And Don’t Forget The Black Holes

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Abstract

The discovery of the highly relativistic neutron star (NS) binary (in which both NS's are pulsars) not only increases the estimated merging rate for the two NS's by a large factor, but also adds the missing link in the double helium star model of binary NS evolution. This model gives \( \sim 20 \) times more gravitational merging of low-mass black-hole (LMBH), NS binaries than binary NS's, whatever the rate for the latter is.

The recent discovery of Burgay et al. \cite{1} of the double pulsar PSR J0737–3039A and PSR J0737–3039B \cite{2} is very interesting for many reasons. One that is not so obvious is that it involves just about the lowest possible mass main sequence giants as progenitors, which have not been encountered in the evolution of the other binary NS's, even though there are 20 to 30 times more of them, as we show below.

The observational evidence is strong that NS binaries evolve from double helium stars, avoiding the common envelope evolution of the standard scenario.
(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. In the system in which the NS is at rest, it sees the envelope matter coming at it. Some of it 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 [4].

Chevalier [5] first estimated that in the common envelope evolution the NS would accrete sufficient matter to evolve into a black hole (BH). This was made quantitative by Bethe & Brown [4] who calculated that in a typical case, the NS would accrete $\sim 1M_\odot$, taking it into an $\sim 2.4M_\odot$ low mass black hole (LMBH), similar to the BH we believe resulted from SN1987A.

Thus, if the NS had to go through common envelope evolution in a hydrogen envelope of $\gtrsim 10M_\odot$ 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.) The above scenario was estimated [4] 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.

We review the known NS binaries and show that they are consistent with the two NS’s in a given binary having very nearly the same mass, as would follow from the double helium star scenario.

We list in Table 1 the 5 observed NS binaries with measured masses. The very nearly equal masses of pulsar and companion in 1534+12 and 2127+11C is remarkable. We show below that 1913+16 comes from a region of giant progenitors in which the masses could easily be as different as they are. The uncertainties in 1518+49 are great enough that the masses could well be equal. The main point in our letter is to show that the masses in 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
Table 1
5 observed neutron star binaries with measured masses.

| Object          | Mass ($M_\odot$)     | Object          | Mass ($M_\odot$)     | Refs. |
|-----------------|----------------------|-----------------|----------------------|-------|
| J1518+4904      | 1.56$^{+0.13}_{-0.44}$ | J1518+4904 companion | 1.05$^{+0.45}_{-0.11}$ | [6,7] |
| B1534+12        | 1.3332$^{+0.0010}_{-0.0010}$ | B1534+12 companion | 1.3452$^{+0.0010}_{-0.0010}$ | [8]   |
| B1913+16        | 1.4408$^{+0.00003}_{-0.00003}$ | B1913+16 companion | 1.3873$^{+0.00003}_{-0.00003}$ | [9]   |
| B2127+11C       | 1.349$^{+0.040}_{-0.040}$ | B2127+11C companion | 1.363$^{+0.00003}_{-0.00003}$ | [10]  |
| J0737–3039A     | 1.337$^{+0.005}_{-0.005}$ | J0737–3039B      | 1.250$^{+0.005}_{-0.005}$ | [2]   |

J0737–3039A accreted matter from the evolving (expanding) helium star progenitor of J0737–3039B in the scenario of Dewi & van den Heuvel [11].

Since the helium burning in the giant is an order of magnitude shorter than the hydrogen burning in time, for two giants to burn helium at the same time they have to be very nearly equal in mass, within 4%. Thus the binary neutron star scenario is highly selective. If they do burn helium at the same time, they can go through common envelope evolution at this time. The hydrogen envelope of the slightly more massive giant expands in red giant and is transferred to the less massive giant, which in turn evolves in red giant. The time for these evolutions is so short that the helium stars are unable to accept the hydrogen which is lost into space [12] so that the final neutron stars are also close in mass. Each of the helium stars will explode, going into a NS. In about half of each explosion the binary is disrupted, but in about 1/4 of the cases it is preserved and a double neutron star results.

