Neutron Star Mass Distribution in Binaries

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Abstract. Massive neutron stars with $\sim 2M_\odot$ have been observed in neutron star-white dwarf binaries. On the other hand, well-measured neutron star masses in double-neutron-star binaries are still consistent with the limit of $1.5M_\odot$. These observations raised questions on the neutron star equations of state and the neutron star binary evolution processes. In this presentation, a hypothesis of super-Eddington accretion and its implications are discussed. We argue that a $2M_\odot$ neutron star is an outcome of the super-Eddington accretion during the evolution of neutron star-white dwarf binary progenitors. We also suggest the possibility of the existence of new type of neutron star binary which consists of a typical neutron star and a massive compact companion (high-mass neutron star or black hole) with $M \geq 2M_\odot$.

1. Neutron Star Mass Observations

Neutron stars provide opportunities to investigate physics of low-temperature dense Quantum chromodynamics (QCD) matter and are sources of gravitational waves that can be detected by ground-based observatories such as LIGO[1], Virgo[2, 3] and KAGRA[4].

The central densities of neutron stars are expected to reach several times the normal nuclear matter saturation density ($2.04 \times 10^{14}$ g cm$^{-3}$). Many theoretical investigations provide mass-radius relations of neutron stars based on the predicted neutron star equations of state. However, due to the nature of strong interaction which governs the QCD matter, the inner structure of neutron stars are still unknown and the maximum mass of neutron star is still an open question [5]. Until 2010, no firm evidence of a high-mass ($\geq 2M_\odot$) neutron star has been found. High-mass neutron stars were listed in the X-ray binary catalogue, but they were not taken as the evidences of the existence of high-mass neutron stars due to the large uncertainties. The main uncertainty in mass estimates of X-ray binaries lies in finding the actual gravitational center of companion stars. The situation has been changed due to discoveries of two $\sim 2M_\odot$ neutron stars in neutron star-white dwarf binaries [6, 7]. These observations rule out many neutron star equations of state which predict the maximum mass of a neutron star to be less than $2M_\odot$. Recently, we investigated many equations of state that predict a larger neutron star maximum mass than $2M_\odot$ [8, 9, 10].

Double-neutron-star binaries are major sources for the neutron star mass measurements and gravitational-wave detections with current ground-based gravitational-wave observatories [11, 12]. All well-measured neutron star masses in double-neutron-star binaries are still less than $1.5M_\odot$, contrary to the recent $2M_\odot$ observation in neutron star-white dwarf binaries. These observations indicate that a neutron star’s mass may depend on the evolutionary processes. In this presentation, we discuss a hypothesis of super-Eddington accretion during the evolution of binary progenitors.

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2. Evolution of Neutron Star Binaries

Lee et al. [13] worked out the evolution of soft X-ray transient sources, i.e., black holes in binaries with main sequence or more-evolved companions. Based on the common envelope evolution, they estimated masses and spins of black holes at the time of black hole formation and found a correlation between the black hole’s mass and binary’s orbital period. Their predictions on black hole spins were confirmed by Shafee et al. [14] and McClintock et al. [15]. Moreno M´endez et al. [16] further discussed the consequences of black hole spins in soft X-ray transient sources to gamma-ray bursts and hypernovae. Based on the success of the evolution of black hole binaries, Lee and Cho [17] applied the same common envelope evolution [13] to the evolution of neutron star binaries. The key ingredient in their scenario is the super-Eddington accretion during the common envelope evolution.

In a spherical accretion, the Eddington luminosity is the maximum luminosity at which radiation pressure balances with the gravitational force. The main source of an accreting star’s luminosity is the gravitational energy of accreting material. The Eddington accretion rate is the mass accretion rate with 100% conversion efficiency from the gravitational energy to the luminosity. For a typical accreting star, the Eddington accretion rate is considered to be the upper limit of the mass accretion rate. However, in the case of a core collapsed supernova, a neutron star is formed in a time scale of minutes with hyper-Eddington accretion rate, reaching $10^8$ times of the Eddington accretion rate. If the Eddington accretion limit is hold, neutron stars cannot be formed from core collapsed supernovae. The hypothesis of super-Eddington accretion with an accretion rate of $10 \sim 100$ times of the standard Eddington accretion rate, have been discussed in the literature [18] and it is considered to be the origin of some of ultraluminous X-ray sources [19]. In this work, we assume that the super-Eddington accretion is hold during the common envelope phase in which the primary (first-born) neutron star spirals into the expanding envelope of a companion star [17, 20].

In order to understand the distribution of neutron star mass for a binary population, one has to take into account the evolution of neutron star binary progenitors [17, 20]. Since we are interested in neutron star binaries, we only consider a case in which the mass of more massive progenitor in a binary is large enough to produce a neutron star at the end of its evolution. Depending on the mass of the less massive progenitor, the secondary becomes either a neutron star or a white dwarf. The key property in this evolution is the initial mass difference $\Delta M$ between two progenitors in a binary. In this work, we assume that two progenitors are formed more or less at the same time in a given galaxy. One can consider a few simple cases for the comparison of different evolution processes.

