The origin of single radio pulsars

Portegies Zwart, S.F.; Van den Heuvel, E.P.J.

DOI
10.1016/S1384-1076(99)00029-9

Publication date
1999

Document Version
Final published version

Published in
New Astronomy

Citation for published version (APA):
Portegies Zwart, S. F., & Van den Heuvel, E. P. J. (1999). The origin of single radio pulsars. *New Astronomy*, *4*(5), 355-363. https://doi.org/10.1016/S1384-1076(99)00029-9

New Astronomy 4 (1999) 355–363

New Astronomy

www.elsevier.nl/locate/newast

The origin of single radio pulsars

Simon F. Portegies Zwart[a,b,1], Edward P.J. Van den Heuvel[c,d,2]

[a]Department of General System Studies, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan
[b]Department of Astronomy, Boston University, 725 Commonwealth Avenue, Boston, MA 01581, USA
[c]Astronomical Institute Anton Pannekoek, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[d]Institute for Theoretical Physics UCSB, Santa Barbara, CA 93106-4030, USA

Received 16 July 1998; accepted 25 May 1999
Communicated by Donald C. Backer

Abstract

By comparing relative rates of supernovae versus formation rates of single radio pulsars, recycled pulsars, binary pulsars and X-ray binaries we put strong limits on the progenitors of radio pulsars and on the requirement of an asymmetry in the supernova. The assumption that radio pulsars are only formed in type Ib and type Ic supernovae from interacting binaries (Iben & Tutukov, 1998) breaks down on the implication that in that case either the formation rate of binary pulsars (double neutron stars) should be of the order of 20% of the single pulsar birth rate or, alternatively, almost all single pulsars (85% to 98%) should originate from Thorne-Żytkow stars. In the latter case the pulsar velocity distribution is inconsistent with observations. Also, in that case the difference between the supernova rate and the pulsar formation rate would be about one order of magnitude, i.e. much larger than observed. Allowing type II supernovae from single stars and non-interacting binaries to form radio pulsars solves this conundrum, but then a kick is required in order to explain the high velocities of single radio pulsars. A kick is also required to understand the small birth rate, relative to the supernova rate, of binary pulsars consisting of two neutron stars.

PACS: 97.10.Bt; 97.60.Bw; 97.60.Jd; 97.80.Jp
Keywords: Binaries; Stars: neutron; Supernovae

1. Introduction

Neutron stars are believed to descend from stars which are massive enough to experience a supernova at the end of their fuel processing lifetime. However, it is not completely clear whether or not all massive stars finally produce a radio pulsar (i.e. a highly magnetized and rapidly rotating neutron star); in some cases the remnant may not show up as a radio pulsar and above certain mass limits the star may collapse to a black hole (Van den Heuvel & Habets, 1984; Portegies Zwart et al., 1997a; Ergma & Van den Heuvel, 1998) or the star may completely detonate and leave no remnant at all by a pair creation explosion. The physical parameters at the moment of the supernova which are required to form a radio pulsar are not yet very clear, but strong limits can be set on the possible progenitors.

---

[1] Hubble Fellow, E-mail: spz@komodo.bu.edu
[2] E-mail: edvdh@astro.uva.nl

1384-1076/99/$ – see front matter
PII: S1384-1076(99)00029-9

According to the most simplistic picture, we recognize three types of supernovae: type Ia, Ibc and type II which are of importance for the argumentation which we set out in this paper (see e.g. Nomoto et al., 1995; Thielemann et al., 1996). A type II supernova is the result of the collapse of the core of a single star or a component of a wide, non-interacting binary, with a mass larger than $(9\pm1)M_\odot$ that still has a hydrogen envelope at the time of the collapse (Timmes et al., 1996; Iben et al., 1997). A star in a binary with an orbital separation so large that it evolves unaffected is considered single in this respect.

A type Ib or Ic supernova is thought to be generated by a massive star which, under the influence of another star or due to a strong stellar wind (i.e. initial mass $\gtrsim 35M_\odot$), has lost its hydrogen envelope (subclass Ib) or in addition also its helium envelope (subclass Ic). (Type Ia supernovae are generally assumed to have a different origin and do not leave a compact star, we therefore ignore them here, cf. Canal et al., 1997).

