Double Neutron Star Binaries: Implications for LIGO

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I. INTRODUCTION

The observational evidence as well as the calculational basis, is strong that neutron star (NS) binaries evolve from double helium stars, avoiding the common envelope evolution of the standard scenario [1]. (A helium star results in a giant when the hydrogen envelope is lifted off - in binary evolution by being transferred to the less massive giant in the binary.) In the standard scenario of binary NS formation after the more massive giant transfers its hydrogen envelope to the companion giant, the remaining helium star burns and then explodes into a NS. In about half the cases the binary is not disrupted in the explosion. The NS waits until the remaining giant evolves (and expands) in red giant following its main sequence hydrogen burning. Once the envelope is close enough to the NS, the latter couples to it hydrodynamically through gravity. Some of the material in the envelope is accreted onto the NS, although most flies by in the wake, being heated in the process, and is lost into space. The energy to expel the matter comes from the drop in potential energy as the orbit of the NS tightens. Formulas for the tightening and the amount of mass accreted by the NS were given by Bethe & Brown [2].

Chevalier first estimated that in common envelope evolution the NS would accrete sufficient matter to evolve into a black hole (BH) [3]. Brown suggested the double helium star scenario, in order to save the first born NS [4]. In this scenario, mass exchange of the hydrogen envelope takes place while both stars burn helium. There is not sufficient time for this mass to be accepted by either star [5] and it is lost into space, leaving a binary of helium stars. The two giant progenitors must have main sequence masses within ~ 4% of each other, in order to burn helium at the same time, a highly restrictive requirement. However, the observations of nearly equal masses of the two NS’s within the binaries give support to this scenario, as we show.

The above scenario for binary evolution was made quantitative by Bethe & Brown [2] who calculated that in a typical case, the NS would accrete ~ 1M⊙, taking it into an ~ 2.4M⊙ low mass black hole (LMBH), similar to the BH we believe resulted from SN1987A, although somewhat more massive than the latter. Thus, if the NS had to go through common envelope evolution in a hydrogen envelope of ≥ 10M⊙ from the giant, it would accrete sufficient matter to go into a LMBH. Therefore, when the giant evolved into a helium star, which later exploded into a NS, a LMBH-NS binary would result provided the system was not broken up in the explosion. (About 50% of the time the system survives the explosion.) In this work, we extend Bethe & Brown [2] work to include the hypercritical accretion during both red-giant and super-giant stages of the second star which evolves later.

The above scenario was estimated to take place 10 times more frequently than binary NS formation which required the two stars to burn helium at the same time, and, because of the greater mass of the BH, the mergings of binaries with LMBH to be twice as likely to be seen as those with only NS’s. This is the origin of the factor 20 enhancement of gravitational mergers to be observed at LIGO, over the number from binary NS’s alone.
II. DOUBLE NEUTRON STARS

We list in Table I the 5 observed NS binaries with measured masses. Note that they are consistent with our preferred maximum mass of neutron star $M_{NS}^{max} = 1.5 \, M_\odot$ due to the kaon condensation \[12\]. In addition, the two NS’s in a given binary have very nearly the same mass, as would follow from the double helium star scenario. As we discuss in next section.

| Object          | Mass ($M_\odot$) | Companion Mass ($M_\odot$) | Refs. |
|-----------------|------------------|---------------------------|-------|
| J1518+4904      | $1.56^{+0.14}_{-0.44}$ | $1.05^{+0.45}_{-0.11}$       | \[6, 7\] |
| B1534+12        | $1.33^{+0.0010}_{-0.0010}$ | $1.345^{+0.0010}_{-0.0010}$ | \[8\] |
| B1913+16        | $1.44^{+0.0003}_{-0.0003}$ | $1.387^{+0.0003}_{-0.0003}$ | \[9\] |
| B2127+11C       | $1.34^{+0.040}_{-0.040}$  | $1.363^{+0.040}_{-0.040}$    | \[10\] |
| J0737−3039B     | $1.33^{+0.005}_{-0.005}$  | $1.259^{+0.005}_{-0.005}$    | \[11\] |

The very nearly equal masses of pulsar and companion in B1534+12 and B2127+11C is remarkable. We show below that B1913+16 comes from a region of giant progenitors in which the masses could easily be as different as they are. The uncertainties in J1518+4904 are great enough that the masses could well be equal. The the double pulsar J0737−3039A and J0737−3039B were probably very nearly the same before a common envelope evolution in which the first formed NS J0737−3039A accreted matter from the evolving (expanding) helium star progenitor of J0737−3039B (Case 2 in next section) in the scenario of Dewi & van den Heuvel \[13\].

III. FATE OF COMMON ENVELOPE EVOLUTION

In the standard scenario the first-born NS would go through common envelope evolution with a giant which must have ZAMS mass at least $\sim 10 \, M_\odot$, if it is to later end up as a NS \[1\]. In Fig. 1 three typical cases of binary NS evolution are summarized. In these estimates, we assumed that both the birth rate and the life time are proportional to $M_{ZAMS}^{2.5}$. With these assumption, the 4% difference in the ZAMS mass corresponds to 10% difference in the life time. Hence the population probability for the ZAMS masses to be within 4% difference in mass is about 10%.

- **Case 1:** [90% probability] This corresponds to the case with initial mass difference $\Delta M_{ZAMS} > 4\%$, with life time difference $\Delta T > 10\%$. The first born NS can accrete both in red giant and in super giant stage of the second star which evolves later. Due to the hypercritical accretion, $\Delta M = 0.9 \, M_\odot$ (in giant stage, $0.2 \, M_\odot$ in supergiant stage) can be accreted to the first-born NS. The accreted mass $\Delta M$ was estimated using the formula given in the Appendix of Belczynski et al. \[14\].

