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Are Many Pulsars Processed in Binary Systems?

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Abstract. A detailed statistical analysis of pulsar *current* is presented. The conclusions reached are the following: (1) The birthrate of pulsars is about one in 75 ± 15 years. (2) There is evidence for *injection* of pulsars into the population of solitary pulsars. Such an injection is particularly pronounced in the magnetic field range $12 < \log B < 12.6$. (3) This is interpreted as due to *recycled pulsars* being released into the population. (4) We tentatively conclude that as much as 10 – 15% of all pulsars may have been born and processed in binary systems.

Key words: Pulsars—stars: evolution—stars: magnetic, stars: stellar statistics.

1. Introduction

Ever since their discovery pulsars have been a subject of many statistical studies. There have been several attempts to estimate the birthrate and other statistical properties of the pulsar population, and over the past ten years many new suggestions/ models have emerged to carefully account for various selection effects which enable one to study more reliably the intrinsic properties of the pulsar population (e.g. Narayan 1987; Narayan & Ostriker 1990; Bhattacharya *et al*. 1992). The recent electron density model of Taylor & Cordes (1993) represents an important improvement and its use has led to significant revision of several earlier conclusions (see Lorimer *et al* 1993). In the light of this we feel it may be worthwhile to re-examine the properties of the pulsar population by studying the distribution of the *pulsar current*. Apart from attempting to obtain a more reliable estimate for the pulsar birthrate, we focus on possible evidences for *injection* of pulsars in various field ranges (Vivekanand & Narayan 1981). The motivation for this stems from the recent suggestion by Srinivasan *et al*. (1990) on the mechanism for the magnetic field decay. This mechanism involving the binary history of recycled pulsars predicts an apparent injection of pulsars processed in binaries close to the equilibrium period line (Srinivasan *et al*. 1990).

In the first part of this paper we present the results of our analysis based on the current of pulsars, where we have tried to carefully account for several observational selection effects. In the second part we address the following important question: *What fraction of pulsars comes from binary systems*? We also present evidence for the ‘injection’ of recycled pulsars from binary systems into the population of normal solitary pulsars.

1.1 *The pulsar current*

One of the important questions related to the pulsar population is the pulsar birthrate. There are many methods of estimating this. However, for the result to be reliable the method must allow for the possibility that the birthrate of pulsars with different magnetic fields may not be the same. One of the ways of taking this into account is by calculating the current of pulsars. The pulsar current in a period bin of width ΔP around a period (P) can be formally defined as (Phinney & Blandford 1981; Vivekanand & Narayan 1981),

$$J(P) = \frac{\sum_{i=1}^{n_{psr}} S_i \dot{P}_i}{f \Delta P}. \qquad (1)$$

where n_{psr} is the number of known pulsars in the bin, f is the beaming fraction (which is assumed to be 0.2 throughout our analysis), $\dot{P}_i$ is the time derivative of the period and S_i is the scale factor (which corrects for the observational selection effects) for the ith pulsar. Provided the current in the bin considered has reached its maximum value – i.e. the initial periods of all pulsars are less than the period under consideration, and death of pulsars has not yet set in, then *this maximum value of the current represents the birth rate of pulsars* (Vivekanand & Narayan 1981). The procedure to compute the scale factors involves a detailed Monte Carlo simulation, which is described below.

1.2 *Selection effects*

The observed distribution of pulsars in the Galaxy differs systematically from the *true* distribution due to various observational selection effects. The detectability of a pulsar is affected by both its low luminosity and the pulsed nature of the emission. Effects such as interstellar scattering and dispersion cause broadening of the pulses, resulting in a reducetion of the peak pulsed flux. A detailed treatment of modeling the various selection effects in the Galaxy can be found in Narayan (1987) and Narayan & Ostriker (1990). The parameters which go into the modelling of selection effects are (i) regions covered by the pulsar surveys, (ii) the time resolution used and sensitivities of the surveys, (iii) scattering and dispersion smearing of pulse profiles, and (iv) the assumed luminosity model for pulsars. In the discussion to follow, our sample of pulsars is restricted only to those which in principle could have been detected by any one of the following eight major surveys: (1) Jodrell Bank survey, (2) U. Mass-Arecibo survey, (3) Second Molonglo survey, (4) U. Mass-NRAO survey,(5)Princeton-NRAO Phase-I survey, (6) Princeton-NRAO Phase-II survey, (7) Princeton-Arecibo survey and (8) Jodrell Bank-1400 MHz survey. Of the 570 known pulsars to date, only 325 pulsars satisfy the above mentioned criterion. The globular cluster pulsars, extragalactic pulsars and millisecond pulsars are not included in this analysis.

The *detection probability* is the ratio of the observed number of pulsars to the *true* number. It can be defined for a given pulse period P and a luminosity L, at a given height z from the galactic plane as,

$$\text{Det. Prob.}(P, L, z) \equiv \frac{\iint_{\mathrm{obs}} \rho_R(R) R \mathrm{d}R \mathrm{d}\phi}{\iint \rho_R(R) R \mathrm{d}R \mathrm{d}\phi}. \qquad (2)$$

Here, R and ϕ are the galactocentric radius, and the azimuthal angle, respectively. The function ρ describes the distribution of pulsars with respect to the corresponding variable inside the bracket. The integral in the denominator is over a volume of a slab of the galaxy at a height z from the galactic plane while that in the numerator is only over a subset of the above volume of the galaxy where a pulsar of period P and luminosity L can be detected by at least one of the eight surveys mentioned above. The *scale factor* $S(P, L, z)$ is defined to be the reciprocal of the detection probability.

