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# Slowly rotating pulsars and magnetic field decay

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**Abstract.** Two dozen long period pulsars are separated from the swarm of ordinary pulsars by an obvious gap in the $P$ versus $Sd$ diagram (where $Sd$ = log $\dot{P}$ + 21.0), with a plausible upper boundary for ordinary pulsars. Possible pulsar evolutionary tracks are discussed to explain the diagram in terms of previously suggested scenarios of magnetic field decay. The ($P$–$Sd$) diagram is difficult to understand if there is no magnetic field decay during the active life of pulsars. However, if the magnetic fields of neutron stars decay exponentially, almost all slowly rotating pulsars must have been injected with a very long initial spin period of about 2 seconds, which seems impossible.

Based on qualitative analyses, it is concluded that magnetic fields of neutron stars decay as a power-law, with a time scale related to the initial field strengths. The plausible boundary and the gap are suggested to naturally divide pulsars with distinct magnetic "genes", ie. pulsars which were born from strongly magnetized progenitors — such as Bp stars, and pulsars born from normal massive stars. The possibility remains open that a fraction of slowly rotating pulsars were injected with long initial spin periods, while others would have a classical pulsar evolution history. It is suggested that PSR B1849+00 was born in the supernova remnant Kes-79 with an initial period of about 2 seconds.

**Key words:** pulsars: general – stars: evolution – stars: magnetic fields

## 1. Introduction

Radio pulsars are rotating neutron stars with a strong magnetic field, emitting a beam of radio radiation (Gunn & Ostriker 1970; Lyne, Manchester & Taylor 1985). In the classical pulsar model it is widely accepted that pulsars were born during supernova explosions of massive stars near the Galactic plane, with a short period of a few tens of a millisecond. Due to dipole magnetic radiation they rapidly spin down to longer periods. Therefore, in the diagram of $P$ versus $\dot{P}$ (see Fig. 1a), more than 15 young pulsars, which are even still associated with visible supernova remnants (cf. Frail, Goss & Whiteoak 1994), occupy the top left area and will migrate to the right and downwards as they age. The asymmetry during the explosions results in a mean pulsar birth velocity (Dewey & Cordes 1987) of 450 $\sim$ 500 km·s$^{-1}$ (Lyne & Lorimer 1994), so that pulsars would generally move away from their birth-places near the Galactic plane.

Up to now, more than 700 pulsars have been discovered, with 538 of them having measured period derivatives ($\dot{P}$), according to the updated catalogue of Taylor, Manchester & Lyne (1993). While many astronomers are fond of a log–log plot of $P$ versus $\dot{P}$, especially to show millisecond pulsars, we will nonetheless plot the ($P - \dot{P}$) diagram *on a linear scale* for $P$ to address long period pulsars. For the sake of convenience, we define the pulsar *Spin-down* as $Sd$ = log $\dot{P}$ + 21.0, to replace the period derivative $\dot{P}$ in this paper. [1]

A striking feature in Fig. 1a is that several long period pulsars are separated from the swarm of other ordinary pulsars by an oblique gap at about $P \simeq 2$ seconds. The majority of pulsars are in the left lower area with a plausible upper right boundary for them.

Furthermore,four pulsars, PSRs B0154+61,B1740−31, B1849+00 and B2002+31, which have also a period around 2.2 s and $Sd$ about 8.0, seem to form a sub-group. They have the strongest magnetic fields of known pulsars (log$B$(G)= 13.33, 13.24, 13.17 and 13.10, respectively), and very small Galactic heights (0.01, 0.07 and two at 0.00 kpc, respectively).

Since selection effects in early pulsar surveys (Dewey et al. 1987; Taylor & Stinebring 1986) and certainly in later surveys (e.g. Manchester 1995) are not biased against the discovery of these long period pulsars, then the gap and grouping phenomenon of these pulsars hints at something which is directly related to pulsar evolution. We then wonder if all slowly rotating pulsars, which appear in $P - Sd$ diagram distinct from the bulk of pulsars, were normal pulsars evolved from a short initial period, or whether they were born with a long period of about 2 seconds.