Pulsars appear to be high-velocity objects. A careful analysis of the measured proper motions of pulsars indicates a mean characteristic velocity at birth of the order of 250 to 300 km/s, with a possible flat distribution towards low velocities and a tail extending to >800 km/s (Lyne & Lorimer, 1994; Hartman, 1997; Hansen & Phinney, 1997; Cordes & Chernoff, 1997; Lorimer et al., 1997). These high peculiar velocities of single radio pulsars (some 10% have $v>600$ km/s) suggest that there is a mechanism which gives the newly born pulsar a push. In today's literature two models for this push are most favored:

A. Rapidly rotating young radio pulsars are born only from type Ib and Ic supernovae in binaries and mass loss in the supernova unbinds the binary (the so-called Blaauw mechanism, Blaauw, 1961; Blaauw, 1964); the radio pulsar is ejected with its orbital velocity and the neutron stars that are formed in this way are the only ones that spin rapidly enough to be observed as radio pulsars; neutron stars originating from single stars or wide binaries rotate too slowly to produce radio pulsars. This model for explaining pulsar velocities was proposed by Tutukov et al. (1984) and worked out in detail by Tutukov & Yungelson (1993) and Iben & Tutukov (1998).

B. An asymmetry in the supernova results in a ''velocity kick'' imparted to the newly born pulsar (Shklovskii, 1970; Gunn & Ostriker, 1970; Dewey & Cordes, 1987). An asymmetry of a few per cent suffices to explain the observed peculiar velocities (Woosley, 1987; Woosley & Weaver, 1992). The origin of the kick can be an asymmetry in the neutrino out flow from the newly born radio pulsar (Janka & Müller, 1994; Herant et al., 1994) or an off center detonation (Burrows & Hayes, 1996). The reasons, however, why such asymmetries occur are not understood from a theoretical point of view.

In this paper we argue, using simple estimates and the results of detailed population synthesis, that type II supernovae, (i.e. supernovae from stars that have **not** lost their hydrogen envelopes, and that may be single or in wide binaries) are required to add to the formation of radio pulsars and that intrinsic kicks are most favored to explain the observed characteristics of the population of radio pulsars.

A number of arguments for the occurrence of kicks is summarized by Van den Heuvel & Van Paradijs (1997) (see however, Iben & Tutukov (1998), for an alternative view) and a lower limit to the velocity of the kick is provided by Portegies Zwart et al. (1997b). Kalogera & Webbink (1998) show that without kicks it is not possible to produce low-mass X-ray binaries with an orbital period smaller than a day (see, however, Iben et al. (1995) who report to have no difficulty producing low-mass X-ray binaries in the absence of kicks). Tauris & Bailes (1996) demonstrate that it is difficult to produce millisecond pulsars with a velocity $\gtrsim 270$ km s^{-1} without an asymmetric kick. Asymmetric velocity kicks in supernovae are also favored in various population synthesis calculations pioneered by Dewey & Cordes (1987) who showed that without kicks many more double neutron stars would be produced than are observed (see also Meurs & Van den Heuvel, 1989; Dalton & Sarazin, 1995; Portegies Zwart & Spreeuw, 1996; Lipunov et al., 1996; Lipunov et al., 1997; Terman et al., 1998).

2. A simple analytical consideration

2.1. Birth rates without kicks

If all stars are born single and there are no binaries in the galaxy, scenario A implies that no radio pulsars are formed at all. In other words, this scenario for the formation of single radio pulsars excludes a star which is born single as a progenitor. The majority of the observed well-studied stars are members of a binary system anyway, so this poses no direct problem for scenario A. For simplicity we will now assume that all stars are born in binaries and that model A is correct: supernovae are symmetric (no velocity kick is given to the stellar remnant which is formed in the supernova) and only stars which have lost their envelopes in the interaction with a companion star produce radio pulsars in the supernova, as Iben & Tutukov (1998) have proposed.

The requirement for the formation of a single radio pulsar is then that the binary must (1) experience a phase of mass transfer or common-envelope evolution; (2) be dissociated in the first or the second supernova; and (3) completely spiral-in, in a phase of mass-transfer following the first supernova producing a Thorne-Żytkow object (Thorne & Żytkow, 1975; Thorne & Żytkow, 1977) that leaves a single pulsar as a remnant (Podsiadlowski et al., 1995; Iben & Tutukov, 1998). We return to the uncertainty of forming a Thorne-Żytkow star at the end of this section.

In practice this type of evolution will happen only to a small subset of all binaries. A binary with a very short orbital period and/or a small mass ratio will not survive the first phase of mass transfer and merges into a single object. Such a single star is, according to Iben & Tutukov (1998), no candidate for producing a radio pulsar. Neither are the binaries which are initially too wide to experience a phase of mass transfer. Only the binaries in the range of orbital periods between several days and a few decades are consequently candidates for producing single radio pulsars.

