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FURTHER EVIDENCE FOR THE BIMODAL DISTRIBUTION OF NEUTRON-STAR MASSES

J. Schwab[1,2], Ph. Podsiadlowski[3], and S. Rappaport[1]
[1] 37-602B, M.I.T., Department of Physics and Kavli Institute for Astrophysics and Space Research, 70 Vassar St., Cambridge, MA, 02139, USA;
sar@mit.edu, jschwab@mit.edu
[2] Department of Physics, University of California, 366 LeConte Hall, Berkeley, CA 94720, USA; jwschwab@berkeley.edu
[3] Department of Astrophysics, University of Oxford, Oxford OX1 3RH, UK; podsi@astro.ox.ac.uk

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ABSTRACT

We use a collection of 14 well-measured neutron-star masses to strengthen the case that a substantial fraction of these neutron stars were formed via electron-capture (e-capture) supernovae (SNe) as opposed to Fe core-collapse SNe. The e-capture SNe are characterized by lower resultant gravitational masses and smaller natal kicks, leading to lower orbital eccentricities when the e-capture SN has led to the formation of the second neutron star in a binary system. Based on the measured masses and eccentricities, we identify four neutron stars, which have a mean post-collapse gravitational mass of $\sim 1.25\ M_\odot$, as the product of e-capture SNe. We associate the remaining 10 neutron stars, which have a mean mass of $\sim 1.35\ M_\odot$, with Fe core-collapse SNe. If the e-capture SN occurs during the formation of the first neutron star, then this should substantially increase the formation probability for double neutron stars, given that more systems will remain bound with the smaller kicks. However, this does not appear to be the case for any of the observed systems and we discuss possible reasons for this.

Key words: stars: evolution – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Precise neutron-star mass determinations, coupled with a theoretical knowledge of the pre-collapse mass, can be used to test the neutron-star equation of state. Podsiadlowski et al. (2005) used the double pulsar system J0737−3039 for such a test. They inferred from the low mass ($1.249 \pm 0.001\ M_\odot$) of Pulsar B in this system, that it formed via an electron-capture (e-capture) supernova (SN), an inference first made by Podsiadlowski et al. (2004) and independently by van den Heuvel (2004). In addition to such uses, well-measured neutron-star masses are extremely helpful in understanding the formation scenarios of these objects.

In this work, we consider the entire sample of known neutron stars with well-measured masses. We find that the mass distribution is most compatible with the existence of two distinct populations, a higher-mass ($\sim 1.35\ M_\odot$) population and a lower-mass ($\sim 1.25\ M_\odot$) population. We interpret these two populations to be the result of distinct evolutionary formation scenarios: the low-mass population originates in e-capture SNe and has received low kicks, while the high-mass population is the result of iron core-collapse SNe.

In Section 2, we compare and contrast the two principal channels for the production of neutron stars: e-capture SNe and Fe core-collapse SNe. The current sample of 14 well-measured neutron stars is presented and discussed in Section 3; these all have mass uncertainties of $\lesssim 0.025\ M_\odot$. In Section 4, we perform some statistical tests which provide support for the hypothesis that there are two parent populations of pre-collapse core masses. We carry out a simple population synthesis study in Section 5 of the expected eccentricity distributions for e-capture and Fe core-collapse SNe, using their different anticipated core masses and natal kick speed distributions. In Section 6, we attempt to fit the observed systems with well determined neutron-star masses into the two principal evolutionary scenarios: the "standard" channel and the double-core channel. We summarize our results and draw some general conclusions in Section 7. In particular, we find that (1) a substantial fraction of neutron stars are formed in e-capture SNe and (2) there is evidence from our work that the double-core formation scenario is less unlikely than previously thought by most workers in the field.