We computed this scale factor for various luminosities, periods and z heights by a Monte Carlo simulation. A detailed description of such a procedure to estimate the scale factors can be found in Narayan (1987) (see also Narayan & Ostriker 1990; and Bhattacharya *et al.* 1992).

A model for the luminosity as a function of P and $\dot{P}$ then enables one to evaluate $S(P, \dot{P}, z)$ from $S(P, L, z)$ (see Prozynski and Przybycien 1984; Narayan & Ostriker 1990, for luminosity models). To account for the dispersion of luminosities around the model luminosity one finds two methods in the literature. The first method can be summarized by the following equation (Narayan 1987),

$$S(P, \dot{P}, z) = \int S(P, L, z)\rho_L[\log L - \log L_m(P, \dot{P})]\,\mathrm{d}\log L, \tag{3}$$

where the *scale factor* $S(P, L, z)$ is averaged with the luminosity spread function $\rho_L[\ ]$, giving a weighted harmonic mean of the detection probability ($S^{-1}(P, L, z)$). The second way is to average the detection probability (note that the scale factor is the reciprocal of the detection probability) with the luminosity spread function (Narayan & Ostriker 1990). According to this prescription,

$$\begin{aligned} S(P, \dot{P}, z) &= \left[\int \rho_L[\log L - \log L_m(P, \dot{P})](\text{det. prob.})\,\mathrm{d}\log L\right]^{-1} \\ &= \left[\int \frac{\rho_L[\log L - \log L_m(P, \dot{P})]}{S(P, L, z)}\,\mathrm{d}\log L\right]^{-1}. \end{aligned} \tag{4}$$

Noting that the spread function $\rho_L[\ ]$ is a *probability distribution function* and that the reciprocal of the scale factor gives the pulsar detection probability, it is clear that the procedure given in equation (4) is more appropriate. Hence we adopt the second method in the following analysis. The use of the first method (equation 3) leads to the overestimation of the scale factors.

The scale factors thus evaluated as a function of P and $\dot{P}$, can also be expressed as scale factors as a function of P and B viz., $S(P, B, z)$, where B is the surface magnetic field. This is done in a straight-forward way with the help of the simple relation $B^2 \propto P\dot{P}$.

2. The birthrate of pulsars

As explained in section 1 the pulsar current is a measure of the birthrate minus the deathrate. Figure 1 shows the pulsar current calculated by us, as a function of the rotation period. As may be seen from this histogram the current continues to rise till a period of ~0·6 sec. A straightforward interpretation of this is that not all pulsars are

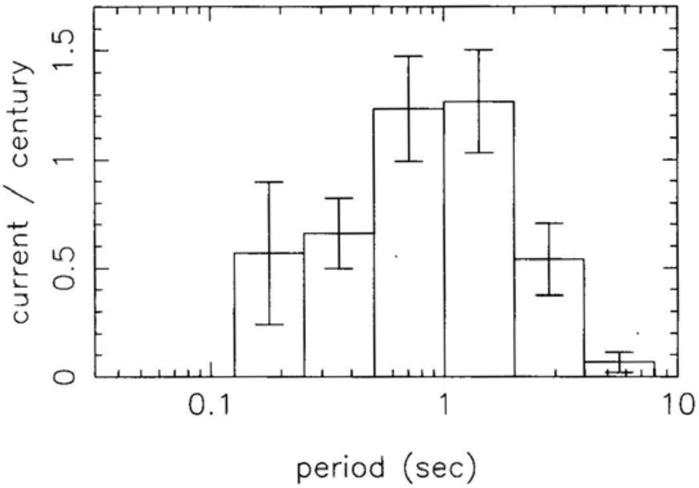


Figure 1. The current distribution as a function period. As may be seen, the current reaches its maximum value around a period of 0.5 s, and begins to decline at around 2 s. The maximum value of the current corresponds to a pulsar birth rate of about 1 in 75 years.

born spinning as rapidly as say, Crab pulsar. The current is roughly constant in the period range of 0·6–2 sec. Beyond a period of ~ 2 sec. the current decreases presumably because the death of pulsars becomes important. The maximum current attained implies a birthrate of pulsars of one in 75 ± 15 years (the error indicated is only the Statistical error). This should be compared with one in about 100 years derived by Narayan & Ostriker (1990) and one in 125250 years for a luminosity limited set of samples by Lorimer *et al.* (1993).

To understand the sensitivity of the derived birthrate to the assumed distance model (Taylor & Cordes 1993) as well as the luminosity model (Narayan & Ostriker 1990), we repeated the current analysis using luminosity model of Narayan (1987), and the distance model of Lyne *et al.* (1985). The corresponding birthrates are summarized in Table 1. In every case the spread of luminosities about the model value was taken into account in a manner given in equation (4).

As one can see, *the old luminosity model severely underestimates the birthrate*. This should be expected because this model does not allow for observational selection effects. The revision in the birthrate due to the change in the distance model is roughly by a factor of two.

Table 1. Galactic birthrate of pulsars obtained by old and new distance model and luminosity model.

	Old dist. model (per century)	New dist. model (per century)
Old lumin. model	0.32	0.15
New lumin. model	2.8	1.4

Refs. **1.** Narayan(1987), **2.** Narayan & Ostriker (1990), **3.** Lyne *et al.* (1985) and **4.** Taylor & Cordes (1993).

