Astron. Astrophys. 325, 1031–1034 (1997)

ASTRONOMY AND ASTROPHYSICS

On the absence of mildly recycled radio pulsars amongst the population of ordinary single radio pulsars

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Received 12 December 1996 / Accepted 25 March 1997

Abstract. Current scenarios for the evolution of binaries predict that only 1% or less of the single radio pulsars in the galactic disk have been recycled in a binary. The fraction of such pulsars amongst the detected single radio pulsars is smaller than this. For magnetic field strengths $B > 10^{12}$ G the period vs. magnetic field diagram shows no evidence for injection of pulsars at $P \sim 0.5$ s. For magnetic field strengths $10^{10.5} < B < 10^{11.5}$ G recycled single pulsars cannot be discriminated from ordinary pulsars, i.e. there is no reason to assume that they are recycled.

Key words: stars: neutron – pulsars: general

1. Introduction

Many stars are in binaries. The fraction of binaries is known to be high also amongst the more massive stars, the presumed progenitors of radio pulsars (e.g. Garmany et al. 1980). Radio pulsars in binaries are observed to have lower magnetic fields and shorter pulse periods, on average, than single pulsars, which indicates that the presence of a companion affects the properties of a radio pulsar (see, e.g. the review by Phinney & Kulkarni, 1994).

Deshpande et al. (1995) use the pulsar-current method to investigate the possibility that the population of single radio pulsars also harbours a significant sub-population of pulsars whose properties have been affected by the erewhile presence of a companion, that has since been lost. We may call such pulsars mildly recycled pulsars. They investigate two cases in particular. The first case is that of single radio pulsars with magnetic fields $B \simeq 10^{12.0-12.6}$ G. The population of such pulsars may harbour pulsars whose period has been reduced by accretion of matter from a companion, but whose magnetic field strength is little affected. Deshpande et al. suggest that such pulsars are injected in the population at a period of about 0.5 s. The second case investigated is that where both the magnetic field and the rotation period have been reduced. Deshpande et al. suggest that virtually all pulsars with magnetic field $B \lesssim 10^{11.5}$ G fall in this category.

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In this article we investigate these suggestions. In Sect. 2 we study the evolution scenarios of binaries to investigate how often a neutron star accretes mass from a binary companion and then becomes a single radio pulsar, as compared to the number of radio pulsars that are single immediately upon formation. In Sect. 3 we study the evolution of radio pulsars in the period vs. magnetic field diagram to investigate the relation between the fraction of injected and the fraction of detected recycled pulsars among single pulsars. A discussion of our results forms Sect. 4.

2. Prediction of birthrate of single recycled pulsars from scenarios for binary evolution

We may discriminate three types of neutron stars that remain in a binary upon formation and become single later on. The first type is a neutron star that resulted from the first supernova event in a wide non-interacting binary, which is unbound when the companion to the neutron star explodes as the second supernova. The second and third type are the neutron stars formed from the first supernova event in a closer binary, which are later engulfed by their evolving companion and spiral in. For the second type, the spiral in ends in the formation of a close binary in which the neutron star is accompanied by the core of the evolved companion; the neutron star becomes single when this core becomes the second supernova in the binary. For the third type, the spiral-in ends in a merger with the core of its companion into a Thorne-Żytkow object, or alternatively a neutron star with a high-mass accretion disk around it; the neutron star becomes a pulsar when it sheds the mass surrounding it.

Neutron stars are often born with appreciable velocities (e.g. Lyne & Lorimer 1994; but see Hartman 1997). This has consequences for the three scenarios outlined above. As regards the first scenario, an appreciable kick velocity of the neutron star means that a large majority of wide binaries is disrupted at the first supernova event, and only a few remain bound. This scenario is not expected to produce many recycled radio pulsars, even though almost all binaries that survived the first supernova event are disrupted at the second supernova. The neutron stars released from such binaries also have had virtually no accretion from the companion, i.e. they are not recycled. As regards the second and third scenario, close binaries with very unequal masses are prone to merge even before the first supernova; thus only those in a small range of initial orbital periods and mass ratios may evolve into a close binary with a neutron star, or into a Thorne-Żytkow object (e.g. Portegies Zwart et al. 1997). Thus the second and third scenarios also are unlikely to contribute many recycled single radio pulsars. We estimate the birth rates of single recycled pulsars in two ways.