2. EVOLUTIONARY HISTORY

Neutron stars are believed to form through two main evolutionary channels: iron core-collapse and e-capture SNe. The first occurs in a massive star when it has developed an iron core which exceeds the Chandrasekhar mass and no more nuclear burning can take place. The resulting mass of the neutron star depends not only on the neutron-star equation of state but also on the mass of the iron core and the maximum iron core mass for which a successful SN can occur. The latter depends on the details of the SN mechanism that are still not fully understood. If the iron core mass is too large, the explosion mechanism fails and the core collapses to a black hole. In what is presently the most popular paradigm of delayed neutrino-driven explosions (see, e.g., Mezzacappa et al. 2007; Janka et al. 2008), the explosion takes place when enough neutrino energy has been deposited in the gain region outside the proto-neutron star to overcome the binding energy of the remaining core, stop the accretion, and initiate an outflow. The characteristic energy of such a delayed explosion has to be of the order of the characteristic binding energy of the remaining core ($\sim 10^{51}$ ergs). Hence, successful iron core-collapse SNe are expected to have explosion energies close to this characteristic energy.

In contrast, an e-capture SN occurs in a very degenerate ONeMg core, long before an iron core has developed, and is triggered by the sudden capture of electrons onto Ne nuclei, taking away the hydrostatic support provided by the degenerate electrons (e.g., Nomoto 1984). This occurs at a characteristic density ($\sim 4.5 \times 10^9$ g cm^{-3}; Podsiadlowski et al. 2005), which in turn can be related to a critical pre-collapse mass for the ONeMg core of ∼1.37 $M_\odot$. Hence, an e-capture SN is expected to occur when a degenerate ONeMg core reaches this critical mass either by accretion from an envelope inside an asymptotic giant branch star (e.g., Siess 2007; Poelarends et al. 2008) or in a helium star (e.g., Nomoto 1987), by accretion from a companion star (so-called accretion-induced collapse; e.g., Nomoto & Kondo 1991), or as a consequence of the merger of two CO white dwarfs and the subsequent formation of an ONeMg core (e.g., Nomoto & Iben 1985). Since the collapse occurs at a characteristic ONeMg core mass, the resulting neutron-star mass is entirely determined by the equation of state and the amount of core material that is ejected in the SN.[4] The case of Pulsar B in the double pulsar system J0703−3039 suggests that this mass is close to 1.25 $M_\odot$ (Podsiadlowski et al. 2005). Furthermore, since essentially the whole core collapses to form a neutron star, the remaining envelope is relatively easy to eject, leading to a fainter SN with the ejection of very few heavy elements (see, e.g., Dessart et al. 2006; Kitaura et al. 2006). It has recently been argued that the large kicks most neutron stars receive at birth (Hobbs et al. 2005) are caused by an accretion shock instability that causes a wobbling of the core, imparting momentum in the process (e.g., Blondin & Mezzacappa 2006, 2007; Foglizzo et al. 2007; but see Fryer & Young 2007 for a more skeptical point of view). Since, in the case of an e-capture SN, the explosion occurs before these instabilities have time to grow, no large kick is expected for a neutron star formed through this channel.

The suggestion that e-capture SNe may produce low SN kicks and a distinct low-mass neutron-star population was first independently made by Podsiadlowski et al. (2004) and van den Heuvel (2004).[5] van den Heuvel (2004) specifically discussed this low-mass, low-kick population in the context of binary radio pulsars and used the then-current observations of several neutron star–neutron star binaries and a neutron star–white dwarf binary to argue that they formed via e-capture.

Table 1 summarizes the main differences in neutron-star and SN properties for these two channels. Note, in particular, that for neutron stars formed from iron core-collapse one expects a range of masses that is determined by the range of iron core masses in the progenitors that allows a successful explosion, while in the case of neutron stars from an e-capture SN one expects a fairly well-determined mass. Thus, the distribution of post-SN neutron-star masses directly constrains not only the equation of state but also the properties of successful SN explosions.

3. NEUTRON-STAR SAMPLE

There are 14 neutron stars which have masses known with an accuracy of better than ∼0.025 $M_\odot$. The majority of these (12) are from double neutron-star systems; two are in binary systems with suspected white dwarf companions. The properties of these systems are summarized in Table 2 (for references, see, e.g., Stairs 2008). A histogram of the measured gravitational masses is shown in the top panel of Figure 1.