Our population synthesis calculations given in Section 3 demonstrate that the majority of binaries that experience and survive their first mass transfer or first common-envelope phase stay bound after the first (symmetric) supernova (see Section 3). Only those binaries for which the mass which is lost in the supernova exceeds half the total binary mass prior to the supernova are dissociated. With conservative mass transfer it is always the lowest mass component which explodes first, and no systems are disrupted. Even if the initial mass-ratio distribution strongly favors small mass ratios and if mass is not conserved in the binary system during mass transfer or common-envelope evolution the unbound fraction is still small. A simple way to see this is to consider the shape of the initial mass function: stars between $\sim 8 M_{\odot}$ and $\sim 15 M_{\odot}$ contribute about half of all supernova progenitors; they leave helium cores with a mass smaller than $\sim 3.8 M_{\odot}$ after the first mass transfer or common-envelope phase. Since companions $\lesssim 1 M_{\odot}$ will spiral in completely and coalesce, and neutron stars have a mass of about $1.4 M_{\odot}$, the systems that survive the first mass transfer then lose less than half the total mass and therefore remain bound after the first supernova explosion. Since the masses of companions of stars $> 15 M_{\odot}$ are in most cases expected to be considerably more massive than $1 M_{\odot}$, also a large fraction of the systems with more massive primaries remain bound. Therefore, the majority of the binaries that survive the first phase of mass transfer will remain bound after the first supernova explosion. The fraction that is disrupted in the first supernova (of binaries that experience and survive the first mass transfer), denoted as y. A conservative estimate of y is: $y < 0.25$ (our simulations in Section 3.1.3 show y to be $\lesssim 0.1$).

A binary which survives the first supernova explosion becomes a high-mass X-ray binary as soon as the companion of the neutron star starts to transfer mass. Most of these systems will go through a Be/X-ray binary phase (see e.g. Van den Heuvel & Rappaport, 1987). The neutron star is spun up in this phase and it may become a recycled pulsar.

Subsequently a fraction of the binaries where a neutron star accretes from its companion will spiral-in in a common-envelope phase and merge to form a Thorne-Żytkow object. Of the systems that survive as binaries after the spiral-in, only those will be disrupted in a symmetric explosion for which the exploding helium star is more massive than $4.2 M_{\odot}$.

We will denote the fraction of systems that survive the second supernova as binaries as α. The dissociated binary ejects two radio pulsars; one young and one recycled. Again with the initial-mass function argument, of the order of half of these helium-star binaries have companions to the neutron stars that have helium cores $\lesssim 4.2 M_\odot$, and therefore about half of these systems will not be disrupted in the second (symmetric) supernova[3].

According to Iben & Tutukov's (1998) model there are then three types of radio pulsars originating from high-mass X-ray binaries: (1) single pulsars resulting from binaries disrupted at the second supernova [producing two pulsars]; (2) single pulsars resulting from complete spiral-in of high-mass X-ray binaries, to form a Thorne-Żytkow object and then a recycled pulsar; (3) double neutron stars. We chose y to be the fraction of post mass-transfer systems which are disrupted in the first supernova explosion. So, if a fraction x of all high-mass X-ray binaries spiral in completely to form Thorne-Żytkow objects and then single pulsars, the fraction $(1-x)$ of high-mass X-ray binaries that survive the spiral in will leave helium star plus neutron star binaries, producing $\alpha(1-x)$ double neutron stars and $2(1-\alpha)(1-x)$ single pulsars. As the X-ray binaries formed a fraction $(1-y)$ of all post mass-transfer systems one thus will have that the fraction of double neutron stars among all pulsars is

$$\frac{\alpha(1-x)(1-y)}{y + x(1-y) + 2(1-\alpha)(1-x)(1-y)}. \tag{1}$$

The observed fraction of double neutron star among the entire pulsar population is about 0.6% (~6 binary pulsars among ~1000 single pulsars). Assuming $y = 0.25$ we then obtain, for $\alpha = 0.5$, that $x = 0.984$. Pulsars in close binaries are probably under represented because they are plagued by extra selection effects due to the acceleration of the pulsar in the binary (Johnston & Kulkarni, 1991). If the real fraction of double pulsars would be an order of magnitude larger than observed (i.e. 6%) then, with $\alpha = 0.5$, still we obtain $x = 0.849$, i.e. 85% of all pulsars would decend from Thorne-Żytkow objects.

