Double Neutron Stars: Evidence For Two Different Neutron-Star Formation Mechanisms

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Abstract. Six of the eight double neutron stars known in the Galactic disk have low orbital eccentricities (\(< 0.27\)) indicating that their second-born neutron stars received only very small velocity kicks at birth. This is similar to the case of the B-emission X-ray binaries, where a sizable fraction of the neutron stars received hardly any velocity kick at birth (Pfahl et al. 2002). The masses of the second-born neutron stars in five of the six low-eccentricity double neutron stars are remarkably low (between 1.18 and 1.30\(M_\odot\)). It is argued that these low-mass, low-kick neutron stars were formed by the electron-capture collapse of the degenerate O-Ne-Mg cores of helium stars less massive than about 3.5\(M_\odot\), whereas the higher-mass, higher kick-velocity neutron stars were formed by the collapses of the iron cores of higher initial mass. The absence of low-velocity single young radio pulsars (Hobbs et al. 2005) is consistent with the model proposed by Podsiadlowski et al. (2004), in which the electron-capture collapse of degenerate O-Ne-Mg cores can only occur in binary systems, and not in single stars.

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THE BIRTH KICK VELOCITIES OF NEUTRON STARS

Pfahl et al. (2002) discovered the existence of a separate class of B-emission X-ray binaries (abbreviated here as Be/X-ray binaries) with wide orbits of low eccentricity (\(< 0.25\)). The systems in this class tend to have relatively low X-ray luminosities (\(< 10^{34}\) ergs/s). A well-known example is X-Per, in which the neutron star has an almost circular orbit with a period of 250 days. About half of all Be/X-ray binaries with known orbits appear to belong to this class and the relatively low X-ray luminosities of these sources imply that these systems are on average considerably nearer to us than the high-eccentricity Be/X-ray binaries (which during outbursts can reach a luminosity of \(10^{38}\) ergs/s). Therefore, as Pfahl et al. (2002) pointed out, the systems in the low-eccentricity class probably form the bulk of the Be/X-ray binary population, since the known numbers of sources in both classes are about the same. These authors pointed out that the neutron stars in the low-eccentricity systems cannot have received a kick velocity at their birth exceeding 50 km/s. Until the discovery of this class of X-ray binaries it was generally thought that all neutron stars receive a high kick velocity at their birth, of order at least a few hundred km/s (see e.g.: Lyne and Lorimer 1994; Hansen and Phinney 1997, Hobbs et al.2005). Often a Maxwellian distribution is used to represent the observed distribution of pulsar velocities, and the characteristic velocity of these Maxwellsians is typically around 300 – 400 km/s (Hansen and Phinney 1997).
A recent very detailed study by Hobbs et al. (2005) of the accurately determined proper motions of 233 radio pulsars shows that there is no room for a separate population of low-velocity single pulsars. Particularly, these authors found that the velocity distribution of young pulsars (age < 3 million years) is very well represented by a single Maxwellian with a characteristic velocity of about 400 km/s, and there is no evidence for a bimodal velocity distribution as had been argued by Cordes and Chernoff (1998).

On the other hand, Pfahl et al. (2002) showed, by means of population synthesis calculations that include the evolution of binaries and the presence of birth kicks imparted to neutron stars, that with the assumption of only one Maxwellian with a high characteristic velocity (several hundred km/s) one can reproduce the high-eccentricity population of the Be/X-ray binaries, but one totally fails to reproduce the presence of a large population of systems with low eccentricities. They convincingly showed that the only way in which both the observed high-e and the low-e populations of the Be/X-ray binaries can be reproduced is: by assuming that there are two distinct populations of neutron stars: one population that receives hardly any kick velocity at birth ($v_k < 50$ km/s) and another which receives the “canonical” high velocity kick of order several hundreds of km/s at birth.