While the birthrate estimated by us is in good agreement with that of Narayan & Ostriker (1990), the estimate by Lorimer *et al.* (1993) is somewhat on the lower side. We wish to comment upon this briefly. As already mentioned, Lorimer *et al* consider only pulsars with radio luminosities greater than 10mJy kpc^2. The recent discovery of PSR J0108-1431 indicates that active pulsars with radio luminosities as low as 0-06 mJy kpc^2 may not be uncommon. Tauris *et al.* (1994) have argued that the number of pulsars in the Galaxy similar to J0108-1431 could be at least 5×10^5. The inclusion of such a population will increase the estimated birthrate substantially. A short field decay timescale ~ 5 Myr as assumed by Tauris *et al* (1994), will revise the birthrate upwards to one in 40 years. Even a more reasonable field decay time scale ~ 25 Myr will give a birthrate of about one in 120 years. We therefore conclude that there is no serious discrepancy between our birthrate and that derived by Lorimer *et al.* (1993).

The pulsar birthrate should ideally match the rate of Supernovae that results in the formation of neutron stars. The core-collapse supernova rate (Type Ib + II) inferred from the observations of external galaxies (van den Bergh 1991 and references therein) of morphology similar to ours is about 1.6 per century per $10^{10} L_{\odot}$(B) (about one in 60 years). Using the Initial Mass Function of Scalo (1986) and the Population-I star model of Ratnatunga & van den Bergh (1989), van den Bergh (1991) estimates the Galactic core-collapse supernova rate to be one in about 100 years. Given the uncertainties in the determination of the birthrate of pulsars as well as the frequency of Supernovae, we do not consider them to be discrepant.

3. Fraction of pulsars from binary systems

Although the number of known binary pulsars is still only a couple of dozens, there is no reason to conclude that the vast majority of the solitary pulsars may not have come from binaries. After all, one expects the majority of the binaries to disrupt during supernova explosions. The question is, *can one estimate the fraction of pulsars that comes from binaries*? Radhakrishnan & Srinivasan (1981) were the first to address this question. If the magnetic field of the first-born pulsar had decayed significantly in the time interval between its birth and the onset of mass transfer from the companion, then it will be spun up to relatively short periods and will stand out from the general population of pulsars like PSR 1913 + 16. Based on this criterion, PSR 1541-52 and PSR 1804-08 were tentatively identified by Radhakrishnan & Srinivasan (1981) as recycled pulsars. If on the other hand the magnetic field of the first-born pulsar had not decayed significantly, then even after it is spun up it will be deposited close to the spin-up line but this time inside the main island of pulsars. It now appears that the magnetic fields of solitary neutron stars do not decay significantly during their lifetime as pulsars. But there are strong reasons to believe that the magnetic fields of neutron stars born and processed in binary systems do decay (Srinivasan *et al.* 1990; Bhattacharya *et al.* 1992). In the model due to Srinivasan *et al.* (1990), the decay is related to the expulsion of flux from the interior as the neutron star is dramatically spun down during the main sequence phase of the companion. If one accepts this scenario, then there are three possibilities as showninFigure2. In the case of low mass binaries, which are presumably the progenitors of millisecond pulsars, the neutron stars are possibly spun down sufficiently for the field to decay to very low values ~ 10^8 G (Jahan Miri & Bhattacharya 1994). In intermediate mass and/or wide binaries, the spin-down and the consequent flux expulsion may be less pronounced as shown m the alternative

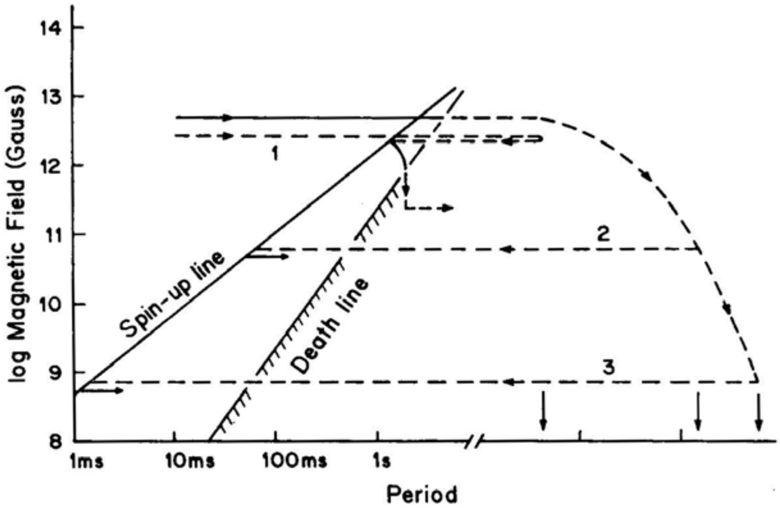


Figure 2. (From Srinivasan *et al.* 1990). Three possible evolutionary scenarios for recycled pulsars are shown here. Track 3 corresponds to the life history of the firstborn neutron star in low mass binary systems. In such systems the magnetic field of the neutron star presumably decays by many orders of magnitude and is spun up during accretion to a period of a few milliseconds. Track 2 represents the life history of recycled pulsars such as PSR 1913 + 16 and **PSR** 0655 + 44. The progenitors of such pulsars are thought to be intermediate mass binaries, and the decay of the magnetic field of the firstborn neutron star is still quite significant. In massive binary systems the first born neutron star may not be spun *down* significantly enough for a substantial fraction of the core field to be expelled. Consequently the magnetic fields of such pulsars will still be close to its original value when it is spun up during the mass transfer phase. These pulsars will consequently be injected into the normal population of high field solitary pulsars. This scenario is labelled as Track 1. The 'spin-up line' in this figure is the equilibrium period line corresponding to accretion at the Eddington rate.