2.1. Birthrate from binary pulsars

A simple rough estimate for the formation rate of mildly recycled single radio pulsars can be made from the birthrate of binaries consisting of two neutron stars. The probability that the second supernova disrupts the binary depends on the pre-supernova mass of the exploding star, on the orbital period and on the kick velocity imparted to the neutron star at birth. For orbits similar to that of PSR 1913+16 and with a kick velocity of a few hundred km/s, the probability of disruption is of a similar order of magnitude as the probability that the binary remains bound. From the birthrate of binaries with two neutron stars, shown by Bailes (1996) to be less than 10^{-5}/yr, and a birthrate of order 10^{-2}/yr for neutron stars, we estimate that the fraction of all neutron stars born as a mildly recycled pulsar made free by a second supernova explosion in a binary is of order 0.1%. Note that this estimate does not include the neutron stars emerging from Thorne-Żytkow objects.

2.2. Birthrate from population synthesis

To quantify these statements, we look at the work by Portegies Zwart & Verbunt (1996). These authors simulate an evolving binary population and calculate the relative frequencies of different evolutionary scenarios. In their Table 4, they list the frequency of stars exploding as the second supernova in a binary. In their model AK, for each supernova of type II arising from a (current or erewhile) binary star, the fraction exploding as the second star in a binary is about 0.8%, subdivided as 0.03% exploding as supergiant, 0.31% exploding as Wolf Rayet star, 0.06% exploding as helium rich star, and 0.37% exploding as carbon rich star. The total galactic type II supernova rate consists for about half of supernovae from primordially single stars, and half of supernovae from stars of a binary. Taking into account the supernovae arising from single stars, we thus find that less than about 0.4% of all supernovae occur as the second one in a binary, according to these calculations. From Table 5 of Portegies Zwart & Verbunt we learn that about 0.1% of all neutron stars resulting from type II supernovae remain bound in a binary with another neutron-star; thus less than 0.3% of all neutron stars enter the population of single radio pulsars following the supernova explosion of their companion. Only those exploding as helium rich or carbon-oxygen rich (i.e. having lost much of their envelope during the binary evolution) will release neutron stars that probably have undergone effects of accretion from their companion. Thus, the mildly recycled pulsars released by a supernova explosion of their companion according to scenario AK makes up only about 0.15% of the pulsar formation.

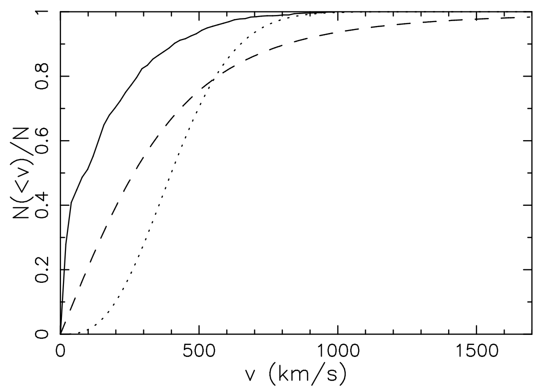

Fig. 1. Cumulative velocity distributions for neutron stars born from a single star, according to Lyne & Lorimer (1994; in our approximation as a Maxwellian, dotted line) and to Hartman (1997, dashed line). The solid line shows the cumulative velocity distribution of mildly recycled single radio pulsars, according to model AK of Portegies Zwart & Verbunt (1996).

A more efficient way to make mildly recycled radio pulsars would be via the third scenario outline above: according to Table 5 of Portegies Zwart & Verbunt (1996) the formation rate of Thorne-Żytkow objects is about 0.4% of that of the type II supernova rate.

In conclusion, the binary evolution scenarios that take account of the kick velocities imparted to the newly born neutron stars predict that less than 1% of the single neutron stars are recycled.

2.3. New synthesis models

In the models by Portegies Zwart & Verbunt (1996), the initial mass ratios of binaries are chosen from a distribution $\Phi(q) = 2/(1+q)^2$, where $q \leq 1$. (Thus, if M is the mass of the primary, and m of the secondary, $q \equiv m/M$.) This predicts a fair number of low-mass companions to high-mass primaries. The observations however suggest that many high-mass stars are accompanied by high-mass companions. In the models by Portegies Zwart & Verbunt the newly born neutron stars were given a kick velocity from the distribution determined from the observations by Lyne & Lorimer (1994), approximated with a Maxwellian velocity distribution with an average root mean square velocity of 450 km/s. It has been argued that the actual distribution of initial velocities has a fair number of pulsars at low velocities, $v_i < 200$ km/s, say, as is the case for an adaptation of the Paczyński (1990) function

$$p(u)du = \frac{4}{\pi}\frac{du}{(1+u^2)^2} \qquad \text{where} \qquad u \equiv \frac{v_i}{\sigma_v} \tag{1}$$

which has $\sigma_v \simeq 600$ km/s (Phinney & Hansen, private communication; see also Hartman 1997). The two velocity distributions are compared in Fig. 1.