The rapidly rotating pulsars have likely been spun up by the accretion of a small to modest amount of matter (0.001–0.07 $M_\odot$). We correct for this effect by subtracting the mass which would be necessary to spin up the star, treating it as a classical uniform-density sphere accreting from a disk that extends down to its surface. We have verified that for a range of plausible equations of state for neutron-star matter, more sophisticated treatments lead to accreted (gravitational) masses that differ from our simple model by less than ∼10% (see, e.g., Cook et al. 1994). The results are shown in the middle panel of Figure 1. Note the high degree of similarity of this histogram with that for the uncorrected masses; the maximum mass correction for any one neutron star is ∼0.07 $M_\odot$ (for J1909−3744). The corrections for the other neutron stars were less than ∼0.02 $M_\odot$.

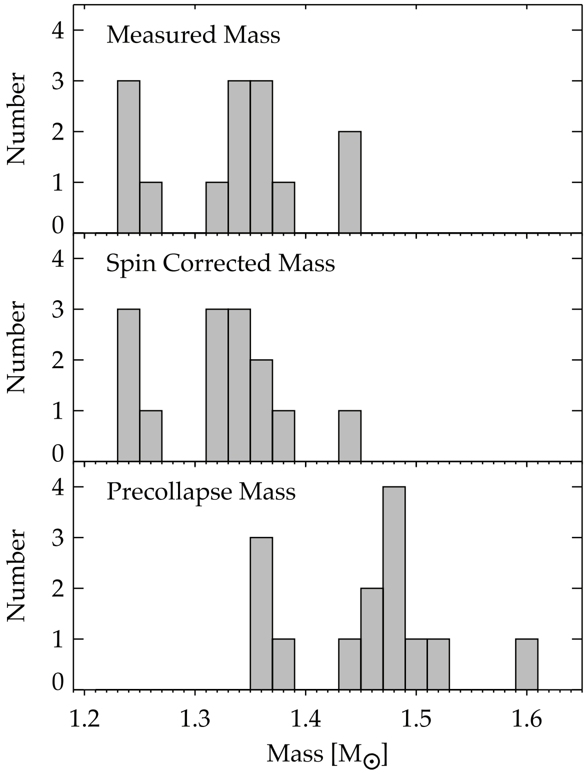

Figure 1. Mass histograms for the sample of 14 neutron stars. Top panel: the measured (gravitational) masses of the neutron stars. Middle panel: the masses of the neutron stars corrected for accretion as discussed in the text. Bottom panel: the pre-collapse (baryonic) masses of the neutron stars, based on one particular illustrative neutron-star equation of state.

Finally, we used a representative equation of state for neutron-star matter ("MPA," Müther, Prakash, & Ainsworth 1987) to translate the observed gravitational mass into a pre-collapse mass by calculating the baryonic mass corresponding to each gravitational mass. The results are shown in the bottom panel of Figure 1. In general, the pre-collapse masses are shifted upward by ∼0.13 $M_\odot$.

As the equation of state remains theoretically uncertain, we calculated the corrections for each of the equations of state collected in Lattimer & Prakash (2001). Within this collection, the correction to the mass of a 1.25 $M_\odot$ neutron star varied over the range 0.09–0.18 $M_\odot$. However, given the small range in mass considered (1.25–1.4 $M_\odot$), the choice of equation of state has little effect on the relative correction between any two systems within this range. The net result of choosing a different equation of state would be a systematic shift in the bottom panel of Figure 1, as opposed to any significant stretching or skewing.

One can see from Figure 1 that there are two apparent populations of neutron-star mass: one centered at ∼1.25 $M_\odot$ and one at ∼1.35 $M_\odot$ (measured, post-collapse mass). In terms of the

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[4] This ignores the role of rotation which may be important, in particular, in the case of an accretion- or merger-induced collapse.