(2) in the figure. In the case of massive and tight binaries the companion may evolve so quickly that there may not have been time for the flux to be expelled from the interior, let alone decay in the crust. This is scenario (1) in the figure. Keeping in mind these various possibilities we looked for *injection* of pulsars close to the spin-up line within the main population of pulsars.

3.1 *Evidence for injection in the low field range* 10^{10}–$10^{11\cdot 5}$ G

Let us first concentrate on the pulsars with fields less than about $10^{11\cdot 5}$ G (encircled in Fig. 3) and ask how these pulsars might have evolved to their present position in the log B-log P diagram. Let us first consider the possibility that they might have evolved to their present positions in the diagram from the *left.* This admits two alternative scenarios: (i) Their fields are relatively low because of rapid field decay, or (ii) they were born with low fields. The first alternative, i.e., they are old aged Crab or Vela pulsars is inconsistent with the present estimates of the field decay time scales. Infact, it may be appropriate to mention in this context that it is this scenario (i) that led one to erroneously conclude earlier that magnetic fields of neutron stars decay rapidly (Radhakrishnan & Srinivasan 1981; Radhakrishnan 1982). Such a conclusion is in

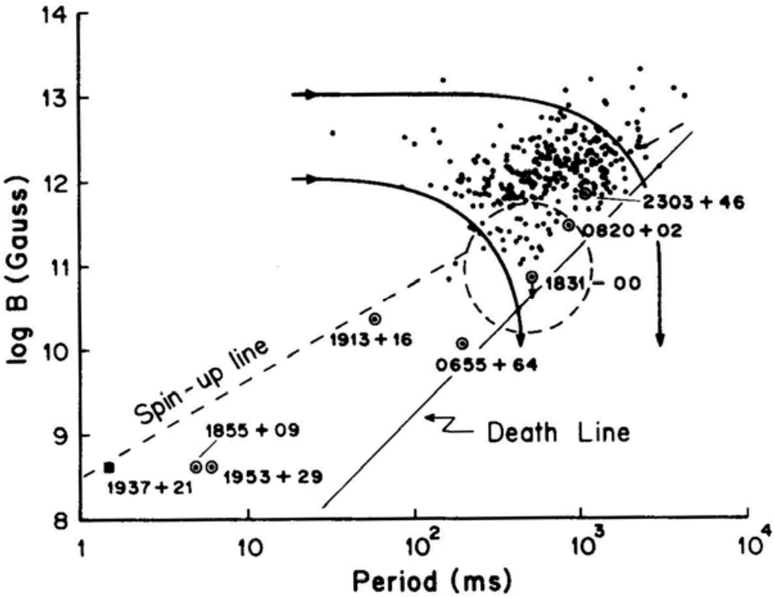


Figure 3. (From Srinivasan 1991). The distribution of observed pulsars. As argued in the text, it is quite likely that the low field pulsars inside the *dashed circle* did not evolve from the left of the diagram due to rapid field decay (as was suspected earlier), but were 'injected' close to the spin-up line. In other words, these are most likely *recycled pulsars.*

contradiction with what an analysis of pulsar statistics reveals. The second alternative viz., that they were born with short period and low magnetic field cannot be ruled out so easily. At first sight one would be tempted to say that the absence of a few pulsars with low magnetic fields and periods in the range of a few hundred milliseconds rules out this possibility. But this would not be a sound argument since one is dealing with a very low birthrate in this field range and the absence of low field pulsars to the left of the diagram may merely be a consequence of small number statistics (Fig. 4 suggests that one may be dealing with a birthrate as low as one in ~ 5000 yr). In addition the recently discovered pulsar PSR J0108-1431 with P = 0·8076 sec. and log B = 10·92 Gauss may be a counter example. Despite this we now wish to suggest that the pulsars with fields less than $\sim 10^{11\cdot 5}$ G might have evolved to their present position from the *right* of the diagram.

Figure 5 shows the distribution of *true* number of pulsars in the P – B plane. The *true* number of pulsars in any given bin of width ΔP around a period P and ΔB around field B is given by,

$$N_B(P) = \frac{1}{f} \sum_{i=1}^{n_{psr}} S(P_i, \dot{P}_i, z_i), \tag{5}$$

where f is the beaming factor and $S(P_i, \dot{P}_i, z_i)$ is the scale factor corresponding to the period P, period derivative $\dot{P}$ and the height z from the plane of the ith pulsar. One sees that the low field pulsars that we have been discussing appear to form a distinct island in the *true*-number distribution shown in Fig. 5, there appears to be a valley between

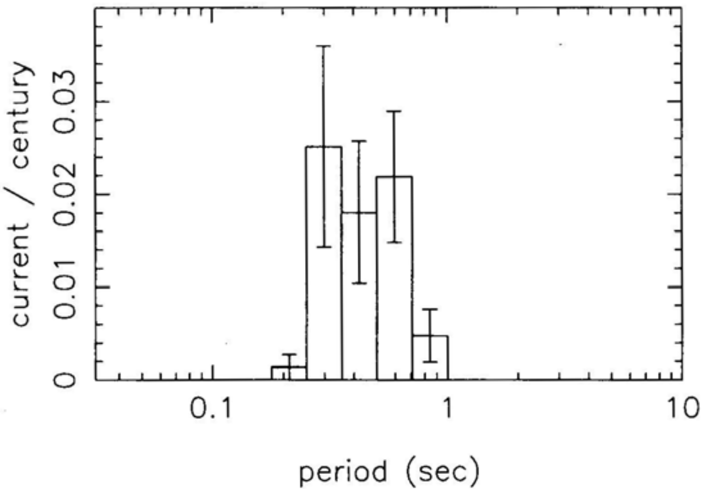


Figure 4. The current of pulsars in the field range log B = 10.5 –11.5. As may be seen, the birth rate of these pulsars is roughly 1 in 5000 years.

