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A NEW CLASS OF NEUTRON STAR BINARIES AND ITS IMPLICATIONS

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ABSTRACT

Recent discovery of $2M_\odot$ neutron stars in white dwarf-neutron star binaries, PSR J1614-2230 and PSR J0348+0432, has given strong constraints on the maximum mass of neutron stars. On the other hand, all well-measured neutron star masses in double neutron star binaries are still less than $1.5M_\odot$. These observations suggest that the neutron star masses in binaries may depend on the evolution process of neutron star binaries. In addition, recent works on LMXB (low-mass X-ray binaries) provides us the possibility of estimating the masses and radii of accreting neutron stars in LMXBs. In this talk, we discuss the implications of recent neutron star observations to the neutron star equation of states and the related astrophysical problems. For the evolution of neutron star binaries, we also discuss the possibilities of super-Eddington accretion onto the primary neutron stars.

Key words: neutron star: black hole: super-Eddington accretion: binary evolution

1. MAXIMUM MASS OF NEUTRON STARS

Neutron stars are the best astrophysical compact object with which the physics of dense matter can be tested. The central density of a neutron star is expected to reach several times the normal nuclear matter density, $\rho_0 \approx 2.3 \times 10^{17}$ kg m^{-3}. However, since one cannot directly observe the inner part of neutron star, the macroscopic properties, such as mass and radius of neutron star are mainly considered when testing neutron star structure.

Masses of observed neutron stars in various types of neutron star binaries are estimated as briefly summarized below (Prakash, 2013).

Double neutron star binaries: The most accurate mass measurements of neutron stars are done in double neutron star binaries mainly due to the fact that the radius of neutron star is much smaller than the orbital distance. All well-measured neutron star masses are below $1.5M_\odot$, consistent with soft neutron star equations of states.

White dwarf-neutron star binaries: $2M_\odot$ neutron stars are observed in white dwarf-neutron star binaries, PSR J1614-2230 and PSR J0348+0432 (Demorest et al., 2010; Antoniadis et al., 2013). These observations ruled out many soft equations of states with which maximum neutron star masses are less than the observed neutron star masses.

X-ray/Optical binaries: In these binaries, X-rays are generated from the accreting neutron stars and the companion stars were observed by optical telescopes. Since the radius of the companion star is comparable to the orbital separation, the mass estimation of neutron star is quite uncertain. Even though high-mass ($> 2M_\odot$) neutron stars have been reported in these binaries, they are not considered to be evidence of the existence of high-mass neutron stars.

Other types of neutron star binaries: Neutron star binaries with main sequence or brown dwarf companions have been observed. However, the mass estimations in these binaries are still too uncertain to give any firm constraints to the maximum mass of neutron stars.

Based on these observations, especially the mass measurements in white dwarf-neutron star binaries, the maximum mass of neutron stars is believed to be bigger than $2M_\odot$. In this talk, following the argument of Lee & Cho (2014), we would like to discuss why all well-measured neutron star masses in double neutron star binaries are less than $1.5M_\odot$ while $2M_\odot$ neutron stars are observed in white dwarf-neutron star binaries. We suggest the possibility of a new class of neutron star binary with a $1.5M_\odot$ neutron star and a high-mass ($> 2M_\odot$) companion (neutron star or black hole) as a result of super-Eddington accretion in the evolution of binary progenitors.

2. SUPER-EDDINGTON ACCRETION IN THE EVOLUTION OF NEUTRON STAR BINARY PROGENITORS

Eddington luminosity is determined by the condition that the thermal photon pressure balances with the gravitational force acting on the accreting material in the uniform spherical accretion. For uniform spherical accretion onto a neutron star, it becomes

$$L_{\rm Edd} \approx 1.3 \times 10^{38} \frac{M_{\rm NS}}{M_\odot} {\rm erg~s^{-1}} \quad (1)$$

where $M_{\rm NS}$ is the neutron star mass (Lee & Cho, 2014). The Eddington luminosity can be connected to the mass accretion rate with an efficiency η

$$L_{\rm Edd} = \eta \dot{M}_{\rm NS} c^2. \quad (2)$$

An Eddington limit of $\dot{M}_{\rm Edd}$ corresponds to a mass accretion rate with $\eta = 1$. Our super-Eddington accretion corresponds to the case where $\dot{M} \geq 10^3 \dot{M}_{\rm Edd}$. Super-Eddington accretion can happen during the evolution of neutron star binary progenitors as we discuss below. For a black hole, if the accretion rate is bigger than $10^4 \dot{M}_{\rm Edd}$, the accreted material can fall into the black hole. In this case, thermal neutrinos can take the energy and pressure out of the system, allowing super-Eddington accretion. However, for a neutron star, whether the accreted material will be expelled or absorbed by the neutron star (increasing the neutron star mass as a result) is still an open question (Brown et al., 2000). In this work, we assume that super-Eddington accretion works in the evolution of neutron star binaries.