Bethe & Pizzochero [13] used for SN 1987A a schematic but realistic treatment of the radiative transfer problem which allowed them to follow the position in mass of the photosphere as a function of time. They showed that the observations determine uniquely the kinetic energy of the envelope once the mass is known. From the envelope masses considered, the range of energies was 1 to $1.4 \times 10^{51}$ ergs. Using the fact that the pressure following the supernova shock is radiation dominated, Bethe & Brown [14] showed from the known value of 0.075$M_\odot$ of $^{56}$Ni production, an upper limit on the gravitational mass of 1.56$M_\odot$ could be obtained. This is just the calculated Fe core mass for the known 18$M_\odot$ progenitor of 1987A.

Calculations of Woosley are shown in Table 3 of Brown et al. [15] where the amounts of fallback material from distance of 3500 km and 4500 km are given. The fallback simply cancels the gravitational binding energy from the Fe core evolving into a NS. Since the density of matter is thin at the estimated 4000 km bifurcation point, this cancellation is relatively insensitive to the precise point of bifurcation. Thus, we can use the Fe core mass as the mass of the NS.

In Fig. 1, we show both recent and older calculations of Fe core masses. The
Fig. 1. Fe core masses for a grid of stellar masses. See text for explanation.

filled circles and crosses correspond to core masses at the time of iron core implosion for a finely spaced grid of stellar masses [16]. The circles were calculated with the Woosley & Weaver code [17], whereas the crosses employ the vastly improved rates for electron capture and beta decay [18].

A rapid increase in Fe core masses occurs at $M_{\text{giant}} \sim 18M_\odot$, just the mass of the progenitor of 1987A which we believe went into a LMBH. The Burrows & Woosley [19] evolution of 1913+16 took place in terms of $M_{\text{giant}} \sim 20M_\odot$. (In this evolution the Fe core mass will be slightly less than given in Fig. 1 because the mass transfer in binary evolution removes the hydrogen envelope, leaving a “naked” helium star. The wind loss from naked helium stars is great.) Now one can see that the difference in masses between, 19 and $20M_\odot$ giants is greater than $0.1M_\odot$, so that the $0.05M_\odot$ difference in masses between the pulsar and its companion in 1913+16 can easily be furnished out of the calculated Fe core masses.

There is some tendency for the Fe core masses to decrease from $M_{\text{giant}}$ of 15 to $16M_\odot$, where we would estimate 1534+12 and its companion to come from.
(The companion is slightly more massive than the pulsar.)

The pulsar and companion in the double pulsar should come from \( M_{\text{giant}} \sim 10M_\odot \), at the 1.25\( M_\odot \) of the present J0737–3039A. Following Dewi & van den Heuvel [11], the first pulsar formed is increased in mass with mass transfer from the companion when the latter is a helium star. Low-mass helium stars, 2.3 to 3.3\( M_\odot \) have to burn hotter than higher mass ones because of the greater energy loss from their surfaces. In reaction to this, they expand in a helium red giant phase. The pulsar now goes through a common envelope stage with the envelope of the helium star once the latter expands far enough to make contact.

As noted, the NS accretes some of the matter and most is expelled in the wake. Thus, from the coefficient of dynamical friction \( c_d = 2 \ln(b_{\text{max}}/b_{\text{min}}) \simeq 6 \) [20], it is found [4] that

\[
\frac{M_{\text{pulsar},f}}{M_{\text{pulsar},i}} = \left( \frac{M_{\text{He},f}/a_f}{M_{\text{He},i}/a_i} \right)^{1/5}.
\]

We take \( M_{\text{He},i} = 2.5M_\odot \) and \( M_{\text{He},f} = 1.5M_\odot \). Now the orbit in the double pulsar is decreased a factor of \( \sim 3.7^{2/3} \) from that of the binary NS. (The average of periods of 1913+16 and 1534+12 is 0.37 days, whereas that of the double pulsar is 0.1 day.) The \( 2/3 \) exponent is the Kepler relation between orbital period and radius, and we then find

\[
\frac{M_{\text{pulsar},f}}{M_{\text{pulsar},i}} = 1.075
\]

which gives the correct 1.34\( M_\odot \) for J0737–3039B given \( M_{\text{pulsar},i} = 1.25M_\odot \), the same as the unrecycled neutron star. The 1.5\( M_\odot \) He star will burn into the unrecycled pulsar, with mass decreased \( \sim 15\% \) by the general relativity binding energy.