the two populations of pulsars. We have tried to test the statistical significance of this valley by doing a variety of tests. For example, a valley was defined in the field range 11.5 < log $B(G)$ < 11.6 and the period range from 0.1 second to the period at the deathline. Then the number of known pulsars in the valley was counted. This number was taken as a reference. Then (i) every pulsar was randomly assigned the luminosity of some other pulsar, (ii) every pulsar was randomly assigned the $\dot{P}$ of some other pulsar, (iii) the number of pulsars in the valley was counted. Steps (i) to (iii) were repeated a large number of times (~ 10000). From the distribution of the number of pulsars in the valley the significance of the reference number was found to be 98·37%.

Although the significance level is not extremely high we wish to advance the view that these pulsars form a distinct population. Their location close to the *spin-up line* suggests that they may, infact, be recycled pulsars. As we shall see later, additional support for this comes from the location of these pulsars with respect to the Galactic plane. The birthrate of these relatively low field pulsars suggests that they constitute roughly 3% of the total population.

3.2 *High field injection*

Let us now examine the pulsar population with larger magnetic fields (log B > 12) in the upper part of Fig. 3. If at all there is *injection* of firstborn pulsars (from massive binaries) into this population, then one expects to see a step in the current in the vicinity of the spin-up line. The integrated current of pulsars shown in Fig. 1 shows such a step at a period ~ 0.5 sec. If such an injection is not an artefact, and if it were due to recycled pulsars then one would expect pulsars contributing to that step to have magnetic fields in a narrow range defined by the spin-up line. To see if this is true or not we have plotted in Fig. 6 histograms of current in three different field ranges. As may be seen, only in the narrow field range 12 < log B < 12.6, there is a step in the current. It one takes the step in the

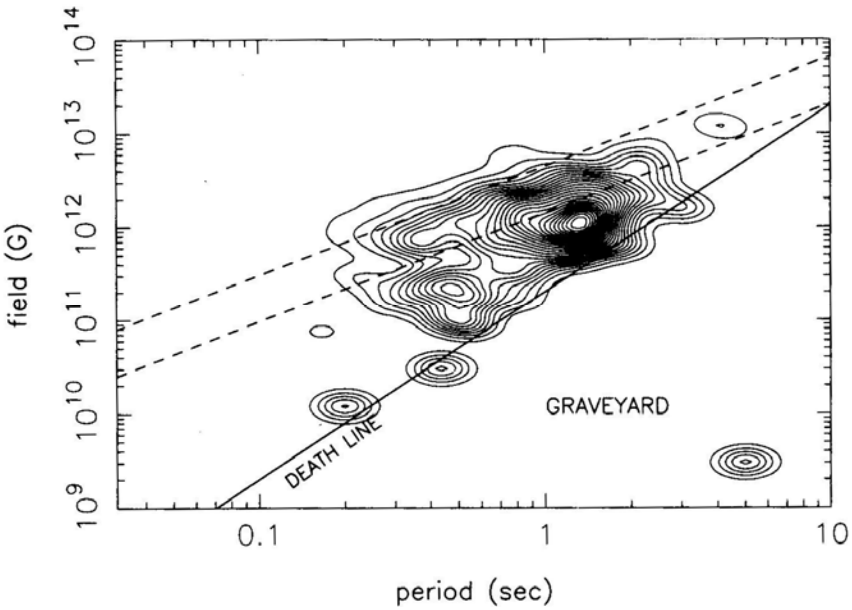


Figure 5. The *true* number distribution of pulsars as defined by equation 5. The contours have been smoothed with a function shown in the bottom right hand corner of the panel. It may be seen that pulsars in the field range log B = 10.5–11.5 appear to form a distinct island; there appears to be a *valley* between the distribution of these pulsars and the high field pulsars. As discussed in section 3, the statistical significance of this valley is 98.37%. The two 'dash' lines are equilibrium period lines; the lower one corresponds to accretion at the Eddington rate, and the upper one to accretion at 10 times the Eddington rate.

current seriously then there certainly appears to be a tight correlation between the magnetic field and the periods of the pulsars contributing to the step in the current, thus lending support to the suggestion that a reasonable number of recycled, but solitary pulsars are present in the pulsar population. It should be pointed out that an injection of pulsars at a period of ~0·5 sec. was originally pointed out by Vivekanand & Narayan (1981). More recently Narayan & Ostriker (1990) noted that injection occurs in a narrow field range (however their approach was very different from the present current analysis). The new suggestion we wish to make is to relate the injection to recycled pulsars.