The lifetime of a massive star is approximately given by

$$\tau \propto \frac{1}{(M_{\rm ZAMS})^{2.5}} \quad (3)$$

where $M_{\rm ZAMS}$ is the zero age main sequence (ZAMS) mass of a massive star. A massive star spends about 90% of its lifetime on the main sequence and then expands in radius in the giant stage in the hydrogen shell burning phase. Depending on the mass, at the final stage before the core collapse (during the final 1% of its lifetime), a massive star can reach the super-giant stage in the He shell burning phase. The expansion of massive stars has a strong impact on the evolution of binary stars. A significant amount of the hydrogen envelope of an expanding giant can be expelled due to binary interaction in the common envelope phase. As a result, the inner core of the giant evolves without a hydrogen envelope, producing a low-mass Fe core before the core collapse. Brown et al. (2001) discussed how the masses of fresh neutron stars in close binaries cannot exceed $1.5M_\odot$ due to the binary evolution, independent of neutron star equations of states. Based on this work, we assume that the masses of fresh neutron stars born in close binaries are less than $1.5M_\odot$. When the primary (first-born) neutron star is formed, the companion (initially less massive) star is still in an earlier evolution stage.

We discuss the implications of super-Eddington accretion for three different binary types, mainly focusing on the progenitor lifetime difference $\Delta\tau$ which is mainly caused by the original mass difference $\Delta M_{\rm ZAMS}$. Below, we only consider a neutron star binary progenitor in which more massive star evolves into a neutron star. Note that $\tau_{\rm NS,prog}$ indicates the lifetime of the primary neutron star progenitor until the core collapse.

Case A: $\Delta\tau/\tau_{\rm NS,prog} < 1\%$

In this case, both stars in a binary evolve at nearly the same time. The hydrogen envelopes of both stars can be removed during the common envelope phase when they go through the giant and super-giant stages. The cores of both stars will evolve without hydrogen envelope and the resulting Fe cores will collapse into neutron stars nearly at the same time, forming a typical double neutron star binary. Since both progenitors evolves without a hydrogen envelope (Brown et al., 2001), the resulting neutron star masses will not exceed $1.5M_\odot$. This expectation is consistent with the current observation of double neutron star binaries, in which all well-measured neutron star masses are less than $1.5M_\odot$.

Case B: $1\% < \Delta\tau/\tau_{\rm NS,prog} < 10\%$

In this case, the giant phase of two stars in a binary overlap and significant amounts of hydrogen envelope can be removed in the common envelope phase. When the primary neutron star is formed, the companion hasn't gone through the super-giant stage yet. The mass of the primary neutron star cannot exceed $1.5M_\odot$ because the core of the progenitor evolves without a hydrogen envelope. Later, the companion will go through the super-giant stage and expand in radius. As a result, the primary neutron star can go through the expanding envelope of a giant. At this last stage, some material will be accreted onto the primary neutron star. Lee & Cho (2014) estimated the accreted amount to be less than $0.2M_\odot$. This estimation can explain the small mass differences in the observed double neutron star binaries (Prakash, 2013).

Case C: $\Delta\tau/\tau_{\rm NS,prog} > 10\%$

In this case, when the primary neutron star is formed the companion is still in the main sequence stage. The mass of the primary neutron star is expected to be less than $1.5M_\odot$ because the progenitor will lose significant amounts of its hydrogen envelope due to interaction with main sequence companion. When the companion goes through the giant and super-giant stage, the primary neutron star can go through the expanding envelope and can accrete significant amounts of material, up to $0.9M_\odot$ (Lee & Cho, 2014). The observed white dwarf-neutron star binaries correspond to this case because the lifetime difference between two stars in a binary is quite large due to the ZAMS mass difference.