How pulsars evolve is a long-standing controversy with respect to possible magnetic field decay. Therefore, to explore the origin of the group of slowly rotating pulsars and to explain the

[1] Quantitatively, $Sd$ = 10.0 indicates a pulsar slowdown of about 1.16 $\mu$s every day, while, $Sd$ = 9.0 corresponds to 0.116 $\mu$s every day, and so on.

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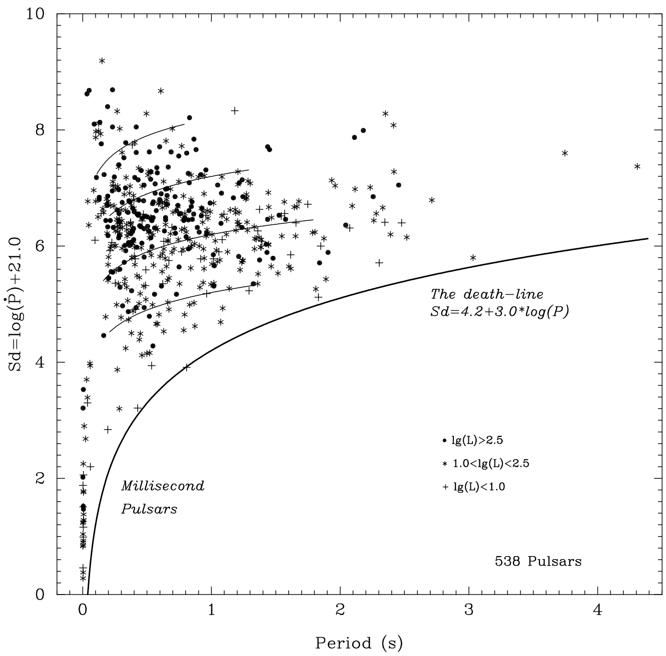


**Fig. 1a.** The $(P\text{–}Sd)$ diagram of 538 pulsars for which the $\dot{P}$ has been measured. The thick line is the death line, and the thin lines indicate characteristic ages of $10^5$, $10^6$, $10^7$ and $10^8$ years, respectively. Dot, asterisk, and the plus sign are used to represent different radio luminosities of the pulsars.

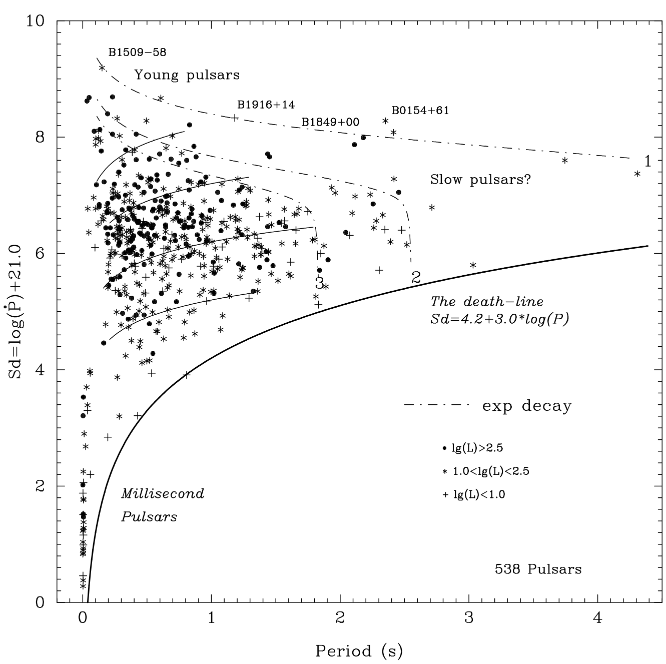


**Fig. 1b.** The same as Fig. 1a, but with pulsar evolutionary tracks for exponential magnetic field decay. The three tracks are for $t_0$= 5Myr, and $\log B_0$ = 13.2, 12.85, and 12.7 respectively.