DOUBLE NEUTRON STARS AND THE LOW KICK VELOCITY NEUTRON STAR POPULATION

At present 9 double neutron stars are known, 8 of them in the galactic disk and one in a globular cluster (see Stairs 2004, Lorimer et al. 2006). The eight systems in the galactic disk are listed in table 1. As the table shows, the double neutron stars tend to have very narrow orbits. They are the later evolutionary products of wide high-mass X-ray binary systems with orbital periods $> 100$ days (van den Heuvel and Taam 1984), mostly B-emission X-ray binaries (for an alternative view, see Brown 1995). When the massive star in such a system has expanded to become a red giant, its envelope engulfs the neutron star, causing this star to spiral down into this envelope, reducing its orbital separation by several orders of magnitude. The large energy release due to friction and accretion during this spiral-in process is expected to cause the hydrogen-rich envelope of the giant to be expelled such that a very close binary remains, consisting of the helium core of the giant together with the neutron star (van den Heuvel and Taam 1984; Dewi and Pols 2003). (Depending on the orbital separation at the onset of spiral in, the helium core itself may already be (somewhat) evolved and possibly contain already some C and O in its core). [In Be/X-ray systems that started out with orbital periods $< 100$ days the neutron star spirals in so deeply that it most probably merges with the core of the giant, and so no binary will be left; e.g. see Taam 1996]. Due to the large frictional and tidal effects during spiral in the orbit of the system is expected to be perfectly circular. The helium star generates its luminosity by helium burning, which produces C and O, and subsequently by carbon burning, producing Ne and Mg.

If the helium star has a mass in the range 1.6 to 3.5 M$_\odot$ (corresponding to a main-sequence progenitor in the range 8 to 11 (±1) M$_\odot$, the precise limits of this mass range depending on metallicity and on the assumed model for convective energy transport; Sugimoto and Nomoto 1980; Miyaji et al. 1980; Podsiadlowski et al. 2004) it will
during carbon burning develop a degenerate O-Ne-Mg core, surrounded by episodic C- and He-burning shells (e.g. Nomoto 1984, Habets 1986). When such a degenerate core develops, the envelope of the helium star begins to expand, causing in a binary the onset of mass transfer by Roche-lobe overflow (Habets 1986; Dewi and Pols 2003). Roche-lobe overflow leads to the formation of an accretion disk around the neutron star and accretion of matter with angular momentum from this disk will cause the spin frequency of the neutron star to increase. Therefore one expects that during the later evolution of these helium stars of relatively low mass the first-born neutron star in the system will be “spun up” to a short spin period. This neutron star had already a long history of accretion: first when it was in a wide binary with an early-type (presumably Be) companion; subsequently during the spiral-in phase into the envelope of its companion and now as companion of a Roche-lobe overflowing helium star. Since all binary pulsars which had a history of mass accretion (so-called “recycled” pulsars; Radhakrishnan and Srinivasan 1982) tend to have much weaker magnetic fields than normal single pulsars, it is thought that accretion in some way causes a weakening of the surface dipole magnetic field of neutron stars (Taam and van den Heuvel 1986) and several theories have been put forward to explain this accretion-induced field decay (Bisnovatyi-Kogan and Komberg 1974; see Bhattacharya and Srinivasan 1995 for a review; Zhang 1998 and Cumming 2004).

With a field weakened to about $10^{10}$ Gauss (as observed in the recycled components of the double neutron stars (see table 1), and an Eddington-limited accretion rate of helium of $\sim 4 \times 10^{-8}$ M$_{\odot}$/yr, a neutron star can be spun-up to a shortest possible spin period of a few tens of milliseconds (Smarr and Blandford 1976, Srinivasan and van den Heuvel 1982). When the helium star finally explodes as a supernova, the second neutron star in the system is born. This is a newborn neutron star without a history of accretion and is therefore expected to resemble the “normal” strong-magnetic field single radio pulsars (Srinivasan and van den Heuvel 1982), which have typical surface dipole magnetic fields strengths of $10^{12}$ – $10^{13}$ Gauss. This theoretical expectation has been beautifully confirmed by the discovery of the double pulsar systems PSRJ0737-3039AB, which consists of a recycled pulsar (star A) with a very rapid spin ($P = 23$ ms) and a weak magnetic field ($7 \times 10^9$ G) and a normal strong-magnetic-field ($1.2 \times 10^{12}$ G) pulsar (star B) with a “normal” pulse period of 2.8 sec (Burgay et al. 2003, Lyne et al. 2004; see table 1). The explosive mass loss in the second supernova has made the orbit eccentric and since the two neutron stars are basically point masses, tidal effects in double neutron star systems will be negligible and there will be no tidal circularization of the orbit. (On timescales of tens of millions of years the orbits may circularize by a few percent due to the emission of gravitational waves in the shortest-period system of PSRJ0737-3039, but in all the other double neutron stars this is a negligible effect, except in the final stages of spiraling together; see e.g. Shapiro and Teukolsky 1983).

