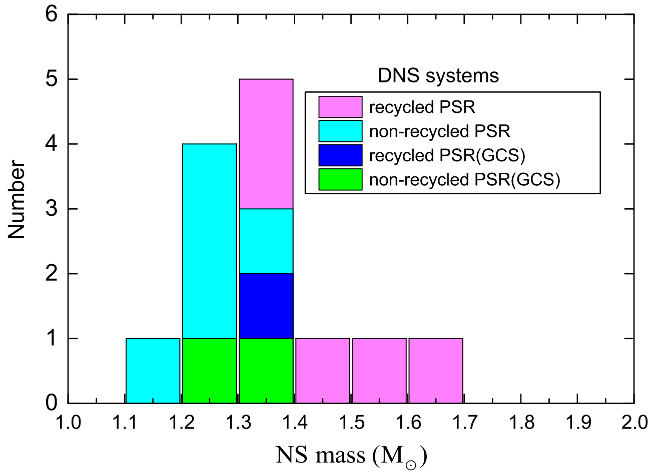

Figure 1. Histogram of measured NS masses in DNS systems, including the recycled pulsars and non-recycled ones, where GCS represents the globular cluster system.

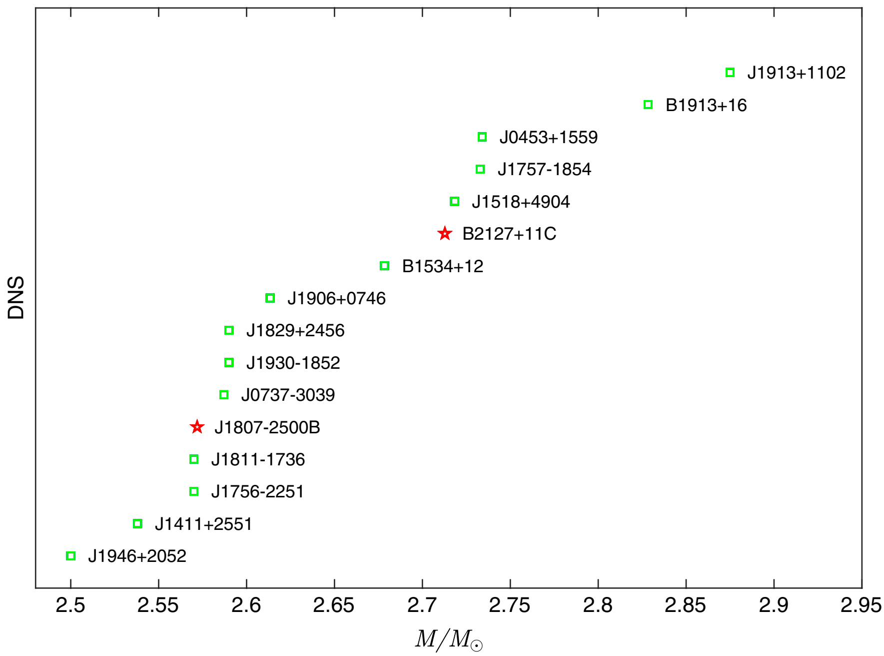

Figure 2. The measured total masses of 16 pairs of DNS systems, **where the squares (pentagrams) represent Galactic (GCS) DNSs.**

separate a distance much over the radii of stars that corresponds the orbital period of about 10 days. In such an orbital span, both stars, primary one and secondary companion, have the mass of 20 and 10 solar masses, respectively, and they will interact each other and the mass exchange happens at the initial stage of binary evolution, the illustration of which is shown in Fig. 3 (e.g., Bhattacharya & van den Heuvel 1991). On the formation process of DNS, we divide it into different evolution phases, where we estimate and discuss the mass status of both components, based on the knowledge of star and NS evolution.