[5] The latter author also suggested a third more massive population of neutron stars with masses around 1.85 $M_\odot$ from stars with an initial mass around 20 $M_\odot$.

Table 1
Comparison of Fe Core-collapse and e-capture SNe

Properties	Iron Core Collapse	e-capture SN
SN properties		
Explosion energy	$\sim 10^{51}$ ergs	$\lesssim 10^{50}$ ergs[a]
Ejecta	Rich in heavy elements (Fe, Si, O)	Few heavy elements
Neutron-star properties		
Masses	Range of masses	Characteristic mass $\simeq 1.25\ M_\odot$
Neutron-star kick	Large standard kick ($\sigma \simeq 265$ km s^{-1})[b]	Low kick
Binary properties		
Occurrence	Single or binaries	Preferentially in binaries[c]
Eccentricity	High	Low
Recycled pulsar spin	Misaligned with orbit (e.g., geodetic precession)	Aligned with orbit

Notes.
[a] Dessart et al. (2006); Kitaura et al. (2006).
[b] Hobbs et al. (2005).
[c] Podsiadlowski et al. (2004).

Table 2
14 Well-measured Neutron-star Masses

Pulsar Name	Mass of Recycled Neutron Star ($M_\odot$)	Mass of Young Neutron Star ($M_\odot$)	$P_{\rm orb}$ (hours)	Eccentricity	Pulse Period (ms)	Reference
J0737−3039A/B	1.3381 ± 0.0007	1.2489 ± 0.0007	2.4	0.088	23	Kramer et al. (2006)
B1534+12	1.3332 ± 0.0010	1.3452 ± 0.0010	10.1	0.273	38	Stairs et al. (2002)
J1756−2251	1.32 ± 0.02	1.24 ± 0.02	7.67	0.18	28	Stairs (2008)
J1906+0746	1.365 ± 0.018	1.248 ± 0.018	3.98	0.085	144[a]	Kasian (2008)
B1913+16	1.4414 ± 0.0002	1.3867 ± 0.0002	7.92	0.617	59	Weisberg & Taylor (2005)
B2127+11C	1.358 ± 0.010	1.354 ± 0.010	8.05	0.681	30	Jacoby et al. (2006)
J1909−3744	1.438 ± 0.024	White dwarf	36.7	$\lesssim 10^{-6}$	2.9	Jacoby et al. (2005)
J1141−6545	White dwarf	1.27 ± 0.01	4.74	0.172	393[a]	Bhat et al. (2008)

Notes. All known neutron stars with a mass measured with better than 0.025 $M_\odot$ accuracy.
[a] These periods are said to be associated with the "young pulsar."

pre-collapse mass (for the assumed "MPA" neutron-star equation of state) these populations are centered at $\sim 1.37\ M_\odot$ and $\sim 1.48\ M_\odot$. The higher of these two mass groups is suggestive of an origin in an Fe core-collapse SN, while the lower of the two groups likely comes from e-capture SN events.

4. STATISTICAL TESTS

We make use of two statistical tests to try to quantitatively evaluate our hypotheses: the Kologorov–Smirnov (KS) test and the Anderson–Darling (AD) test (e.g., Press et al. 2007). The AD test is more powerful as it takes into account the integrated difference between the cumulative distributions one is comparing, while the KS test considers only the maximum difference.

The first test we perform is for normality, checking whether the distribution is consistent with a single Gaussian which has the mean and standard deviation of the observed populations. The cumulative distribution for the observed neutron stars is shown in Figure 2 as filled circles connected by a solid black line. The cumulative distribution for the single Gaussian described by a mean mass of 1.325 $M_\odot$ and standard deviation of 0.056 $M_\odot$ is shown as the dash-dotted red curve in Figure 2. We were not able to reject this hypothesis of a single Gaussian mass distribution with a KS test but were able to marginally reject it at the 70% confidence level with the AD test.