In case of spherically symmetric mass ejection in the supernova there is a simple relation between the orbital eccentricity and the amount of mass $\Delta M_{sn}$ ejected in the supernova:

$$e = \Delta M_{sn} / (M_{ns1} + M_{ns2})$$  \hspace{1cm} (1)

where $M_{ns1}$ and $M_{ns2}$ are the masses of the first- and the second-born neutron stars. The “conventional” kick velocities of neutron stars of about 400 km/s (Hobbs et al.2005) are
quite similar to the orbital velocities of the neutron stars in close double neutron stars such as the Hulse-Taylor binary pulsar PSR B1913+16 ($P_{\text{orb}} = 7.75$ hours). Therefore, a kick velocity of this order produces a major disturbance of the orbit and – unless it is imparted in a very specific direction – will in general impart a large eccentricity to the orbit, of order 0.5 or more. The Hulse-Taylor binary pulsar has a large eccentricity $e = 0.617$ and the same is true for the system PSR J1811-1736 ($e = 0.828$), which indeed might be due to such large kick velocities. However, as Table 1 shows, very surprisingly all of the other 6 double neutron stars in the galactic disk have very small orbital eccentricities, in the range 0.088 to 0.27. Such eccentricities are the ones which one expects from the pure sudden mass loss effects in the supernova explosion, given by equation (1), but not in case a randomly directed kick velocity of order 400 km/s is imparted to the second-born neutron star at birth. [In particular, the small orbital eccentricities of the two relatively wide double neutron stars PSR J1518+4909 and PSR J1829+2456 are impossible to reconcile with high kick velocities].

Furthermore, Dewi et al. (2005) and van den Heuvel (2005) have pointed out that the relation between spin period of the recycled neutron star and orbital eccentricity observed in double neutron star systems (Faulkner et al. 2005) can only be understood if the second-born neutron stars in these systems received a negligible velocity kick in their birth events. Interestingly, also the Hulse-Taylor binary pulsar PSR B1913+16 and PSR J1811-1736 fit this relation, which suggests that also their high orbital eccentricities were purely due to the effects of the sudden mass loss in the second supernova. And indeed, since their first-born neutron stars are quite strongly recycled, they must have had a quite extended episode of disk accretion. This implies an extended episode of stable Roche-lobe overflow from the helium star progenitor of the second-born neutron star. And this in turn suggests that these helium stars had a degenerate O-Ne-Mg core, as only the development of such cores causes the envelopes of helium stars to expand.

It thus appears that the second-born neutron stars in these 6 low-eccentricity systems belong to the same “kick-less” class as the neutron stars in the low-eccentricity class of Be/X-ray binaries (van den Heuvel 2004, 2005, 2006). The same holds for the young strong-magnetic-field pulsar in the eccentric radio-pulsar binary PSR J1145-6545 which has a massive white dwarf as a companion (Kaspi et al. 2000; Bailes et al. 2003; Bailes 2005). The orbital eccentricity of 0.172 of this binary shows that the neutron star was the last-born object in the system (Portegies Zwart and Yungelson 1999, Tauris and Sennels 2000; formation of a white dwarf cannot introduce an orbital eccentricity). The low value of its eccentricity would be hard to understand if the neutron star received the canonical 400 km/s kick at its birth.
### TABLE 1. Double neutron star binaries and the eccentric-orbit white-dwarf neutron star system J1145-6545.