The correlation between the rotation periods and the magnetic fields of the injected population may be seen better in Fig. 7 where we have plotted the current as a contour diagram in the B — P plane. This current is calculated using equation (1) in various magnetic field 'bins'. Concentrating for a moment in the field range $10^{12} < B < 3 \times 10^{12}$ Gauss, one can see that the current builds up rather continuously till a period of about 0.5 sec., at which there is a step or a cliff (as may be readily seen, the contour plot reveals many 'hills'. These are merely individual high $\dot{P}$ pulsars which appear as 'little hills' due to the fact that the current distribution has been smoothed with the function shown in the right hand bottom corner of the plot. Contrary to this, the step in current referred to above, and also discussed in the above paragraph, is a statistically significant feature since a fairly large number of pulsars contribute to it). Also shown in the figure are two equilibrium period lines corresponding to the Eddington accretion

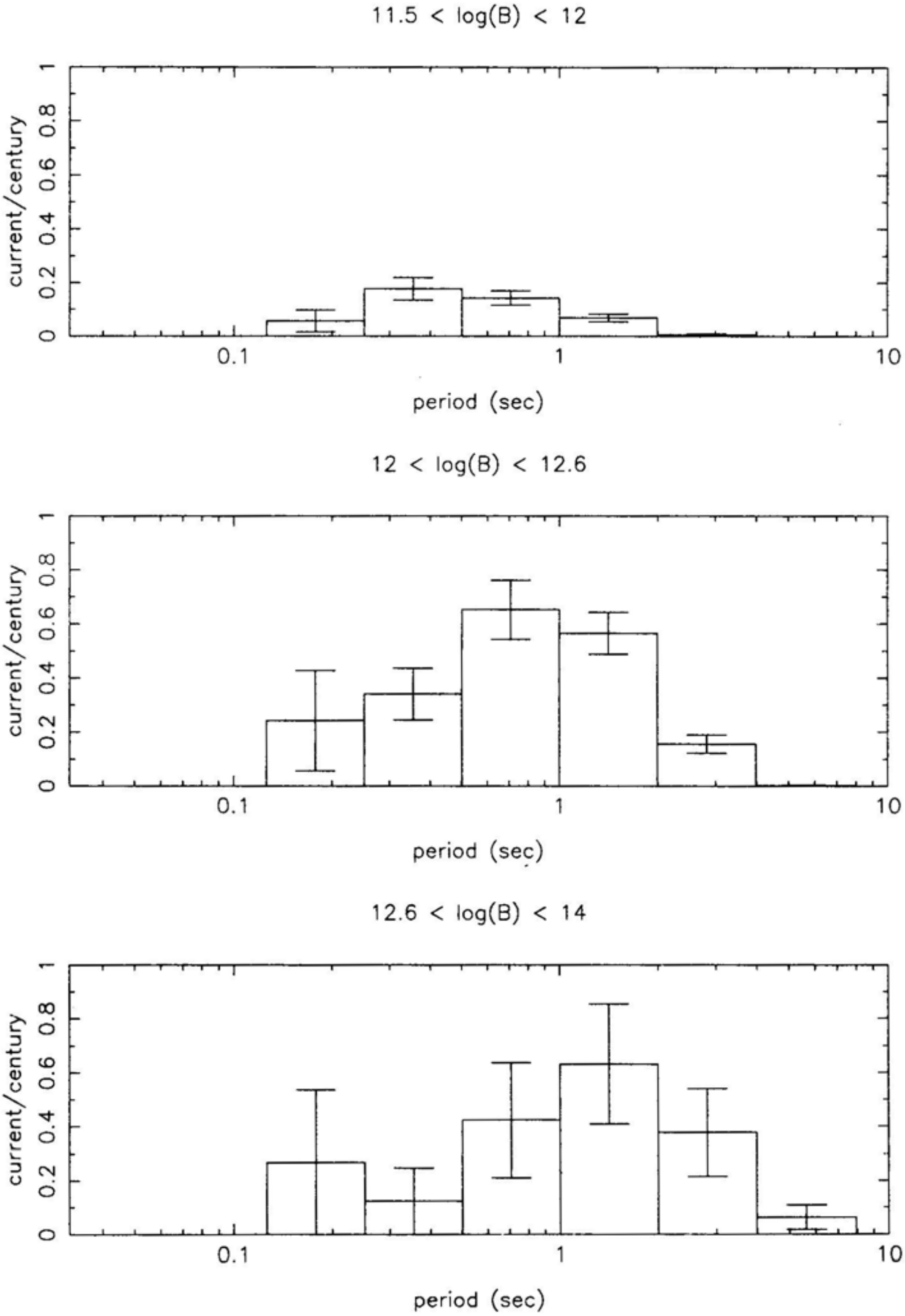


Figure 6. The current distribution shown in Fig. 1 has been binned into three magnetic field ranges. As may be seen, it is only in the central panel which corresponds to $12 < \log B < 12.6$ that one sees a *step* in the current at a period of about 0.5 s.