We also tested the hypothesis that there are two distributions present, each of which is represented by a Gaussian. The best such fit is given by:

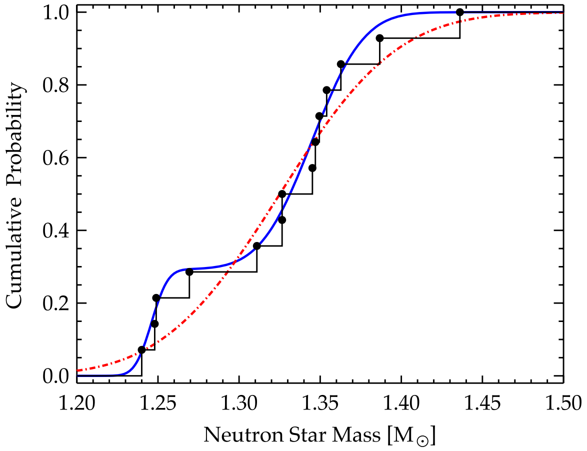

Figure 2. Cumulative distribution of neutron-star masses. The observed distribution is shown by the black dots and solid black line. The cumulative distribution function (CDF) for the best two population model is shown by the solid blue curve (see the text). The dash-dotted red curve is the CDF for a single Gaussian with the population mean and standard deviation.

(A color version of this figure is available in the online journal.)

$$dN/dM = 0.707\, e^{(M-1.345)^2/2\sigma_1^2} + 0.293\, e^{(M-1.246)^2/2\sigma_2^2}, \quad (1)$$

with $\sigma_1 = 0.025 \pm 0.004\ M_\odot$ and $\sigma_2 = 0.008 \pm 0.005\ M_\odot$. The uncertainties on the mean masses of the two Gaussians are $1.345 \pm 0.005\ M_\odot$ and $1.345 \pm 0.004\ M_\odot$, respectively.

The cumulative distribution function corresponding to this distribution is plotted as a solid blue curve in Figure 2. The amplitudes of the two Gaussians are, as expected, reflective of the fact that 4 of the 14 neutron stars are in the lower-mass group. As can be seen from the cumulative distribution for the double Gaussian, the fit is very good, compared to a single Gaussian with the population mean and standard deviation.

While these statistical tests and fits do not, by themselves, constitute a proof of two populations, coupled with the other pieces of evidence (i.e., appropriate system eccentricities and theoretically expected masses for e-capture SNe), they do lend support for the hypothesis of two populations.

5. ECCENTRICITY CALCULATIONS

In order to illustrate what the eccentricity distributions of e-capture versus Fe core-collapse SNe might look like, we carried out the following simple statistical study. In all cases, we assume that the *second* SN explosion takes place with a He or CO core in a circular orbit with the first-born neutron star. We take the core mass to be in the range 1.5–2.0 $M_\odot$ for the e-capture scenario and 2.5–6.0 $M_\odot$ for the Fe core-collapse scenario (e.g., Podsiadlowski et al. 2004; Dewi et al. 2005). The orbit is assumed to have been circularized during a prior episode when the evolving core expands sufficiently to transfer at least a small amount of mass to the first-born neutron star, thereby spinning it up to millisecond rotation periods. The orbital separation at the time of the second SN explosion is taken to be uniformly distributed over the range 1–3 times the orbital separation needed for the He or CO core to fill its Roche lobe (a result expected from more detailed population synthesis calculations, e.g., Dewi et al. 2006). Finally, the natal kick distribution is taken to be a Maxwellian with σ equal to either 30 km s^{-1} or 265 km s^{-1}, for the e-capture and Fe core-collapse scenarios, respectively (e.g., Dewi et al. 2006). The resulting orbital eccentricities are computed from the expression given by Brandt & Podsiadlowski (1995). The above assumptions should hold for both the standard formation channel as well as for the double-core channel.