References: (1) Lyne et al. (2004); (2) Nice et al. (1996); (3) Stairs (2004); (4) Faulkner et al. (2005); (5) Champion et al. (2004); (6) Bailes (2005); (7) Lorimer et al. (2006).

| Pulsar Name | Spin Per. (ms) | P<sub>orb</sub> (d) | e | Companion Mass (M<sub>⊙</sub>) | Pulsar Mass (M<sub>⊙</sub>) | Sum of masses (M<sub>⊙</sub>) | B<sub>s</sub> (10<sup>10</sup> G) | Ref |
|-------------|---------------|-----------------|---|-----------------|-----------------|-----------------|-----------------|----|
| J0737-3039A | 22.7          | 0.10            | 0.088 | 1.250(5)        | 1.337(5)        | 2.588(3)        | 0.7             | (1) |
| J0737-3039B | 2770          | 0.10            | 0.088 | 1.337(5)        | 1.250(5)        | 2.588(3)        | 1.2 x 10<sup>2</sup> | (1) |
| J1518+4904  | 40.9          | 8.63            | 0.249 | 1.05 (+0.45)    | 1.56 (+0.13)    | 2.62(7)         | 0.1             | (2) |
| B1534+12    | 37.9          | 0.42            | 0.274 | 1.3452(10)      | 1.3332(10)      | 2.678(1)        | 1               | (3) |
| J1756-2251  | 28.5          | 0.32            | 0.18  | 1.18(3)         | 1.40(3)         | 2.574(3)        | 0.54            | (4) |
| J1811-1736  | 104           | 18.8            | 0.828 | 1.11 (+0.53)    | 1.62 (+0.22)    | 2.60(10)        | 1.3             | (3) |
| J1829+2456  | 41.0          | 1.18            | 0.139 | 1.27 (+0.11)    | 1.30 (+0.05)    | 2.53(10)        | ~1              | (5) |
| J1906+0746  | 144.1         | 0.165           | 0.085 | —               | —               | 2.61(2)         | 1.7 x 10<sup>2</sup> | (7) |
| B1913+16    | 59            | 0.33            | 0.617 | 1.3873(3)       | 1.4408(3)       | 2.8281(1)       | 2               | (3) |
| J1145-6545  | 394           | 0.20            | 0.172 | 1.00(2)         | 1.28(2)         | 2.288(3)        | ~10<sup>2</sup>  | (6) |

### THE MASSES OF THE SECOND-BORN NEUTRON STARS IN THE DOUBLE NEUTRON STAR SYSTEMS AND IN PSR J1145-6545

In the eccentric white-dwarf/neutron-star system of PSR J1145-6545 the mass of the neutron star is known from the measurement of relativistic effects to be 1.28(2) M<sub>⊙</sub> (Bailes 2005). Also in two of the low-eccentricity double neutron stars the masses of both stars are accurately known from measured relativistic effects (see Stairs 2004): 

(i) in PSR J0737-3039 the second-born neutron star has M<sub>B</sub> = 1.250(3) M<sub>⊙</sub> and the first-

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1 The number within parentheses indicates the 95% confidence uncertainty of the last digit; the total mass of the system is 2.30 M<sub>⊙</sub> and the mass of the white dwarf is at least one solar mass.
born one has $M_A = 1.330(3) \, M_\odot$ (Lyne et al. 2004).
(ii) in PSR J1756-2251 the second-born neutron star has a mass of $1.18(3) \, M_\odot$ and the
first-born one a mass of $1.40(3) \, M_\odot$ (Faulkner et al. 2005).

In most of the other double neutron stars the masses of the stars are not yet accurately
known, but in two of the other low-eccentricity systems the second-born neutron stars
must be less massive than $1.30 \, M_\odot$ for the following reasons. In all double neutron
star systems the relativistic parameter that can be measured most easily is the General
Relativistic rate of periastron advance, which directly yields the sum of the masses of
the two neutron stars (e.g. see Stairs 2004). In the low-eccentricity systems of PSR
J1518+4904, PSR J1829+2456 and PSR J1906+0746 the resulting sum of the masses
turns out to be $2.62$, $2.53$ and $2.61 M_\odot$, respectively. The individual masses of the neutron
stars in these systems are still rather poorly determined, but in the first two of these
three systems the already crudely determined other relativistic parameters indicate that
the second-born neutron star has the lowest mass of the two (see references in van den
Heuvel 2004). As in these systems the sum of the masses is around $2.60 \, M_\odot$, the second-
born neutron stars in these two systems cannot be more massive than $1.30 \, M_\odot$.