Scenario A would therefore imply that between 85 and 98% of all radio pulsars descend from Thorne-Żytkow objects, which is an absurd result. (Even in the very unrealistic case that in a symmetric explosion only 20% of the helium-star plus neutron star binaries would survive the second supernova explosion, still an ''observed'' 6% of binary pulsars would imply that more than half of all radio pulsars have decended from Thorne-Żytkow objects.)

Moreover as the bulk of the high-mass X-ray binaries which produced the Thorne-Żytkow objects are Be-type X-ray binaries, which have small runaway velocities (11±6.7 km/s; Chevalier & Ilovaisky, 1998), between 85 and 98% of the pulsars would, according to the model of Iben & Tutukov (1998) be very low-velocity objects, contrary to the observations.

There might possibly be an alternative evolutionary path in the case of symmetric supernovae to avoid these contradictions as follows: the suggestion provided by Chevalier (1993) (see also Bisnovatyi-Kogan & Lamzin (1984); Fryer et al. (1996); Brown & Bildsten (1998)) that a neutron star in a common envelope may accrete hyper critically and transforms to a black hole. In this case the old neutron star does not become a recycled pulsar but collapses into a black hole instead. In that case, if the binary survives the common-envelope phase altogether, a high kick velocity is required to dissociate the binary upon the second supernova; the higher mass of the black hole easily prevents dissociation of the binary in a symmetric supernova. Scenario A (with no kicks) thus predicts in this case that, while the birth rate of double neutron stars is small, many young pulsars should be accompanied by a black hole in a short period orbit, which is obviously contradicted by the observations. Furthermore in this case, also Thorne-Żytkow objects will always produce black holes, so this channel for pulsar formation is lost.

Thus already from these simple analytical considerations one observes that with symmetric supernova explosions either many binary radio pulsars with black holes are produced or between 85 and 98% of

---

[3] The phase of mass transfer which preceded the first supernova affects the secondary mass and the initial-mass function argument cannot be applied trivially; the mass transfer process has increased the secondaries mass and therefore the mass of its core. However, taking this into account, still not more than half the systems are expected to be disrupted in the symmetric second super nova.

all pulsars must result from Thorne-Żytkow objects and will have low space velocities – in complete disagreement with the observations.

We will now show that population-synthesis calculations completely confirm the results from the analytical calculations.

3. Results from population synthesis

For the numerical simulations we use the binary evolution program SeBa (see Portegies Zwart & Verbunt, 1996) with more than a million binaries with a primary mass between $8M_\odot$ and $100M_\odot$ selected from a power-law distribution with exponent 2.5 (Salpeter = 2.35). All binaries are evolved in time until the second supernova occurs (see Portegies Zwart & Yungelson (1998) for a detailed description of the models and initial conditions). We assume that all stars are born in binaries with a semi-major axis up to $a = 10^6 R_\odot$ to be present in a flat distribution in log a (Duquennoy & Mayor, 1991). The mass of the secondary is selected between $0.1M_\odot$ and the mass of the primary from a distribution flat in mass ratio (Hogeveen, 1992). We consider cases with and without kicks and discuss the outcome for the different models for pulsar formation mentioned above.

Table 1 summarizes the results of the population synthesis calculations. The number of neutron stars formed are normalized to the total number of supernovae for two models; without a kick (columns two and three; see model A from Portegies Zwart & Yungelson, 1998) and in which a kick is imparted to the newly formed neutron star (columns four and five; see their model B). The table presents the numbers in three decimals in order to be able to recognize them. In practice the last decimal may easily be omitted due to the uncertainties in initial conditions, physics and model parameters.

Table 1
Results of the population synthesis calculations

Result	Without kick		With kick	
	SN Ibc [naked]	SN II [+WR]	SN Ibc [naked]	SN II [+WR]
	After the first supernova			
{*ns*}	0.003	0.157	0.003	0.155
(*ns*, ★)	0.075	0.244	0.025	0.012
ns, ★	0.012	0.241	0.061	0.469
	After the second supernova			
ns	0.001	0.055	0.004	0.211
(*ns*, *ns*)	0.011	0.026	0.002	0.000
ns, *ns*	0.017	0.104	0.004	0.008
Total:	0.119	0.827	0.100	0.855
TŻO	0.001		0.004	