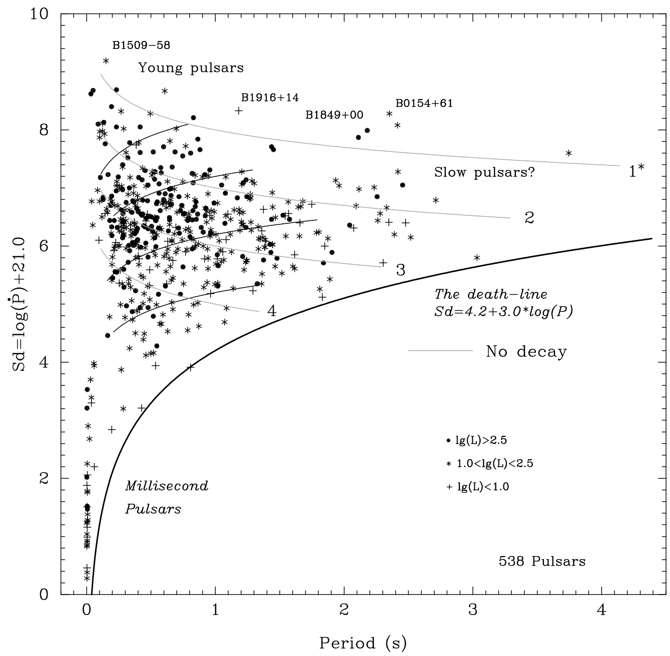


**Fig. 1c.** The same as Fig. 1b, but without any magnetic field decay. The four evolution tracks are for $\log B_0$=13.0, 12.5, 12.0 and 11.5 respectively.

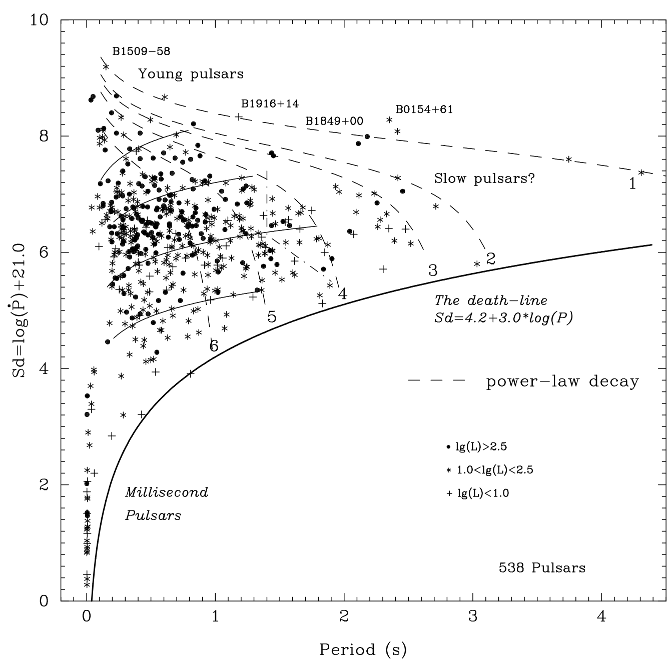


**Fig. 1d.** The same as Fig. 1b, but for power-law field decay. The six evolution tracks are for ($\log B_0$/G, $t_0$/Myr) = (13.2, 2.0), (13.05, 1.12), (13.0, 1.0), (12.9, 0.8), (12.75, 0.74), (12.6,0.63). The dash-dot-dash lines and track 4 in Fig. 1d define the location of the comparison pulsar sample (including 3 pulsars just above the track) used for Fig. 2.

apparent upper boundary in Fig. 1a, possible pulsar evolution trajectories in the ($P$–$Sd$) diagram are discussed in Sect.2 by assuming different ways of field decay: (1). exponential decay, (2). no field decay and (3). power-law decay. We find that the power law magnetic field decay fits the data the best. The results are discussed in Sect.3 and Sect. 4.

## 2. Pulsar evolution tracks

Since we are interested in long period pulsars in the ($P$–$Sd$) diagram, instead of the underlying properties of pulsars (e.g. birth rate, birth place, or luminosity functions), it is emphasized again that selection effects in pulsar discovery surveys have a negligible effect on the following discussion. The term *pulsar current*, which will be qualitatively used below, means the number of pulsars which pass through the transection between two evolutionary trajectories in the ($P$–$Sd$) diagram.