Thus we find that in at least four of these six systems the second-born neutron star
has a low mass, in the range $1.18$ to $1.30 \, M_\odot$ and belongs to the low-kick category. And
the same holds for the second-born neutron star in the low-eccentricity white-dwarf-
neutron-star binary PSR J1145-6545, which has a mass of only $1.28 \, M_\odot$. Also in the
system of PSR J1909+0746 the masses of the neutron stars cannot differ much from
$1.30 \, M_\odot$. We thus see that in at least five cases a low (or no) kick velocity is correlated
with a low neutron star mass of on average around $1.25 (\pm 0.06) \, M_\odot$.

A neutron star of $1.25 \, M_\odot$ corresponds to a pre-collapse mass of about $1.44 \, M_\odot$, as
during the collapse the gravitational binding energy of the neutron star of about $0.20 \, M_\odot$
(slightly depending on the assumed equation of state of neutronized matter) is lost
in the form of neutrinos. So apparently the cores, which collapsed to these second-born
neutron stars, had a mass very close to the Chandrasekhar mass.

FORMATION MECHANISMS OF NEUTRON STARS AND
POSSIBLE RESULTING KICKS

It is long known (Miyaji et al. 1980, Sugimoto and Nomoto 1980) that there are two
basically different ways in which neutron stars are expected to form, i.e.:
(i) In stars which originated in the main-sequence mass range between 8 and about 11
$(\pm 1) \, M_\odot$, which in binaries produce helium stars in the mass range $1.6$ to $3.5 \, M_\odot$
(Habets 1986, Dewi and Pols 2003), the O-Ne-Mg core which forms during carbon
burning becomes degenerate and when its mass approaches the Chandrasekhar mass,
electron captures on Mg and Ne cause the core to collapse to a neutron star. Since
these stars did not reach Oxygen- and Silicon burning, the baryonic mass of the neutron
star, which forms in this way, is expected to be purely determined by the mass of the
collapsing degenerate core, which is the Chandrasekhar mass. The gravitational mass of
this neutron star is then the Chandrasekhar mass minus the gravitational binding energy
of the neutron star, which is about $0.20 \, M_\odot$. Thus a neutron star with a mass of about
$1.24 \, M_\odot$ is expected to result.
In stars initially more massive than 11 \((\pm 1)M_\odot\), the O-Ne-Mg core does not become degenerate and these cores proceed through Oxygen and Silicon burning to form an iron core. When the mass of this iron core exceeds a critical value it collapses to form a neutron star. The precise way in which here neutrino transport during core bounce and shock formation results in a supernova explosion is not yet fully understood. It appears that first the shock stalls and then several hundreds of milliseconds later, is revitalized. Some fallback of matter from the layers surrounding the proto neutron star is expected to occur (see Fryer 2004) such that the neutron star that forms may be substantially more massive than the mass of the collapsing Fe-core.

In fact there are two expected mass regimes for the resulting neutron stars: for stars with initial main-sequence masses in the range 11 \((\pm 1)\) M_\odot \text{ to } 19 M_\odot the collapsing cores are expected to be about 1.3 M_\odot, whereas for stars more massive than 19 M_\odot the collapsing iron core is expected to have a mass \(> 1.7 M_\odot\) (Timmes et al. 1996), leading to the formation of neutron stars with (gravitational) masses \(> 1.6 M_\odot\). Taking some fallback of matter into account, the neutron stars formed from these types of iron cores may be expected to have gravitational masses \(> 1.3 M_\odot\) and \(> 1.7 M_\odot\), respectively.