For each scenario, the initial system parameters (i.e., core mass and orbital separation) and the natal kick were chosen via Monte Carlo techniques for 10^7 systems. The results are shown in Figure 3. The gray (red) curve represents the eccentricity distribution for the e-capture scenario while the black curve is for the Fe core-collapse explosions. Note that in the latter case the eccentricity distribution is rather broad (in fact some ~60% of the systems become unbound) while for the e-capture events the eccentricity distribution peaks at $e \simeq 0.2$ and extends down to rather low values of e. In fact, we observe that these two distinct distributions are rather consistent, respectively, with the three cases we tentatively identify with e-capture SNe and those three with higher eccentricities that we associate with Fe core-collapse SNe.

6. CONSISTENCY OF THE SCENARIOS

There are two main scenarios for the formation of double neutron-star systems. They both start with a pair of massive primordial stars, i.e., with masses between ~8 and 25 $M_\odot$. In the "standard scenario" the more massive star evolves first, fills its Roche lobe, and stable, quasi-conservative mass transfer to the secondary may occur if the mass ratio is not too extreme and if the initial orbital period is in the right range (i.e., ~ a month to a year). In this scenario, the system cannot undergo a common envelope phase during the first stage of mass transfer, otherwise the orbit would not be sufficiently wide after the formation of the first neutron star to allow for the successful production of the second neutron star (as discussed below). Given the fact that the orbit should initially be wide, it is actually advantageous for the first SN explosion to occur via an e-capture SN, in order to yield a small natal kick and thereby help the system remain bound. There is indeed a class of such wide binaries containing a neutron star in nearly circular orbit with a massive donor (see, e.g., Pfahl et al. 2002; Podsiadlowski et al. 2004). After the formation of the first neutron star, the companion star evolves, fills its Roche lobe, and the subsequent mass transfer onto the neutron star leads to a common envelope phase due to the extreme mass ratio of the system. In order for the common envelope phase to avoid a merger of the neutron star and the core of its companion, the orbit must be wide to begin with, as alluded to above. The result of a "successful" common envelope phase is a He or CO core in close ($\lesssim$1 day) orbit with the first neutron star. The original neutron star is spun up via accretion from its He/CO star companion as it evolves toward core collapse. If the subsequent SN explosion is via e-capture (for He-star companions of mass $\lesssim 2\ M_\odot$; Nomoto 1984), then the natal kick may be small and the final binary pair of neutron stars would have a modestly small eccentricity and low systemic space velocity (van den Heuvel 2007). Whether the second neutron star would form via an e-capture SN or Fe core-collapse SN would depend on the original mass of the secondary star and the orbital period after the first neutron star has been formed.

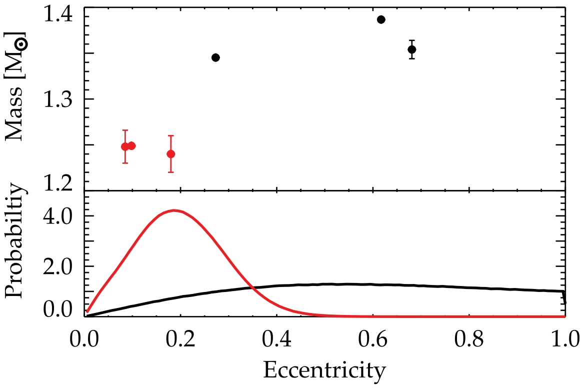

Figure 3. Comparison of system eccentricities of the double neutron star binaries. Top panel: the measured masses of the young neutron star plotted against the system eccentricity. We identify the low-mass, low-eccentricity systems as being the result of e-capture SNe, marking them as red. An amount 0.01 was artificially added to the eccentricity of J0737 to separate it from J1906 on the plot. Bottom panel: the results of the Monte Carlo eccentricity simulation described in the text. The black curve is the distribution of Fe core-collapse systems and the gray (red) curve is for e-capture systems.

(A color version of this figure is available in the online journal.)