The first column in Table 1 identifies the system which results from the supernova. Notation is taken from Portegies Zwart & Verbunt (1996): *ns* stands for a neutron star and ★ for any non-remnant star, parentheses '(,)' indicate a detached but bound binary and braces '{ }' a merged object. The second column gives the relative fraction of the various systems which originate from exploding naked helium or carbon–oxygen stars (supernovae type Ib and Ic) the third column gives the results for supernova type II (single stars or stars in wide binaries which have lost their hydrogen envelopes by their own radiation pressure in a Wolf-Rayet phase are also included in this column and denoted as type II supernovae as according to Iben & Tutukov (1998), these do not contribute to pulsar formation). The results for the model with a kick (according to the distribution from Hartman, 1997) are presented in the last two columns. The data for the binaries which are dissociated upon the second supernova include also the binaries where the primary produced a black hole. This pollution, however, is not that big; ~5% and ~22% for the models without and with a kick, respectively. The total does not add to unity because some supernovae produce black holes instead of neutron stars; note that in the model without a kick ~20% more black holes are formed than in model B. The last row presents the formation rate of Thorne-Żytkow objects relative to the total supernova rate.

3.1. *Single and double pulsar formation rate if only type Ib and Ic supernovae produce pulsars*

3.1.1. *The case of symmetric mass ejection*

In the model which does not incorporate a velocity kick the fraction of type Ibc supernovae from binaries which produce a neutron star to the total number of type Ibc + II supernovae is ~11.9% (see Table 1).

A binary which survives the first phase of mass transfer becomes a (*he*, ★) binary. If such a binary is disrupted in the first (type Ibc) supernova (which occurs in 1.2% of all supernovae) a single *ns* (pulsar) and a single ★ are released. In some rare cases the binary experiences, and survives, two phases of mass transfer before the first supernova occurs and becomes a double helium star (*he*, *he*) binary. Dissociation of such a (*he*, *he*) binary upon the first supernova releases, next to a single pulsar, a single helium or carbon–oxygen star which may explode at a later instant. Since this single helium star has lost its hydrogen envelope due to the interaction with its companion it is, according to Iben & Tutukov (1998), also a candidate for the formation of a single radio pulsar contributing with a modest 0.1%. A (*he*, *he*) binary which experiences an additional phase of mass transfer before the first supernova occurs may merge and become a single rapidly rotating helium or carbon–oxygen star. The explosion of this single helium star in a type Ibc supernova contributes with 0.3% to the pulsar formation rate as fraction of the total supernova rate (see Table 1 after {*ns*}).

A (*he*, ★) binary which remains bound after the first type Ibc supernova but is dissociated upon the second supernova releases two pulsars and contributes with $2 \times 1.7\% = 3.4\%$ to the production rate of single neutron stars: both are pulsars. Thorne-Żytkow objects contribute only little (~0.1%) to the pulsar formation rate (see Table 1). Assuming only type Ib supernovae to produce pulsars, the total number of single radio pulsars produced as a fraction of the total number of supernovae (type Ib, Ic and type II together) according to this model is ~5.1% ($\equiv 1.2 + 0.1 + 0.3 + 2 \times 1.7 + 0.1$). As to the double pulsar (neutron star binary) formation rate, Table 1 shows that in the model without kicks one expects 0.011 double ones relative to 0.051 single ones, hence about 20% of all pulsars is expected to be born double.

3.1.2. Comparison with other population synthesis results

For our models without kicks the fractions of pulsars produced from type Ibc supernovae relative to the total supernova rate is much smaller than that derived by Iben & Tutukov (1998) who find a birth rate for radio pulsars of 0.007 per year relative to a total birth rate for neutron stars of 0.028 per year; i.e. 25% of all supernovae produce a single radio pulsar (see also Tutukov & Yungelson, 1993). At least part of this discrepancy is a result of the difference in the fraction of binaries which experience mass transfer during their lifetime. In the calculations of Iben and Tutukov a relatively large fraction of binaries experience mass transfer at some time during their evolution and the contribution of type II to the total supernova rate is therefore considerably smaller. We can estimate this effect from the results in Table 1 by counting only the binaries which experience a phase of mass transfer and re-normalizing our results to the type Ibc supernova rate.