Therefore, in the double pulsar, the masses of the two giant progenitors must be very close, since the two NS’s would have had nearly equal masses (as in 1534+12), except for the mass transfer during the helium red giant stage.

The Salpeter mass distribution of giants gives the relative number proportional to \((M_{\text{giant}})^{-2.35}\), so for two equal mass giants, the distribution goes as \((M_{\text{giant}})^{-4.7}\). Thus, the probability of two 10\( M_\odot \) giants is 26 times greater than that of two 20\( M_\odot \) giants, as would be progenitors of 1913+16. Burgay et al. [1] estimated the ratio \( N_{0737}/N_{1913} \) to peak at \( \sim 6 \), whereas Dewi & van den Heuvel [11] estimate that there are many of the PSR J0739-like systems not seen because of their weak signals compared with those from 1913+16, possi-
bly giving a factor $\sim 30$ in mergings. Our estimate based on the large number of low-mass giant progenitors confirms this.

With $\gtrsim 10 M_\odot$ hydrogen envelopes and a proportional tightening of the orbit in the common envelope evolution in the standard scenario, the Bethe & Brown result of accretion of $\sim 1 M_\odot$ onto the first NS seems reasonable. After only part of this is accreted, the neutron star, like in 1987A, goes into a black hole.

Why haven’t we seen any LMBH-NS binaries? Van den Heuvel [21,22] 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

$$\tau_{sd} \sim 5 \times 10^6 \text{ years}$$

and then disappear into the graveyard of NS’s. (The pulsation mechanism requires a minimum voltage from the polar cap, which can be obtained from $B_{12}/P_2 \sim 0.2$ with $B_{12} = B/10^{12} \text{G}$ and $P$ in seconds [22].) The relativistic binary PSR 1913+16 has a weaker field $B \simeq 2.5 \times 10^{10}$ gauss and therefore emits less energy in magnetic dipole radiation. Van den Heuvel estimates its spin-down time as $10^8$ yrs. There is thus a premium in observational time for lower magnetic fields, in that the pulsars can be seen for longer times.

Taam and van den Heuvel [23] found empirically that the magnetic field of a pulsar dropped roughly linearly with accreted mass. This accretion can take place from the companion in any stage of the evolution. A pulsar that has undergone accretion is said to have been “recycled”.

Now as mentioned, in 1913+16 the pulsar magnetic field is $\sim 2.5 \times 10^{10}$ gauss and in 1534+12 it is $\sim 10^{10}$ gauss. In J0737–3039A it is only $6.3 \times 10^9$ gauss. These “recycled pulsars” will be observable for $\gtrsim 100$ times longer than a “fresh” (unrecycled) pulsar.

The same holds for LMBH-NS binaries. The NS is certainly not recycled, so there is an about 1% chance of seeing one as the recycled pulsar in a binary NS. But we propose 10 times more of the LMBH’s than binary NS’s, of which we observe 5. Thus the total probability of seeing the LMBH binary should be about 50%. However, there may be additional reasons that the LMBH-NS binary is not observed. NS’s in binaries in which the nature of the companion star is unknown are observed. 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 $1.6 M_\odot$, and there should be $\sim 20$ times more of the latter.

In order to estimate the number of mergings per year for the LIGO we begin from the estimate of Kim et al. [24] and multiply by a factor of 26 to account for
the increase in this estimate by the large number of low-mass giant progenitors, neutron stars from two of these having been observed in the double pulsar. Additionally we multiply by the factor of 20 to include NS-LMBH binary mergings. This brings our estimate up to 0.5 to 3.6 mergings per year for the initial LIGO, and about 6000 times greater for the advanced LIGO.

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