Both this standard scenario and the "double core" scenario that we describe next are summarized in schematic diagrams in Podsiadlowski et al. (2005, Figure 1) and Dewi et al. (2006, Figure 1). The various possible orderings for the different core-collapse mechanisms for the two neutron stars in the standard scenario are summarized in Table 3, along with some qualitative comments on the likelihood of each. In particular, in a recent detailed population synthesis study of double neutron stars, which included both the standard and the double-core channel, Belczynski et al. (2009) predicted that category II systems should be by far the most dominant systems. From the above discussion and the notes in Table 3, we would expect double

Table 3
Order of Fe Core-collapse Versus e-capture SNe

Category	Neutron-star Formation Type and Order	Standard Scenario	Double Core Scenario	Observed
I	Fe core collapse + Fe core collapse	Possible	Probable	Yes
II	e-capture + Fe core collapse	Most favored	Inconsistent	No
III	Fe core collapse + e-capture	Possible	Probable	Yes
IV	e-capture + e-capture	Possible	Some fine tuning	No

neutron stars formed via the standard scenario to consist of a recycled pulsar with a mass indicative of an e-capture SN formation (Categories II and IV; i.e., $\sim 1.25\,M_\odot$). Moreover, if the orbital eccentricities are low, then both neutron stars would most likely be formed via e-capture SNe (i.e., Category IV). Neither of these expectations is borne out by the observational data in Table 2.

In the "double-core" scenario (Brown 1995; Bethe & Brown 1998; Dewi et al. 2006), the primordial binary is required to have a pair of stars whose mass is the same to within ~3%–7% of each other. Given that massive stars seem to often reside in binaries whose stars have comparable mass, this ~5% "window" is not nearly as rare as it might seem. In fact, roughly speaking some several percent of all massive stars may occur in such comparable-mass binaries if the binary fraction is high and if the mass ratio distribution is roughly flat. If the two stars have comparable mass and the orbit is relatively wide (i.e., ~months to years), then both stars will enter a double common-envelope phase once the primary starts to transfer mass to the secondary. At that point, the primary is expected to have evolved a CO core while the secondary will also be evolved but will more likely have only a He core. Both of these cores will spiral in inside the common envelope formed of the envelopes of both stars. The result will be a close pair of a CO and a He core (or less likely a pair of CO cores). The orbital period of the primordial binary should be wide (i.e., months to years) if the cores are to avoid merger during the common-envelope phase. The CO core evolves first, most likely, to an Fe core-collapse SN and leaves a $\sim 1.35\,M_\odot$ neutron star (i.e., Categories I and III; see Table 3), though it could also experience an e-capture SN (Category IV). When the He core evolves, it expands somewhat and transfers some mass to the first neutron star, thereby recycling it. If the He core mass is relatively low ($\lesssim 2\,M_\odot$; Nomoto 1984), it will go on to undergo an e-capture SN, leaving a lower-mass neutron star with a smaller natal kick (i.e., Category III). Thus, in this scenario, the recycled pulsar is the more massive of the two, having been formed in an Fe core-collapse SN, while the second, an unrecycled pulsar, should be lower in mass.

This double-core scenario is consistent with the data for the six neutron-star binaries. Three of them have higher orbital eccentricities, $e = 0.27, 0.62, 0.68$, with both neutron stars in the system having masses consistent with Fe core-collapse SNe (Category I). The other three have lower eccentricities ($e = 0.08, 0.09, 0.18$), and the unrecycled pulsar is consistent with having undergone an e-capture SN (with mass $\sim 1.25\,M_\odot$), i.e., Category III (see also van den Heuvel 2007). The eccentricities and NS masses of these six systems are plotted in Figure 3. Since we have only six systems, it is premature to draw any firm conclusions, though it is remarkable that none of the observed systems falls into the a priori most favored standard scenario category.