3.1.3. Formation rates from interacting binaries

In a population where all binaries transfer mass at some stage during their evolution the two sources for type II supernovae are binaries which merge before the first supernova and explode as single stars (0.157 for our model without a kick), and from (*he*, ★) binaries which are dissociated upon the first type Ibc supernova explosion (1.2%), i.e. of which the secondary may explode as if the star was born single. We computed in Section 3.1.1 in case of no kicks, the fraction of type Ibc supernova to the total supernova rate is 11.9%. The contribution of type Ibc and type II supernovae from interacting binaries to the total supernova rate (including the non-interacting binaries) is in our model therefore given by ~0.288 ($\equiv 0.119 + 0.157 + f \times 0.012$); i.e. ~29% of all supernovae originate from interacting binaries. The fraction f ($\simeq 0.92$) is introduced to quantize the fraction of (*he*, ★) binaries which is dissociated upon the first supernova and of which the released companion may explode in a type II supernova). The formation rate of single pulsars formed in type Ibc supernovae as a fraction of the supernova rate in interacting binaries then becomes $5.1\%/0.29 \approx 18\%$. This rate is of similar order as the result of Iben & Tutukov (1998) who derive a fraction of 25%. This may indicate that they underestimate the contribution of wide binaries to the supernova rate. Note, however, that we underestimated the contribution to type II supernovae due to our adopted minimum mass of $8M_\odot$ to the initial primary mass (Iben & Tutukov adopted a minimum of $10M_\odot$). A binary, for example, which contains a $7M_\odot$ and a $4M_\odot$ star that merges in the first, unstable, phase of mass transfer might form a single star which is massive enough to explode; these binaries are not accounted for in our simulation. By comparing our results with those of Portegies Zwart & Verbunt (1996, see their Table 4), who also take lower mass binaries into account, we estimate that this effect contributes with $\lesssim 10\%$ to the total supernova rate.

3.1.4. Birth rates with kicks

Following the same analysis for the model in which a velocity kick is imparted to the newly born neutron star, the total number of single pulsars produced if only type Ib,c supernovae produce pulsars is 8% ($\equiv 0.3 + 6.1 + 0.4 + 2 \times 0.4 + 0.4$) and the pulsar formation rate from interacting binaries among the total super nova rate becomes between 25% and 31% [$8\%/(0.100 + 0.155 + f \times 0.061)$] (see Table 1). In contrast to the models without a kick, a considerable fraction of the (*he*, ★) binaries is dissociated by the first type Ibc supernova (71%) and as a consequence the contribution of the released secondary stars to the type II supernova rate is considerable. In the model with kicks in which only type Ibc supernovae produce pulsars, the fraction of binary pulsars produced is 0.002/0.08, i.e. about 2.5%, i.e. some 8 times lower than in the case without kicks.

3.2. Discrepancy between pulsar formation rate and supernova rate in case pulsars originate only from Type Ibc supernovae

The model without a kick in which only type Ibc supernovae produce pulsars predicts a discrepancy between the observed supernova rate (of the order of ~0.012 type II per year and ~0.002 type Ibc per year, see Cappellaro et al., 1997) and the single-pulsar formation rate (only 5.1% of the total supernova rate, see Section 3.1 above) of a factor 20. This is clearly contradicted by the observations, which indicate a pulsar formation rate of the same order as the supernova rate in the Galaxy: 0.004 to 0.008 per year was derived by Lorimer et al. (1993) and Hartman et al. (1997) arrive at a pulsar birth rate of ~0.003 per year in the Galaxy, i.e. differing by a factor 3 or less from the supernova rate.

The existence of wide binaries is confirmed by the observations, and we use the total supernova rate for interacting as well as the non-interacting binaries in the further discussion.

In the population synthesis models where also type II supernovae produce radio pulsars the discrepancy between the pulsar formation rate and the supernova rate completely vanishes. In addition to the formation rate of single pulsars from type Ibc supernova (0.051 and 0.080 of the total supernova rate for the models without and with a kick, respectively) type II supernovae make a large contribution to the single pulsar formation rate as can be seen from the table. Binaries that merge before the first type II supernova contribute with 15.7% (15.5% for the model with a kick) to the formation of single pulsars. In non-kick models, non-interacting binaries contribute with 24.1% upon the first supernova (which dissociates the binary) and with ~4.3% ($\equiv 0.055 - f \times 0.012$) from the released companion which might also experience a supernova (note that the correction factor $f \times 0.012$ for binaries which are dissociated upon the first type Ibc supernova and of which the secondary experiences a type II supernova must be applied again.) For the model with a kick these fractions are 46.9% and ~15.0% ($\equiv 0.211 - f \times 0.061$) for the first and second type II supernova, respectively. A smaller fraction of the binaries are dissociated upon the second collapse, releasing two pulsars; 10.4% for symmetric and 0.8% for asymmetric supernovae. The total contribution of type II supernovae to the single pulsar formation rate becomes ~65% ($\equiv 0.157 + 0.241 + 0.043 + 2 \times 0.104$) for the model without a kick and ~79% ($\equiv 0.155 + 0.469 + 0.150 + 2 \times 0.008$) if a kick is imparted to a newly formed neutron star.