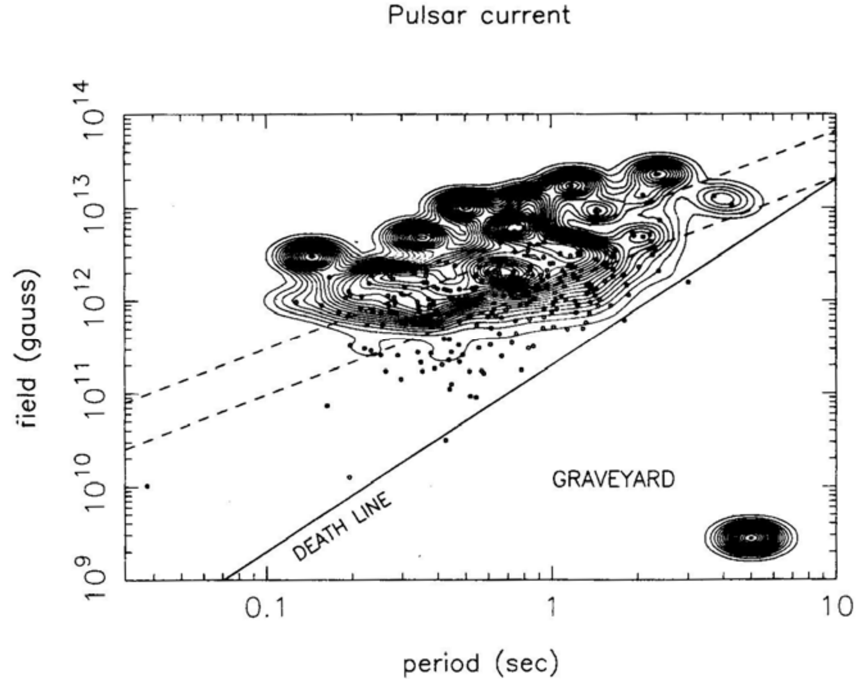


Figure 7. This shows the current distribution as a function of the period and magnetic field. This distribution has been smoothed with a function shown in the bottom right hand corner of the panel. Most of the 'hills' seen in this distribution correspond to individual high $\dot{P}$ pulsars (shown as open circles). But the distinct 'cliff' in the field range $10^{12} < B < 3 \times 10^{12}$G and a period around 0·5 s is a statistically significant feature since a fairly large number of pulsars contribute to it. It is this step in the current close to the upper spin-up line ($\dot{M} = 10\,\dot{M}_{\rm Edd}$) that we interpret an injection of recycled pulsars from massive binaries.

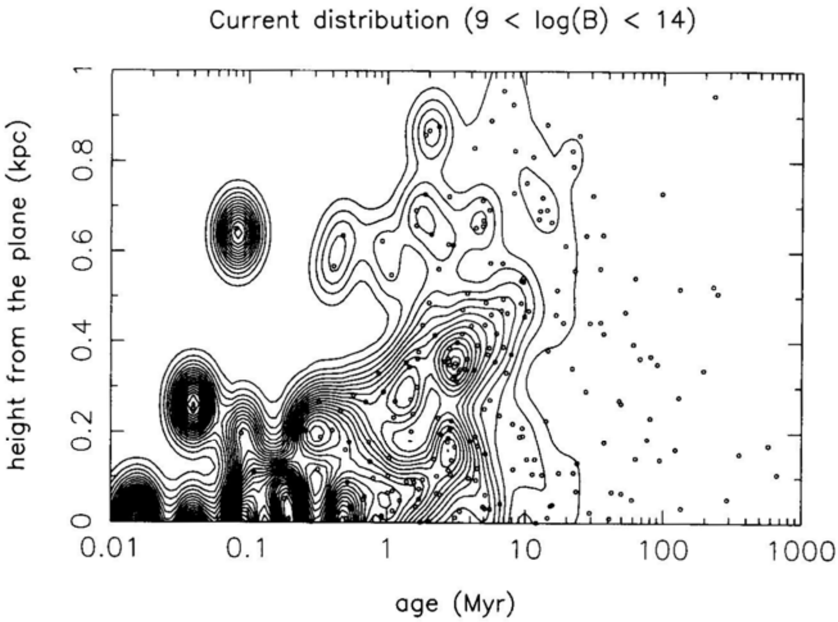
rate and ten times its value. Therefore, if the injection is interpreted as due to the recycled pulsars then it would imply that they experience accretion at super-Eddington rate. In our opinion this is quite likely to happen in massive binary systems.

3.3 *Birth places of injected pulsars*

Further support for the above conjecture namely that recycled pulsars may be injected into the main population of high field solitary pulsars comes from the distribution of pulsars with respect to the Galactic plane. Pulsar current as a function of characteristic age ($\tau_{\rm ch} = P/2\dot{P}$) and the distance z from the Galactic plane can be defined as

$$J_z(\tau_{\rm ch}(P,\dot{P})) = \frac{1}{f}\,\frac{\sum_{i=1}^{n_{\rm psr}} S(P_i,\dot{P}_i,z_i)}{\Delta\tau_{\rm ch}}. \tag{6}$$

In Fig. 8a we show the current distribution in the z– $\tau_{\rm ch}$ plane for the entire field range $9 < \log B < 14$. This can easily be understood in terms of the majority of pulsars