### *2.1. Exponential magnetic fields decay*

Soon after the discovery of pulsars, Ostriker & Gunn (1969) suggested that the magnetic fields decay exponentially, i.e.

$$B(t) = B_0 \exp(-t/t_0),$$

with a time scale $t_0$ of a few million years. This theory was widely accepted over the years, but has been challenged recently. Previous analyses show that the observational data can be explained if the magnetic fields of pulsars are assumed to decay exponentially (Lyne, Anderson & Salter 1982; Lyne, Manchester & Taylor 1985; Stollman 1987; Narayan & Ostriker 1990; Harrison, Lyne & Anderson 1993; Lorimer et al. 1993). However, it has been found that some pulsars were probably born as slow rotators with an initial spin period of about 0.5 to 1 s according to pulsar population analyses (Chevalier & Emmering 1986; Narayan 1987; Narayan & Ostriker 1990; Emmering & Chevalier 1989).

None of these authors, however, considered the very slowly rotating pulsars, on which we focus here. Actually, the most recent *pulsar current* analyses of Lorimer et al. (1993) and Deshpenda et al. (1995) have already shown some marginal evidence for some pulsars being “injected” at $P \simeq 2$ s (see Fig. 5 and Fig. 6 of Lorimer et al. and Fig. 10 of Deshpenda et al). Here, we try to explain the plausible upper boundary in Fig. 1a and to show possible evolutionary tracks for the group of slowly rotating pulsars.

Three tracks were drawn in Fig. 1b for the evolution of given pulsars with a field decay time scale $t_0$ = 5 million years for three different values of $B_0$. As can be seen in Fig. 1b, the plausible upper boundary of the normal pulsars can be well defined by track 3. The abrupt cut-off at $P \simeq 2.5$ of the pulsar distribution can be naturally explained.

Obviously, however, there is an absence of pulsars from $P$ = 0.9s to 1.8s between tracks 2 and 3. That is to say, *if magnetic fields of pulsars decay exponentially, almost all slowly rotating pulsars had to be “injected” with an initial period of about 2 seconds, while pulsars with a period of 0.9s should die very abruptly.* This seems implausible. We will discuss this later.

The pulsars with very strong magnetic fields, including the 4 pulsars in the sub-group, seem to evolve along track 1. The presence of more pulsars located in the sub-group area suggests that some of them could be newly “injected” pulsars.

### *2.2. No magnetic field decay*

Recently it has been suggested that the magnetic fields of neutron stars do not decay appreciably during the active life of normal pulsars (Bhattacharya 1995; Bhattacharya et al. 1992). Support also comes from the long-lived ($> 10^9$ yr) magnetic fields of some pulsars with white-dwarf companions (Kulkarni 1986; see also Bhattacharya 1995 for a list and references therein).

Four evolutionary tracks for log$B$(G)=13.0, 12.5, 12.0, 11.5, without any field decay, are shown in Fig. 1c. Obviously, assuming no magnetic field decay does not help interpreting the ($P$–$Sd$) diagram. Both the abrupt cut-off in the left area and the plausible upper boundary do not seem to be related to the non-decay evolutionary tracks. Pulsar currents between tracks 1 and 2 decrease steadily from $P$ = 0.8s to zero at $P$ = 1.5 s, and then recover at $P$ approximately 2 seconds. The obvious gap can not be explained if there are no selection effects in pulsar discovery. However, selection effects for long period pulsars are actually negligible. Narayan and Ostriker (1990) also definitely rejected the non-decay model according to their considered simulations and tests. In summary, the evolutionary tracks without magnetic field decay are unreasonable to fit the ($P - Sd$) diagram.

### *2.3. Power-law magnetic fields decay*

Sang & Chanmugam (1987) found that the decay of magnetic fields of neutron stars, which is believed to be related to the ohmic decay in the crust, is non-exponential. They approximate the field decay by

$$B(t) = B_0/(1 + t/t_0).$$

Such a power-law decay is found to be fully consistent with observational data (Sang & Chanmugam 1990; Narayan & Ostriker 1990) and superior to exponential decay in its natural explanation of the weak magnetic fields of the oldest millisecond and other low-mass binary pulsars.

Some efforts have been made here to explain the features (see Fig. 1d). It is found that a plausible boundary can be well defined by evolutionary track 4, for which (log$B_0$/gauss, $t_0/10^6$yr) = (12.9, 0.8).