If type II supernovae contribute to the formation of single radio pulsars the models without a kick predict that ~70% ($\equiv 0.051 + 0.65$) of all type Ibc plus type II supernovae produce a radio pulsar, and 3.7% form double neutron stars (binary pulsars). Using a supernova rate of 0.01 per year the birth rate of single radio pulsar then becomes ~0.007 per year and the birth rate of binary pulsar is $\sim 4 \times 10^{-4}$ per year. For the model with a kick these fractions are ~87% and 0.2%, respectively, resulting in a birth rate of single pulsars of ~0.009 per year and for double neutron stars of $\sim 2 \times 10^{-5}$ per year.

The observed fraction of binary pulsars is about

0.6% (6 out of some 1000 pulsars). This fraction can, however, not be simply compared with the above predicted fractions of binary pulsars, since the latter ones are young (newborn) pulsars, whereas at least 4 out of the known double neutron star systems in the galactic disk are recycled ones, i.e. which live much longer than new born pulsars, as they spin down much more slowly. With a 0.2% predicted birth rate of double pulsars among newborn pulsars, one indeed would expect only a few non-recycled double neutron stars among the 1000 pulsars in the galactic disk. It thus seems that the observed (very low) fraction of non-recycled double pulsars is in accordance with the predictions from models with kicks in which also the type II supernovae produce pulsars. On the other hand, the observed fraction of non-recycled double pulsars in the galactic disk (at least one out of 1000) is some 100 times lower than that predicted by the model without kicks in which only type Ibc supernovae produce pulsars, and 37 times lower than predicted by the model without kicks in which both type Ibc and type II supernovae produce pulsars.

4. Conclusions

From order-of-magnitude estimates as well as detailed population synthesis studies we argue that type II supernovae (i.e. supernovae resulting from single stars and components of wide binaries) must contribute to the formation of radio pulsars in order to explain the similar Galactic rates (within a factor of a few) of supernovae and birth of single radio pulsars. If type II supernovae are excluded from the formation of pulsars, the predicted pulsar birth rate is at least an order of magnitude smaller than observed.

An asymmetry in the supernova is required to satisfy the condition that the birth rate of high-mass binary pulsars (double neutron stars) is smaller than the birth rate of single radio pulsar by at least two orders of magnitude (Bailes, 1996). With symmetric supernovae and pulsars forming only from interacting binaries one predicts the birth rate of double neutron stars to be of the order of 20% of the pulsar birth rate, unless the bulk of the single pulsars ($>85\%$) would have formed from Thorne-Żytkow objects. In the latter case most pulsars should have low space velocities – contrary to the observations.

With symmetric supernovae and allowing also pulsar formation from type II supernovae one still predicts a birth rate of double neutron stars of about 3.7% of the supernova rate, four times larger than observed. We therefore firmly conclude that, contrary to the suggestions of Iben & Tutukov (1998):

- Single stars and components of wide – non-interacting – binaries must contribute considerably to the formation of pulsars.
- Supernova mass ejection is asymmetric, giving a considerable kick velocity to the neutron star.

Acknowledgements

We thank Don Backer, Dipankar Bhattacharya, Lev Yungelson, Icko Iben and the anonymous referee for critically reading the manuscript and valuable comments. We thank the Institute for Theoretical Physics of the University of California, Santa Barbara, for its hospitality. This work is supported by NWO Spinoza grant 08-0 to E.P.J. Van den Heuvel, the JSPS fellowship to SPZ and by NASA through grant number HF-01112.01-98A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

References

Bailes, M., 1996, in: Compact stars in binaries, J. Van Paradijs, E.P.J. Van den Heuvel, E. Kuulkers (Eds.), Kluwer, Dordrecht, p. 213.
Bisnovatyi-Kogan, G.S. & Lamzin, S.A., 1984, AZh, 61, 323.
Blaauw, A., 1961, BAN, 15, 265.
Blaauw, A., 1964, ARA&A, 2, 213.
Brown, E.F. & Bildsten, L., 1998, ApJ, 496, 915.
Burrows, A. & Hayes, J., 1996, PhRvL, 76, 325.
Canal, R., Isern, J., & Ruiz-Lapuente, P., 1997, ApJ, 488, L35.
Cappellaro, E., Turatto, M., & Tsvetkov, D.Yu., 1997, A&A, 322, 431.
Chevalier, R., 1993, ApJ, 411, L33.
Chevalier, R. & Ilovaisky, S.A., 1998, A&A, 330, 201.
Cordes, J.M. & Chernoff, D.F., 1997, ApJ, 482, 971.
Dalton, W.W. & Sarazin, C.L., 1995, ApJ, 440, 280.
Dewey, R. & Cordes, J.M., 1987, ApJ, 321, 780.