In the case of the two neutron star–white dwarf binaries, the scenario is likely somewhat different than described above. One of the neutron star–white dwarf systems (J1141−6545) has a significant eccentricity of 0.17 and a lower-mass neutron star. This suggests that, in this case, the white dwarf actually formed before the neutron star, otherwise the second phase of mass transfer, leading to the formation of the white dwarf, would have circularized the orbit. This is the likely consequence of a first phase of conservative mass transfer where the initial masses of the binary components were relatively close and the primary had a mass just below the minimum main-sequence mass for neutron-star formation ($\sim 7\,M_\odot$). After this first mass-transfer phase, the secondary has accreted enough mass to end its evolution as a neutron star (see, e.g., Church et al. 2006). In addition, after the ensuing common envelope phase, the secondary is more likely to have a mass just above the minimum neutron-star formation mass and this naturally favors an e-capture collapse. The formation of this system via e-capture was previously suggested by van den Heuvel (2004, 2006). The other neutron star–white dwarf system (J1909−3744) is highly circularized and it is likely that the neutron star formed first and the orbit was circularized during a common envelope phase involving the progenitor of the white dwarf.

7. SUMMARY AND CONCLUSIONS

We have shown that the population of 14 well-measured neutron-star masses is consistent with being comprised of a subset of four that were likely the result of e-capture SNe, while the others resulted from Fe core-collapse SNe. The lower neutron-star masses ($\sim 1.25\,M_\odot$) of the four candidate e-capture SNe and relatively low orbital eccentricities ($e \lesssim 0.18$) of the systems that contain them are both good indicators of this type of formation mechanism. The remaining 10 neutron stars have larger masses ($\sim 1.35\,M_\odot$) more indicative of Fe core-collapse SNe; in the systems where these more massive neutron stars formed second, larger orbital eccentricities are observed, consistent with a larger natal kick.

We discussed four categories of formation scenarios for producing neutron stars in close binaries, especially double neutron stars. These include the possibilities that (1) either the first or second neutron star was formed via an Fe core-collapse SN and (2) either neutron star might have been formed in an e-capture SN. Any of these four possibilities could be connected either with the "standard scenario," in which a common envelope phase occurs only *after* the first SN explosion, or with the so-called "double-core" scenario, wherein both comparably massed primordial stars are simultaneously stripped of their envelopes. (See Table 3 for a summary of the eight possible combinations.)

None of the observed systems falls into Categories II or IV, because the recycled pulsar is never the lower-mass product of an e-capture SNe. For producing double neutron-star systems, it appears that the standard scenario is somewhat disfavored. The evidence that we have presented and examined seems to favor Category I (both the young and the recycled NS are of higher mass) and Category III (a recycled higher-mass NS and a young lower-mass NS), both forming via the double-core channel (see Table 3).

If our interpretation of the neutron-star mass data is correct, i.e., the double-core channel is the preferred scenario for producing double neutron stars, this has profound implications for the fate of neutron stars within a common envelope. Recall that the original motivation for proposing the double-core channel was the estimation by Chevalier (1993, 1996) that a neutron star within a common envelope might undergo hypercritical accretion and collapse to a black hole. On the other hand, there is evidence that at least some neutron stars survived a common envelope without being converted into a black hole (e.g., PSR B0655+64, Tauris et al. 2000). And, as noted above, the neutron star in J1909−3744 also appears to have spiraled through a massive common envelope. However, it seems possible that systems with massive white-dwarfs secondaries could also be produced via the double-core channel. We note that, even though the double-core channel requires very special initial conditions, such systems are more compact when the first SN occurs and are therefore much more likely to survive as bound systems after the first SN than in the standard channel. As a consequence, the birthrate of double neutron-star systems in the double-core channel can be comparable to the standard model; using binary population synthesis simulations, Dewi et al. (2006) estimated their birthrate to be 10^{-6}–10^{-5} yr^{-1} (but with substantial uncertainties, see Belczynski et al. 2006 for another estimate). This is probably sufficient to account for the observed number of double neutron-star systems (see, e.g., Kalogera et al. 2004). Nonetheless, whether or not neutron stars can survive a common envelope, we believe that we have provided some further support for the double-core channel formation of double neutron-star systems.

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