The fact that the pre-collapse masses of the low-mass, low-kick neutron stars were very close to the Chandrasekhar limit suggests that these neutron stars are the result of the electron-capture collapse of the degenerate O-Ne-Mg cores of helium stars that originated in the mass range 1.6 to \(3.5 M_\odot\) (initial main-sequence mass in the range 8 to 11 \((\pm 1) M_\odot\)). Can one understand why such neutron stars would not receive a birth kick whereas those formed by the collapse of an iron core would? While in the past neutron-star kicks generally were ascribed to asymmetric neutrino emission (e.g. Burrows and Hayes 1996), in recent years the ideas have shifted towards hydrodynamic instabilities during the explosion. For example, Scheck et al. (2004, 2005) found large-scale hydrodynamic instabilities to develop in the layers surrounding the proto neutron star during the explosion of a 15 M_\odot star with a collapsing iron core, which imparted velocities up to 1000 km/s to the neutron star. On the other hand, for collapsing O-Ne-Mg cores, Kitaura et al. (2006) did not find large neutron-star velocities. This is ascribed to the facts that (a) here the ejecta mass in the immediate vicinity of the proto neutron star is very small, and (b) the explosion of the O-Ne-Mg core by neutrino heating occurs very fast (much faster than for iron cores, where the development of the explosion takes hundreds of milliseconds), not allowing hydrodynamic instabilities to develop. It thus appears that a difference in the purely hydrodynamic effects during these very different types of explosions may explain the differences in the kick velocities of the resulting neutron stars.

WHY ARE THERE NO LOW-VELOCITY SINGLE PULSARS?

Podsiadlowski et al. (2004) recently argued that single stars in the mass range 8 to 11 \((\pm 1) M_\odot\) do not produce neutron stars, for the following reason. These stars produce helium cores in the mass range 1.6 to \(3.5 M_\odot\), but when they ascend the Asymptotic Giant Branch (AGB), their convective envelope during the “dredge-up” phase penetrates the helium layers surrounding their degenerate O-Ne-Mg cores, and erodes these helium layers away. Therefore the degenerate cores of these stars can no longer grow by helium
shell burning. These stars lose their envelopes due to the heavy wind mass loss during
the AGB phase, and are expected to leave behind their degenerate O-Ne-Mg cores as
white dwarfs. Only single stars more massive than about 11 (±1) $M_\odot$ will leave neutron
stars, formed in this case by iron core collapse. As argued above, these neutron stars
will be of the high-kick class, so all single neutron stars are expected to be high-velocity
objects, as is indeed observed (Hobbs et al. 2005). On the other hand, as argued by
Podsiadlowski et al. (2004), an 8 to 11 (±1) $M_\odot$ star in an interacting binary system
cannot reach the AGB, as already before reaching that very extended phase, it will in a
binary have lost its hydrogen envelope by Roche-lobe overflow. Therefore, in binaries
such stars will leave helium stars with masses in the range 1.6 to 3.5 $M_\odot$, which will
evolve to e-capture core collapse, which according to our above-described model leaves
a low-velocity neutron star. One therefore expects these low-velocity neutron stars to
only be born in binary systems.

**CONCLUSIONS**

The combination of observations indicating that: (i) among the Be/X-ray binaries and
the double neutron stars there is a substantial group with low orbital eccentricities,
indicating that their last-born neutron stars received hardly any velocity kick at birth,
(ii) the low-kick second-born neutron stars in the double neutron star systems have a low
mass, $\sim 1.25 M_\odot$, and (iii) the absence of low-velocity neutron stars in the young radio
pulsar population can be consistently explained if the low-mass low-kick neutron stars
originate from the electron-capture collapse of the degenerate O-Ne-Mg cores of stars
that started out with main-sequence masses in the range $\sim 8 - 11 M_\odot$, while the high-
kick-velocity neutron stars originated from the iron-core collapses of stars that started
out with masses in excess of $\sim 11 M_\odot$. Such an explanation is fully consistent with
the model proposed by Podsiadlowski et al. (2004) according to which neutron star
formation by electron-capture collapse can only occur in interacting binaries and not in
single stars.

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