Duquennoy, A. & Mayor, M., 1991, A&A, 248, 485.
Ergma, E. & Van den Heuvel, E.P.J., 1998, A&A, 331, L29.
Fryer, C.L., Benz, W., & Herant, M., 1996, ApJ, 460, 801.
Gunn, J. & Ostriker, J., 1970, ApJ, 160, 979.
Hansen, B.M.S. & Phinney, E.S., 1997, MNRAS, 291, 569.
Hartman, J.W., 1997, A&A, 322, 127.
Hartman, J.W., Bhattacharya, D., Wijers, R.A.M.J., & Verbunt, F., 1997, A&A, 322, 477.
Herant, M., Benz, W., Hix, W.R., Fryer, C.L., & Colgate, S.A., 1994, ApJ, 435, 339.
Hogeveen, S.J., 1992, Ap&SS, 196, 299.
Iben, I., Jr., & Tutukov, A.V., 1998, ApJ, 501, 263.
Iben, I., Jr., Tutukov, A.V., & Yungelson, L.R., 1995, ApJS, 100, 233.
Iben, I., Jr., Ritossa, C., & Garcia-Berro C., 1997, ApJ, 489, 772.
Janka, H.-T. & Müller, E., 1994, A&A, 290, 496.
Johnsoton, H.M. & Kulkarni, S.R., 1991, ApJ, 368, 504.
Kalogera, V. & Webbink, R.F., 1998, ApJ, 493, 351.
Lipunov, V.M., Postnov, K.A., & Prokhorov, M.E., 1996, A&A, 310, 489.
Lipunov, V.M., Postnov, K.A., & Prokhorov, M.E., 1997, MNRAS, 288, 245.
Lorimer, D.R., Bailes, M., Dewey, R.J., & Harrison, P.A., 1993, MNRAS, 263, 403.
Lorimer, D.R., Bailes, M., & Harrison, P.A., 1997, MNRAS, 289, 592.
Lyne, A.G. & Lorimer, D.R., 1994, Natur, 369, 127.
Meurs, E.J.A. & Van den Heuvel, E.P.J., 1989, A&A, 226, 88.
Nomoto, K., Iwamoto, K., & Tomoharu, S., 1995, Phys. Rep., 256, 183.
Podsiadlowski, P., Cannon, R.C., & Rees, M.J., 1995, MNRAS, 274, 485.
Portegies Zwart, S.F. & Verbunt, F., 1996, A&A, 309, 179.
Portegies Zwart, S.F. & Spreeuw, F., 1996, A&A, 312, 670.
Portegies Zwart, S.F. & Yungelson, L., 1998, A&A, 332, 173.
Portegies Zwart, S.F., Verbunt, F., & Ergma, E., 1997a, A&A, 321, 207.
Portegies Zwart, S.F., Kouwenhoven, M., & Reynolds, A., 1997b, A&A, 328, L33.
Shklovskii, I.S., 1970, Astr. Zh., 46, 715.
Tauris, T.M. & Bailes, M., 1996, A&A, 315, 432.
Terman, A.L., Taam, R.E., & Savage, C.O., 1998, MNRAS, 293, 113.
Thielemann, F.K., Hoeflich, P., Khokhlov, A., Nomoto, K., & Wheeler, J.C., 1996, AAS, 189, 1203.
Thorne, K.S. & Żytkow, A.N., 1975, ApJ, 199, L19.
Thorne, K.S. & Żytkow, A.N., 1977, ApJ, 212, 832.
Timmes, F.X., Woosley, S.E., & Weaver, T.A., 1996, ApJ, 457, 834.
Tutukov, A.V. & Yungelson, L.R., 1993, AZh, 70, 812.
Tutukov, A.V., Chugaj, N.N., & Yungelson, L.R., 1984, PAZh, 10, 586.
Van den Heuvel, E.P.J. & Habets, G., 1984, Natur, 309, 598.
Van den Heuvel, E.P.J. & Rappaport, S., 1987, in: Physics of Be stars, Cambride Univ. Press, p. 291.
Van den Heuvel, E.P.J. & Van Paradijs, J., 1997, ApJ, 483, 399.
Woosley, S.E., 1987, The origin and evolution of neutron stars; Proceedings of the IAU Symposium, Reidel, Dordrecht, p. 255.
Woosley, S.E. & Weaver, T.A., 1992, in: D. Pines, R. Ramagaki and S. Tsuruta (Eds.), The structure and evolution neutron stars, Addison Wesley, Redwood City, PA, p. 235.