- Case 1: $\Delta M \ll 4\%$
  
  When the mass difference is very small, two progenitors go into H-shell and He-shell burning at the same time such that two neutron stars are formed almost simultaneously and there is no time for the extra accretion. The Fe core masses of evolving giants at the final stage determine the final masses of neutron stars. Brown et al. [21] argued that the Fe core masses of giants in close binaries never grow beyond $1.5M_\odot$ because most of the H envelope is expelled during the common envelope phase and the giant evolves without H envelope at the later stage. The reduction in the gravitational force due to the absence of H envelope results in the less massive Fe cores compared to single star evolution. In this case, the final masses of neutron stars are less than $1.5M_\odot$ mainly because of the Fe core masses, independently of neutron star equations of state.

- Case 2: $\Delta M \leq 4\%$
  
  If the mass difference is not negligible even though $\Delta M \leq 4\%$, the secondary companion is already in H-shell burning stage when the primary neutron star is formed [17]. There is no time for the accretion during H-shell burning stage and the neutron star can accrete
only at the He-shell burning stage. In this case, the primary neutron star can accrete up to $0.2M_\odot$ only during the He-shell burning stage.

- **Case 3: $\Delta M > 4\%$**

  When the mass difference is large enough, the more massive giant produces a neutron star while the less massive companion is still in main sequence. Even in this case, the Fe core mass of more massive giant in a close binary is still less than $1.5M_\odot$ because the H envelope is expelled during the common envelope phase. Hence the mass of the primary (first-born) neutron star is still less than $1.5M_\odot$ at birth. Now, the companion evolves into giant after the formation of the primary neutron star. In close binaries, the primary neutron star goes into the expanding envelope of the companion and has chances for the extra accretion after its formation. Lee and Cho [17] estimated that the primary neutron star can accrete up to $\sim 1M_\odot$. When the evolution is finished, the companion can also produce a compact star, i.e., a white dwarf or a neutron star.

The hypothesis of super-Eddington accretion depends on many other physical parameters such as spin of the progenitor, composition of the giant, etc. In this presentation, we mainly focus on the mass difference.

### 3. Mass Distribution in Neutron Star Binaries

The distribution of final masses of primary neutron stars in neutron star binaries are summarised in Fig. 1. In this figure, case 1 and 2 are indicated by a blue line and an arrows (NS-NS binaries) which are consistent with current observations ($\leq 1.5M_\odot$) of neutron star masses in double-neutron-star binaries. Case 3 is indicated by blue hatched area in the figure. Usually, the progenitor mass difference is larger than 4% for NS-WD binaries and the primary neutron star can accrete significant amount of material, reaching to $2M_\odot$. Since the masses of the progenitors of white dwarfs are less than $\sim 8M_\odot$. Observation of $2M_\odot$ neutron stars in NS-WD binaries is consistent with our estimation in Fig. 1.

The new feature in our approach is the possibility of a new class of neutron star binaries. For the binaries corresponding to the upper half part of Fig. 1, the final mass of the first-born neutron star is larger than $2M_\odot$ while the companion also produce a secondary neutron star. Depending on the neutron star equation of state, the first-born neutron star remains as a high-mass ($> 2M_\odot$) neutron star (HMNS) or collapses into a black hole.

**Figure 1.** Final masses of primary (first-born) neutron stars in neutron star binaries as a function of the progenitor mass of the companion. Note that $2M_\odot$ neutron stars are observed only in neutron star-white dwarf (NS-WD) binaries [6, 7] and well-measured masses in double-neutron-star (NS-NS) binaries are still less than $1.5M_\odot$ [5] as indicated in the figure. This figure is taken from Lee and Cho [17].
4. Implication to Gravitational Waves

There is no observational evidence on the existence of new class of neutron star binaries. If the maximum mass of a neutron star is close to $\sim 2M_\odot$, the primary neutron star in the new class collapses into a black hole. The chance of observing black hole-neutron star binaries as pulsar binaries is very low mainly because there is no recycled pulsar since the first-born neutron stars collapsed into black holes. If the maximum mass of neutron star is much higher than $2M_\odot$, e.g. $2.5M_\odot$, the primary neutron star will remain as HMNS even with super-Eddington accretion. The probability of observing HMNS-NS binaries as pulsar binaries is not easy to predict because it depends on many other physical parameter (e.g., population, magnetic field strength, spin, inner structure, beaming angle, etc.) which we didn’t include in the analysis. However, independently of whether the primary neutron stars remain as neutron stars or evolve into black holes, they are important sources of gravitational waves that can be detected by ground-based gravitational-wave observatories. Since the chirp mass depends on the total mass, in principle, one may be able to distinguish HMNS/BH-NS binaries from typical NS-NS binaries by detecting gravitational waves from these sources [22, 23].

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