To match other features, it is necessary to vary the time scale of magnetic field decay with the initial field strength. For example,pulsars with high magnetic fields can be traced by trajectory 1 of (log$B_0$, $t_0$) = (13.2, 2.0).

Track 3 of (log$B_0$, $t_0$) = (13.0, 1.0) suggests that some slowly rotating pulsars are normal ones which evolved from short periods, as indicated by two pulsars midway. However, it is quite possible that the rest of them would have to be “injected” as

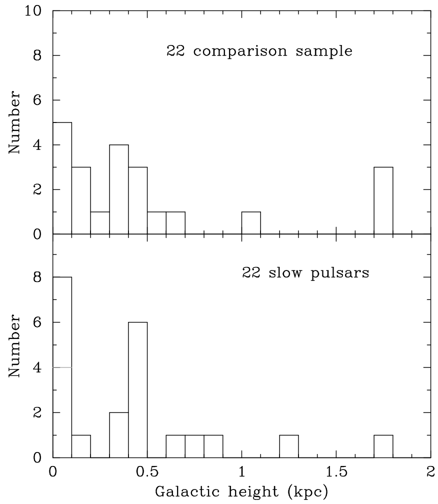


**Fig. 2.** Histograms of the galactic heights of the slowly rotating pulsars and of pulsars in the comparison sample. Four pulsars in the sub-group are in the slowly rotating pulsar sample.

slow rotators, if the pulsar current between tracks 3 and 4 is qualitatively considered (as done in Fig. 10 of Deshpande et al. 1995).

Tracks 5, 6 in Fig. 1d are drawn by extrapolating the parameters $B_0$ and $t_0$ from tracks 1, 3 and 4. They show where the majority of pulsars were born, and how ordinary pulsars evolve.

## 3. Evidence for possible injection of some pulsars?

If any "injection" is involved, then it is possible that (1). the real ages of slowly rotating pulsars, which can not be represented by the charactistic age any more, might perhaps be better indicated by their galactic heights. On average, these pulsars are possibly younger than normally evolved pulsars on the left side of the gap, even if their characteristic ages are similar; (2). there may be some associations between supernova remnants (SNRs) and slowly rotating pulsars.

### *3.1. A comparison of galactic heights*

Fig. 2 shows histograms of the galactic height for the slowly rotating pulsars and a comparison sample as defined in Fig. 1d. The pulsars in the two samples have similar characteristic ages. The distribution of galactic height of the slowly rotating pulsars has two sharp peaks at 0.0 – 0.1 kpc and 0.4 – 0.5 kpc, while only one pulsar has very large galactic height ($\geq$ 1.7kpc). That of the comparison sample has two diffuse peaks at almost the same locations, and 3 pulsars have very large galactic height ($z \geq 1.7 kpc$). The average value of the galactic height $\langle z \rangle$ of slowly rotating pulsars, excluding the four in the sub-group, happens to be the same as that of the comparison sample. Both of them are 0.505kpc.

Though there are some possible selection effects, it has been shown that *apparently* young pulsars with strong magnetic fields tend to have larger transverse velocities than young pulsars with moderate magnetic fields (Frail et al. 1994; Dewey & Cordes 1987) [2]. The similar average galactic heights of both groups of slowly rotating pulsars suggests that those with stronger magnetic fields are perhaps somewhat younger on average but not too much.

If all slowly rotating pulsars were "injected", in other words, if they are very young, a large difference on the distribution of galactic heights should be seen. So, the comparison of the galactic heights suggests that magnetic fields of pulsars do not decay exponentially, but in a power law. Hence, it seems reasonable to say that only some of slowly rotating pulsars located near the Galactic plane, including four in the sub-group, *might* be the newly "injected" pulsars.

By the way, it is not clear whether the two distinct peaks in Fig. 2 are an indication of two populations of pulsars of Narayan & Ostriker (1990).