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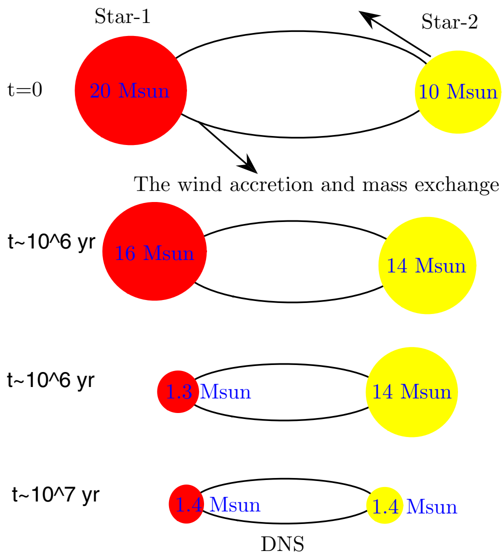

Figure 3. Illustration of DNS formation process. The orbital parameters evolution of DNS have been studied (e.g., Podsiadlowski *et al.* 2005). Tauris showed an illustration of DNS formation, which contains a pair of massive primordial binaries and goes through a supernova explosion to form DNS, and eventually merges into a black hole (e.g., Tauris *et al.* 2017). Here, we focus on the mass exchange during the DNS formation.

Phase 1. As shown in Fig. 3, at the initial phase, both stars have the mass exchange by the stellar winds before the primary enters the post-main-sequence phase, after onset of the Roche-lobe overflow a lot of mass will release from star-1 to star-2 until the SN explosion happens in star-1, while the masses of both stars are 16 and 14 solar masses respectively. This means that the mass distribution of both stars are varied, and the bigger star-1 becomes small while the less massive star-2 becomes bigger than before. The mass exchange will last several million years until star-1 explodes. The shorter the orbit scale (orbit period), more homogeneous of both star masses. If the orbit period is over 100 days, both stars should less interact, then the kick velocity of NS in such a system should generally exceed the orbital velocity and makes both DNSs separate away. This should be the reason why there is no DNS system of long orbital period of 100 days. Say, the mass exchange of binary of short orbit makes the mass difference of both stars decrease. However, the light star will correspond to the light NS mass, since NS mass is formed by the iron core plus the matter of convective elements, which is proportionally related to stellar mass.

Phase 2. At several million years, the first NS is formed by iron core explosion, and some crust matter of NS is lately formed by the fall-back matter of SN materials. At moment the NS mass is expressed by the gravitational energy coefficient 0.85 times Chandrasekha mass $M_{ch} = 1.44$ M$_\odot$ and fall-back mass M_f, shown as M = 0.85 M_{ch} + M_f. If there is no second star or it is far away, $M_f \sim$ 0.1-0.5 M$_\odot$ should be all fallen onto NS, which results in a NS mass of about 1.4 M$_\odot$. At the star explosion stage, outer iron core may be expelled, so the collapsed core mass can be less than M_{ch}, which can explain why some NS masses are close to 1.2 solar mass. However, in binary system, the fall-back mass is almost absorbed by the star-2, which makes $M_f \sim 0.1$M$_\odot$. Thus, the mass of DNS1 is now about 1.3M$_\odot$.

Phase 3. The secondary explodes will follow the similar procedure to star-1, but with less mass. Its fall-back matter will split into two similar parts, and then almost equally

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shared by two NSs. For $M_{f2} = 0.2$ M$_\odot$, $0.5M_{f2} \sim 0.1$ M$_\odot$ will add both NSs, which makes NS1 bigger than 1.4 M$_\odot$ and NS2 less than 1.4 M$_\odot$, like PSR B1913+16. This picture of DNS mass formation can explain why NS1 is almost bigger than NS2. If the star-2 has more convective matter, then NS2 can be bigger than NS1. If the star-2 is a light one with 8 solar masses, the EC will happen and produce a NS of 1.25 M$_\odot$. For the EC, there is little fall-back matter, so both masses are light, 1.3 and 1.25 M$_\odot$ respectively, which can explain the case of double pulsar PSR J0737-3039.

3. Summary

The special properties of DNS masses, which has the systematical low value and is narrowly distributed, are investigated, based on the evolution of binary star. A simple and approximated formula that describes the DNS mass (M_1 and M_2 for recycled and non-recycled NS) is proposed as below,

$$M_1 = 0.85M_{ch} + 0.1M_{f1} + M_{ac} + 0.5M_{f2} \tag{3.1}$$

$$M_2 = 0.85M_{ch} + 0.5M_{f2} \tag{3.2}$$

where $M_{acc} \sim 0.05$M$_\odot$ is the accretion mass of recycled NS. For the fall-back mass of SN-type NS, $M_{f1} \sim M_{f2} \sim 0.2M_\odot$, whereas for the EC-type NS, $M_{f2} \sim 0.1$M$_\odot$, so the above formula can explain the DNS mass distribution properly. The physical detail of the formula will be studied in the subsequent work.

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