- **Case 2:** [10% probability] This corresponds to the case with initial mass difference $\Delta M_{ZAMS} < 4\%$, but not close enough to burn the helium at the same time. $\Delta M = 0.2 \, M_\odot$ can be accreted to the first-born NS during the supergiant stage of the second star.

- **Case 3:** [< 1% probability] This corresponds to the case in which the initial mass differences are so close to burn the helium at the same time. Nothing can be accreted because two NS’s are formed almost at the same time.

As in Fig. 2 if the NS’s are to be born with initial masses between $1.2 \, M_\odot$ and $1.5 \, M_\odot$ as seen in double
NS’s, the first-born NS’s in Case 1 result in $2 M_{\odot}$ each other in ZAMS mass. In fact, the binaries with progenitors of the binary NS having to be within 4% of the maximum mass of NS $M_{\text{max}} = 1.5 M_{\odot}$ is more than 90%. We believe that they must have gone into LMBH’s.

Since we don’t see pulsars with such high masses, we believe the case for such a massive NS to only be settled by the hypercritical accretion. Similarly, those in Case 2 result in $1 M_{\odot}$ pulsar mass.  

Our argument in this note alone does not exclude NS’s in the mass range up to $2.1 M_{\odot}$, but as mentioned earlier the Bethe & Brown [16] argument that the maximum mass of the NS in 1987A, which we believe went into a LMBH, of $1.57 M_{\odot}$ further constrain the maximum NS mass, if our belief is correct. In Fig. 2 we draw the expected maximum mass of NS $M_{\text{max}} = 1.5 M_{\odot}$ which was estimated from kaon condensation [12]. Note that the probability of having higher mass ($> 1.5 M_{\odot}$) companion is more than 90% while there is no observations on such systems. We believe that this indicates that those NS’s with masses $> 1.5 M_{\odot}$ went into black holes after common envelope evolution.

The NS mass in the helium white-dwarf, NS binary J0751−1807 is measured from the period change due to gravitational wave emission. The companion white dwarf mass is constrained by a marginal detection of Shapiro delay. Although the observational indication of high NS mass is strong, this mass would be brought down with the 4/3 power of white dwarf mass if the latter were increased, and still fit the same period change. Thus, we believe the case for such a massive NS to only be settled with a sufficiently accurate measurement of the Shapiro decay which pins down the white dwarf mass. It should be noted that just in the evolution of NS, white-dwarf binaries there is ample possibility for substantial accretion from the evolving progenitor of the white-dwarf, so these binaries are the place to look if one wants to find a high-mass NS.

Why haven’t we seen any LMBH-NS binaries? Van den Heuvel [17, 18] has pointed out that NS’s form with strong magnetic fields $10^{12}$ to $5 \times 10^{12}$ gauss, and spin down in a time

$$\tau_{\text{sd}} \sim 5 \times 10^6 \text{ years} \quad (1)$$

In Table II, the estimated LIGO detection rates are summarized. For completeness we added the contribution from BH-BH mergers obtained by Portegies Zwart & McMillan [20]. They have suggested a large number of gravitational mergings of high-mass BH’s ejected from globular clusters. Their predictions should be tested relatively early in the LIGO development.
TABLE II: Predicted LIGO Detection Rates ($\text{yr}^{-1}$).

| Binary Type | LIGO I LIGO II Chirp Masses ($M_\odot$) |
|-------------|--------------------------------------|
| NS-NS†      | 0.0348 187 1.0 - 1.3                 |
| BH-NS††     | 0.696 3740 1.3 - 2.7                 |
| BH-BH**     | 0.58 2450 $\sim$ 6                  |
| Total       | 1.31 6377                             |

† NS-NS detection rates are from Kalogera et al. [21]. †† BH-NS detection rates are obtained by multiplying factor 20 to NS-NS detection rates from Bethe & Brown [2]. ** BH-BH detection rates are from Portegies Zwart & McMillan [20] with the modification of BH mass $7M_\odot$.

V. CONCLUSION

The discovery of the double pulsar increased estimated rate for gravitational merging by a factor of 6–7 over that of Kim et al. [22]. In addition to these effects, we find 10 times more LMBH-NS binary mergings, with larger chirp mass than NS-NS binaries because of the accretion in forming the BH so that these mergings multiply the binary NS ones by a factor of 20. According to our estimates, LIGO I would be able to detect one merging per year.

The Chirp mass, which will be detected with an estimated accuracy of $\sim 0.002M_\odot$

$$M_{\text{chirp}} = \mu^{3/5} M^{2/5} = \frac{(M_1M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$ (2)

would be 1.22$M_\odot$ for the merging of two 1.4$M_\odot$ NS’s, for the merging of the least massive 2.1$M_\odot$ BH, resulting from the common envelope evolution of a 1.4$M_\odot$ NS in a ZAMS 10$M_\odot$ progenitor companion the chirp mass would be 1.49$M_\odot$. Estimated Chirp masses are summarized in Table II. We may have to wait for LIGO which will be able to measure “chirp” masses quite accurately. The chirp mass of a NS binary should concentrate near 1.2$M_\odot$, whereas the LMBH-NS systems should have a chirp mass of $> 1.4M_\odot$, and there should be $\sim 20$ times more of the latter.

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