### *3.2. PSR B1849+00: a slowly rotating pulsar possibly associated with a SNR*

It is noticed that PSR B1849+00 lies just a few arcminutes beyond the boundary of the SNR G33.6+0.1 (also known as: Kes 79, 4C00.70, HC13). The parameter $\beta = \theta_p/\theta_{SNR}$ (cf. Frail et al. 1994) is about 1.5, where $\theta_{SNR}$ is the angular radius of the SNR, and $\theta_p$ is the angular displacement of the pulsar from the geometric center of the SNR. The positional coincidence suggests an association of the pulsar with the SNR. It is merely the long period of the pulsar that prevented people from believing in this association (eg. Frail & Clifton 1989). However, this should not be a barrier since we could not rule out the possible injection of some (*not all*) of the slowly rotating pulsars.

The strongest support for the association is that both of the objects have almost the same distance. Earlier HI absorption observations (Caswell et al. 1975) of G33.6+0.1 suggest a distance >7 kpc (for a distance of the Sun from the galactic center $d$ = 10.0 kpc), while its surface brightness suggests a distance $\leq$10 kpc (again for $d$ = 10.0 kpc, cf. Caswell et al. 1981). Frail & Clifton (1989) investigated the relative geometry of PSR B1849+00 and the SNR using neutral hydrogen absorption spectra. G33.6+0.1 is then confirmed to have a distance of 10 $\pm$ 2 kpc (for $d$ = 10.0 kpc). Therefore, the distance of the SNR should be 8.5 $\pm$ 1.7 kpc if the $d$ is scaled to 8.5 kpc. The distance to the pulsar, according to Taylor et al. (1993), is well estimated as being 8.4kpc $\pm$1dB, i.e., 8.4(+2.2 $-$ 1.7) kpc.

Also the fact that recent searches for the neutron star inside G33.6+0.1 have failed (Seward & Velusamy 1995), supports our idea that PSR B1849+00 was born inside the SNR and has already moved away from the center of the SNR to its present position. If the real age of the pulsar is equal to the estimated age

[2] We notice the recent paper by Lorimer, Lyne & Anderson (1995), in which the relation between transverse speed ($V$) and the magnetic field ($B$) is discussed. However, if we plot the data in Table 1 of Frail et al. (1994) onto Fig. 1 of Lorimer, we find that $V$ and $B$ of young pulsars are causally related, in contrast to the conclusion of Lorimer et al. (1995). At least apparently, young pulsars with a stronger magnetic field have larger transverse velocities than older pulsars.

of the SNR, which is several thousand years (Green & Dewdney 1992), the initial spin period of the pulsar should be about 2 seconds.

## 4. Discussions

*We have seen that the linear scale for $P$ in the $(P - \dot{P})$ diagram is very helpful for pulsar evolution analyses.* According to the qualitative analyses above, **(1)**. we can rule out the possibility that pulsar magnetic fields do not decay; **(2).** we found that the widely adopted exponential decay is rather questionable. If the magnetic fields decay exponentially, then all slowly rotating pulsars ought to be "injected" with a long initial period; **(3).** it is found that the magnetic field decay described by a power-law is the best match to the $(P–Sd)$ diagram. In this case, it can not be ruled out that some of the slowly rotating pulsars are born with a period about 2 seconds, however most long period pulsars are likely to be evolved from a short period.

For the two latter cases of field decay, the "injection" mechanism is likely to be involved. The scenario for the possible "injection" could be based on whether the progenitor stars of pulsars are very strongly magnetized massive stars (Narayan 1987), Bp stars, for example, or just normal ones. As long as the origin of magnetic fields of a neutron star lies in the flux conservation during the collapse of the progeniting massive star, the strong magnetic field would have enhanced the transfer of angular momentum from the core to the envelope during the early collapse and evolution phase (Chanmugam 1992). Neutron stars formed in this way are likely to rotate slowly and would be "injected" as slowly rotating pulsars.

No matter whether there is any "injection", we can understand that the gap and the plausible boundary, as indicated by track 4 in Fig. 1d, could naturally and reasonably divide two origins of pulsars, based on the different aspects of the magnetic fields of the progenitor stars. Pulsars above the boundary have the strongest magnetic fields *now and when* they were born, indicating that the progenitors are probably strongly magnetized Bp stars, however, pulsars below the gap and boundary have normal massive progenitor stars.

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