3. NEW CLASS OF NEUTRON STAR BINARIES

In Fig. 1, the final masses of primary neutron stars are summarised as a function of the progenitor mass of companion stars (Lee & Cho, 2014). The distribution of observed double neutron star binaries in Case A and

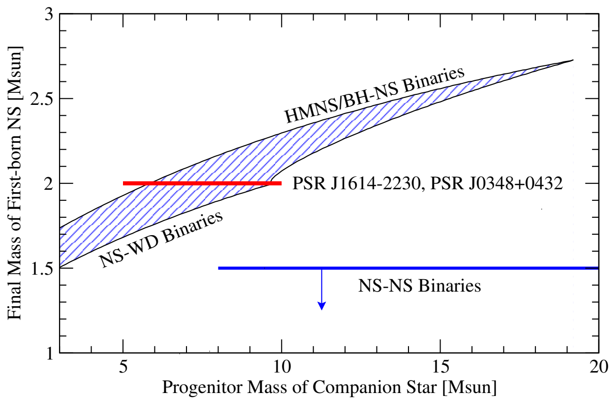

Figure 1. Mass distribution of neutron star binaries, from Lee & Cho (2014).

B are marked by the horizontal blue line and downward arrow in the lower right part. As mentioned in the previous section, this expectation is consistent with the current observation of double neutron star binaries (Prakash, 2013). Case C corresponds to the hatched area in Fig. 1. Note that two $2M_\odot$ neutron stars in white dwarf-neutron star binaries, marked by a horizontal red bar in the figure, are consistent with our estimation.

A new class of neutron star binaries are indicated in the upper right part in Fig. 1. This class corresponds to Case C in which both stars in a binary are massive enough to produce neutron stars. Depending on the maximum mass of neutron stars, the primary neutron star will remain a high-mass neutron star (HMNS) or collapse into a black hole, while the secondary neutron star is a typical neutron star with mass less than $1.5M_\odot$. The hatched area roughly corresponds to the relative probability. Hence, we expect a significant fraction of neutron star binaries in this new class, comparable to that of white dwarf-neutron star binaries.

Whether this new class of neutron star binaries really exists or not is an open question, as there is no observational evidence. If the primary neutron star collapses into a black hole, the chance of observing the new binary class is very low because there is no recycled pulsar. If the primary neutron star remains a high-mass neutron star, the chance of observation is much greated because it can be a recycled pulsar (longer pulsar lifetime) with larger beaming angle compared to that of a fresh neutron star.

4. PROSPECTS

The existence of the new class of neutron star binaries strongly depends on the super-Eddington accretion. For SN1987A, since the neutron star was formed as a result of Fe core collapse on the time scale of minutes, it is clear that the super-Eddington accretion works at the time of neutron star formation (Brown et al., 2000). In this case the accretion rate reaches $\sim 10^8 \dot{M}_{\rm Edd}$ and the temperature reaches $\sim$ 40 MeV. Since thermal neutrino contribution dominates compared to that of thermal photons at a temperature much higher than 1 MeV, weakly interacting neutrons are responsible for the pressure reduction and the resulting neutron star formation. However, in our case, the accretion rate is $10^3 - 10^4 \dot{M}_{\rm Edd}$, and the temperature is only around 1 MeV. The possibility of super-Eddington accretion in this marginal condition has to be clarified by future work.

The possibility of measuring both masses and radii of neutron stars in low-mass X-ray binaries (LMXB) have been discussed in many recent works (Güber et al., 2012a,b; Steiner et al., 2010; Lattimer & Steiner, 2014; Li et al., 2014). Since these estimations are based on Monte Carlo simulations, it's too early to make any firm conclusions. However, in the near future, LMXBs will be able to provide very important clues on the neutron star equations of states. Even though the accretion rate in LMXB is only $\mathcal{O}(\dot{M}_{\rm Edd})$, much smaller than the super-Eddington rate which is required for the new class of neutron star binaries, the LMXB is a good astrophysical object to study the accretion process in neutron star binaries.

If the new class of neutron stars exists, it can provide a significant contribution to gravitational wave observations (Harry, 2010; Aasi et al., 2013). In principle, due to the difference in chirp masses, the detection of gravitational waves will be able to distinguish the new class of neutron star binaries from the typical double neutron star binaries that are observed.

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