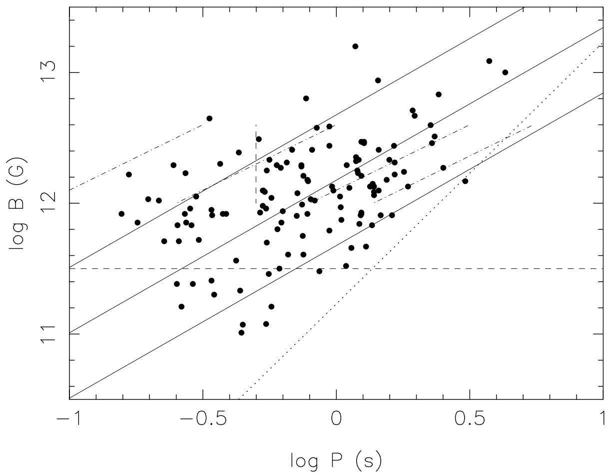

Fig. 2. Periods and magnetic fields of 129 radio pulsars used by Hartman et al. (1997) for comparison with simulated pulsar populations. The dotted line indicates the death-line, to the right of which no pulsars are observed. The solid lines give the periods, as a function of magnetic field, to which neutron stars can be spun up when they accrete at (above to below) 10, 1, and 0.1 times the Eddington limit. The vertical dashed line indicates the location where recycled pulsars with high magnetic field are injected, and the horizontal dashed line the limit below which all pulsars are recycled, according to Deshpande et al. (1995). The dash-dotted lines give locations of constant age of ordinary pulsars of (left to right) 0.1, 1, 10 and 30 Myr.

We have therefore also performed binary population synthesis models in which we choose the mass ratio from a distribution in which $\Phi(q) = 1$, and in which the kick velocities are distributed according to Eq. 1. This boosts the fraction of recycled neutron stars released by a second supernova in a binary to about 1% of all supernova, and those formed from Thorne-Żytkow objects to 2-3%. However, the birth rate of binaries consisting of two neutron stars is also boosted: the ratio of binary pulsars like PSR 1913 + 16 to single recycled pulsars is virtually the same in the different models, in accordance with our reasoning from Sect. 2.1. We therefore conclude that it is not possible – within the framework of the binary evolution models – to boost the number of mildly recycled single radio pulsars without violating the observed birthrate of binary radio pulsars.

3. Prediction of detected fractions of recycled single radio pulsars

The fraction of recycled pulsars amongst detected single pulsars does not necessarily reflect the birth fraction of the recycled pulsars amongst single radio pulsars. To investigate this we take a closer look at the injection as suggested by Deshpande et al. (1995). In Fig. 2 we show the locations in the period magnetic-field diagram where the injection takes place, according to Deshpande et al., together with the death-line, and the spin-up lines for three different accretion rates, together with 129 pulsars used by Hartman et al. for comparison with their simulations.

Deshpande et al. (1995) argue that injection of recycled radio pulsars takes place at a period of about 0.5 s, for $B = 10^{12.0-12.6}$ G. As can be seen in Fig. 2, this location in the $B-P$ diagram cannot be reached if accretion is limited by the Eddington rate. If we allow the ad hoc hypothesis by Deshpande et al. (1995) that the recycled pulsars have accreted at ten times the Eddington limit, we still face the problem that the spin-up hypothesis cannot explain that injection would occur at 0.5 s (or any other fixed period) but rather predicts that injection occurs over a range of periods 0.25 s$\lesssim P \lesssim$ 1.0 s.

At an accretion rate of ten times the Eddington limit, recycled pulsars with $B \simeq 10^{10.5-11.5}$G are injected at $P < 0.1$ s, i.e. they cannot be discriminated at all from ordinary radio pulsars born with low fields.

3.1. Fraction of detected recycled pulsars

As shown by Fig. 2, injection at the spin-up line for ten times the Eddington limit is virtually identical to injection of radio pulsars at an age of 1 Myr, for $B = 10^{12.0-12.6}$ G. For pulsars with these high fields, the total time until the death line is reached is much longer, ranging from 80 to 20 Myr. If we follow Deshapande et al. (1995) in assuming that the dependence of luminosity and beaming on pulse period and magnetic field strength of injected pulsars is the same as for ordinary pulsars, we find that the fraction of detected pulsars that originated as an injected pulsar is about the same as the injection fraction.