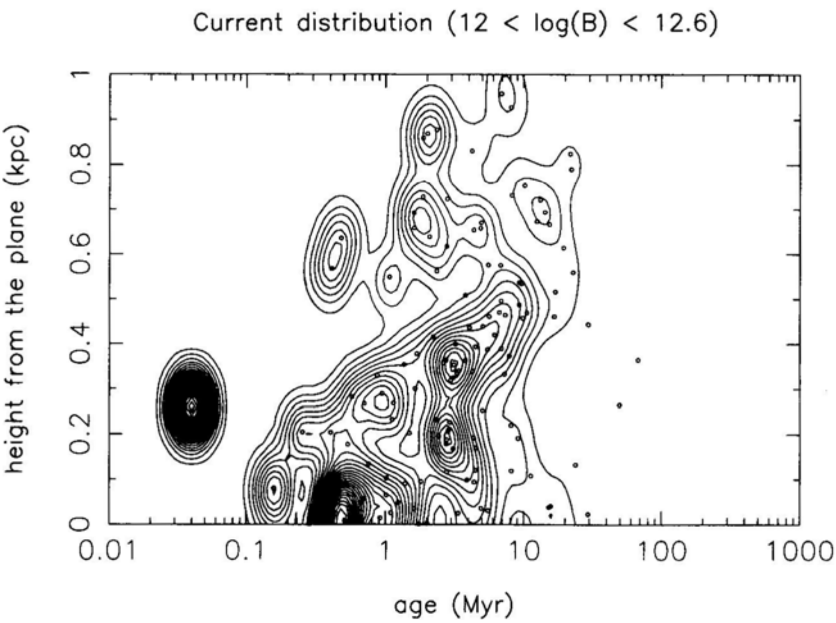


Figure 8. (a) The pulsar current as a function of the characteristic age and the height from the galactic plane. This distribution is easily understandable in terms of the majority of pulsars being born close to the galactic plane and migrating away from it due to velocities acquired at birth; **(b)** In this figure the current of pulsars in the magnetic field range $12 < \log B < 12.6$ alone is shown. We wish to suggest that this distribution is more consistent with pulsars not only being injected with a characteristic age of about 1 Myr but at a variety of distances from the galactic plane ranging all the way up to 800 pc.

being born with short periods and within a hundred parsec or so from the Galactic plane, and their subsequent migration from the plane due to velocities acquired at birth. If one now restricts oneself to pulsars with fields in the range $12 < \log B < 12.6$, then the corresponding current distribution (shown in Fig. 8b) is precisely what we would expect if there is an injection of pulsars with a characteristic age of about 1 Myr and injected at large distances (~ 800 pc) from the Galactic plane.

What could be the progenitors of these pulsars which explode at substantial distances from the galactic plane? The binary hypothesis offers a natural explanation. It is conceivable that a certain fraction of binaries acquires substantial centre of mass velocities during the first explosion, and a certain fraction of them floats away from the galactic plane. When they disrupt during the second supernova explosion two pulsars will be released. The firstborn will have the characteristics of a recycled pulsar, and the second one will have a short characteristic age at birth. This would offer a natural explanation for why some short characteristic age pulsars are seen to be moving towards the galactic plane (Harrison *et al.* 1993).

4. Discussion and summary

If the binary hypothesis for *injection* is correct then a plausible evolutionary scenario is as follows: Most massive binaries are presumably born fairly close to the galactic plane. After the primary evolves and explodes, the centre of mass of the binary system (in most cases the binary is unlikely to be disrupted in the first explosion) will acquire some velocity since the explosion is not symmetric with respect to the centre of mass of the system. A fraction of these binaries can in principle migrate to substantial heights from the galactic plane. The subsequent evolution of such binaries depends upon several factors, in particular their orbital periods. To be specific, we consider below only binaries in which the secondary is either a B-star or a Be-star since they will be much larger in number than binaries with O stars.

If the orbital period is greater than about a year then such systems after the spiral-in phase will become very tight binaries consisting of the firstborn neutron star and the helium core of the companion. If this core is massive enough then it will explode as a supernova and produce a second supernova. Most of such binaries will disrupt during the second explosion releasing two runaway pulsars: the firstborn recycled pulsar, and the second-born neuron star which will be indistinguishable from those born from solitary progenitors. On the other hand, if the binary is sufficiently close to begin with, (orbital periods significantly shorter than about a year) the common envelope formed during the spiral-in may not be expelled, and the first-born neutron star might actually spiral into the core of the companion. The eventual outcome of such systems will be single recycled pulsars (for a detailed review of these and other scenarios see (Bhattacharya & van den Heuvel 1991). Binaries with initially wide orbits which release two neutron stars can naturally account for some of the short characteristic age pulsars which are at considerable distance from the plane and which are moving *towards* the plane (Harrison *et al.* 1993).

Thus the binary hypothesis offers logically consistent explanation for several things; (i) the injection of pulsars into the population of solitary pulsars, (ii) the tight correlation between the rotation period of the injected pulsars and their magnetic field, and (iii) the large spread in their birth places with respect to the galactic plane.

Regarding the actual fraction of solitary pulsars which may be identified with recycled pulsars, one can only make a simpleminded estimate. In a sense, the magnitude of the *step* in the current at a period around 0.5 s will tell us the desired fraction. However, one must bear in mind that such an estimate of the fraction of pulsars from binaries is quite likely to be an overestimate since a part of the step may also be due to a spread in the distribution of initial periods. Faced with this difficulty we wish to tentatively suggest that about 10 –15% of the solitary pulsars might have been processed in binary systems. Given the total birthrate of pulsars this would roughly correspond to one recycled pulsar injected into the population every thousand years. Such a birthrate for recycled pulsars would imply a total number of wide binaries with a neutron star and a B/Be star companion to be roughly 10–1000 (corresponding to an average lifetime of such systems in the range $10^6 - 10^4$yr). The recently discovered pulsar PSR B1259 – 63 is one such system. The estimated distance to this pulsar is about 4kpc. A simple-minded scaling suggests that there could be as many as 100 such systems in the Galaxy, which is certainly consistent with the expected numbers mentioned above.

Finally, we wish to summarize our main conclusions:

1. Our estimate for the birthrate of pulsars in the Galaxy is 1 in 75 ± 15 years.
2. We wish to suggest that pulsars with magnetic fields in the range 10^{10}–$10^{11.5}$ G are recycled pulsars from binary systems.
3. In addition, there may be a substantial number of solitary recycled pulsars which are injected into the normal population of pulsars born from single stars.

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