If injection would occur at the spin-up line for the Eddington limit, the injected pulsars would have similar properties as ordinary pulsars with an age of about 7 Myr. For $B = 10^{12.3}$ G this is about a sixth of the total life time of an ordinary pulsar. An injection of $x\%$ at this spin-up line would thus be predicted to lead to a fraction of $0.86x\%$ of detected pulsars. In fact, even this prediction is an upper limit: the recycled pulsars are injected at relatively long periods, where smaller pulse beamwidths lead to a smaller probability of detection.

We have used the population synthesis code of Hartman et al. (1997) to investigate the relation between injection fraction and detection fraction of recycled pulsars. In our simulations the recyled radio pulsars differ from the ordinary ones in their birth velocities, which are taken from the velocity distribution for neutron stars released at the second supernova event in a binary as calculated by Portegies Zwart & Verbunt (1996). This distribution is compared with those of neutron stars born from a single progenitor in Fig. 1. The velocities reflect the pre-explosion orbital velocities, lessened somewhat by gravitational interaction with the new neutron star. We assume that the luminosity and beaming of mildly recycled pulsars have the same dependences on period and period derivative as the luminosity and beaming of ordinary pulsars. For injection at the spin-up line of ten times the Eddington limit, the complete simulations confirm that the injection and detection fractions are very similar, at $B = 10^{12.0-12.6}$ G. For injection at the spin-up line for the Eddington limit, at the same magnetic field strengths, the detection fraction is about a third of the injection fraction.

4. Discussion

We have argued that the fraction of recycled pulsars hidden in the ordinary pulsar population is very small, less than 1% according to predictions based on our knowledge of binary evolution. In this section we want to elaborate on certain aspects concerning the recycling of radio pulsars.

From observations of millisecond pulsars we know that the magnetic field and period of a neutron star can be reduced in a binary, but the theoretical understanding of the exact processes that take place is still very poor. In particular, it is not possible to predict reliably how much mass the neutron star accretes, nor the effect of this on its period and magnetic field strength. Thus, theory does not predict the location in the B-P diagram where recycled pulsars are injected.

It is important to notice that Hartman et al. (1997) can explain the observed distribution of pulsars in the period vs. magnetic field diagram with *a single pulsar population*, and find no need for a second population. How then can we explain the jump in the pulsar current at $B = 10^{12.0-12.6}$ G and $P = 0.5$ s that has been found by Deshpande et al. (1995)? We note that Lorimer et al. (1993), who limit their analysis to pulsars with luminosities higher than 10 mJy kpc^2 to reduce the impact of selection effects, do not find such a jump in their detailed pulsar current studies. This suggests that the evidence for injection found by Deshpande et al. (1995) is an artefact of selection effects operating on faint pulsars.

At low $B \simeq 10^{10.5-11.5}$ G injected single pulsars cannot be discriminated from ordinary ones. The population synthesis calculations by Hartman et al. (1997) show that enough ordinary pulsars will populate that region even with a very small birthrate of these pulsars. Their standard calculations generate a fraction of 0.8% pulsars with fields $B < 10^{11.5}$ G, but in the simulated sample of detected pulsars this amounts to about 9%, due to the fact that these pulsars are very long-lived and in fact also may experience some field decay. So there is no reason to assume that any of the observed pulsars with $B \simeq 10^{10.5-11.5}$ are recycled pulsars.

References

Bailes, M. 1996, in J. van Paradijs, E. van den Heuvel, E. Kuulkers (eds.), Compact stars in binaries, IAU Symposium 165, Reidel, Dordrecht, p. 213

Deshpande, A., Ramachandran, R., Srinivasan, G. 1995, JA&A, 16, 53

Garmany, C., Conti, P., Massey, P. 1980, ApJ, 242, 1063

Hartman, J. 1997, A&A, 322, 127

Hartman, J., Bhattacharya, D., Wijers, R., Verbunt, F. 1997, A&A, 322, 477

Lorimer, D., Bailes, M., Dewey, R., Harrison, P. 1993, MNRAS, 263, 403

Lyne, A., Lorimer, D. 1994, Nat, 369, 127

Paczyński, B. 1990, ApJ, 348, 485

Phinney, E., Kulkarni, S. 1994, ARA&A, 32, 591

Portegies Zwart, S., Verbunt, F. 1996, A&A, 309, 179

Portegies Zwart, S., Verbunt, F., Ergma, E. 1997, A&A, 321, 207

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