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Letter to the Editor

The magnetic field strength versus orbital period relation for binary radio pulsars with low-mass companions: evidence for neutron-star formation by accretion-induced collapse?

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Abstract. The 24 binary radio pulsars with nearly circular orbits and low-mass companions (0.2-0.4 $M_\odot$ helium white dwarfs in most cases) show a remarkable correlation between spin period P and orbital period P_{or}, and between dipole surface magnetic field strength B_s and P_{or}. The observed B_s vs. P_{or} relation is consistent with increasing decay of the neutron-star magnetic field with increasing amounts of matter accreted, as has been proposed on theoretical grounds by various authors. Neutron stars in binaries to which more than 0.45 $f\,M_\odot$ was transferred have field strengths below $10^9\,G$, where $f(\leq 1)$ is the fraction of the transferred matter that is not lost from the systems. The only one exception in the galactic disk (out of twelve systems) is the PSR 1831−00 system, in which $\geq 0.7\ f\,M_\odot$ was transferred but the pulsar still has a strong magnetic field ($\sim 0.8 \times 10^{11}$ G). Adopting the field decay by accretion models, the only way in which this can be explained is that the neutron star in this system was formed near the end of the mass-transfer phase, by the accretion-induced collapse (AIC) of a white dwarf.

Key words: neutron stars – binary pulsars – pulsars – accretion-induced collapse

In recent years evidence has been mounting indicating that the magnetic fields of isolated (i.e.: non-accreting) neutron stars may not decay spontaneously on a short timescale (i.e $\sim 10^7$ yrs), as had long been thought. This evidence comes from binary radio pulsars with well-determined ages (Kulkarni 1986; Bell et al. 1993; Danziger et al. 1993; Baylin 1993), from pulsating low-mass X-ray binaries with well-determined ages such as Her X-1 (Verbunt et al. 1990), and from revised interpretations of statistical properties of single radio pulsars (Bhattacharya et al. 1992). On the other hand, the evidence for magnetic field decay of neutron stars that experienced accretion in a binary system is very strong (Taam and Van den Heuvel 1986, Bhattacharya and Van den Heuvel 1991): the very weak surface dipole magnetic fields of many binary radio pulsars (often $< 10^9\,G$, see Table 1), for which we know that a considerable amount of accretion has taken place, strongly suggests that due to accretion (or related effects such as spindown and spinup, Srinavasan et al. 1990) the magnetic fields of these pulsars have decayed very much (Shibazaki et al. 1989; Romani 1990; Zang Chengmin et al. 1993). For a possible plausible model of field decay by accretion see for example Romani (1990). Since all available evidence on young pulsars in the Galaxy indicates that neutron stars are born with strong magnetic fields ($B_s \sim 10^{11.5} - 10^{13.5}\,G$, cf. Bhattacharya & Van den Heuvel 1991) we will assume that also neutron stars in the binary pulsars started out with $B_s \sim 10^{12}\,G$ before the onset of accretion. We then examine whether we can deduce a relation between the final magnetic field strength and the amount of matter $\triangle M$ accreted by the neutron star. The binary radio pulsars with circular orbits and low-mass white dwarf companions are particularly suited for such an investigation since (except for the few systems with evaporating companions), they form a quite homogeneous group whose evolutionary history seems well understood (cf. Bhattacharya & Van den Heuvel 1991).

Table 1 lists some important parameters of the 24 known systems of this type, derived from various sources (Taylor et al. 1993; Camilo et al. 1993; Anderson et al. 1993; Foster et al. 1993; Bailes et al. 1994); membership of globular clusters is indicated. In Fig. 1a for these systems the pulse period is plotted against the orbital period and in Fig. 1b the magnetic field strength B_s against the orbital period. The globular cluster pulsars are indicated in Fig. 1a and b by open circles, those in the galactic disk by filled circles. Pulsars with 'evaporating' companions are underlined. The B_s-values were obtained from the usual relation (cf. Bhattacharya & Van den Heuvel 1991):

$$B_s = 3.2 \times 10^{19} (P.\dot{P})^{1/2}, \qquad (1)$$

Table 1. The 24 binary pulsars with nearly circular orbits and low-mass companions.

Pulsar name PSR	P (ms)	$\dot{P}$ (10^{-19})	B_s (G)	P_{orb} (d)	e	M_{cf} ($M_\odot$)	ΔM_t ($M_\odot$)	ΔM ($M_\odot$)	Ref.
B0021−72E[o]	3.536			2.22	0.05	0.19*	>0.7	>0.7	1
B0021−72I[o]	3.48			0.23	0.0	0.02*	>0.7?	>0.7?	2
B0021−72J[o]	2.101			0.1207	0.00	0.03*	>0.7?	>0.7?	1
J0034−05	1.877	0.067	1.1×10^{8}	1.589	$<10^{-4}$	0.17*	>0.7	>0.7	3
J0214+42	2.32			2.029	0.0	0.20*	>0.7	>0.7	4
J0437−4715	5.7575	0.4	4.9×10^{8}	5.7410	1.8×10^{-5}	0.23	0.77	0.77	1
B0820+02	864.872	1.04×10^{3}	3.0×10^{11}	1232.47	1.19×10^{-2}	0.45	0.55	0.04	1
J1045−45	7.45		3.8×10^{8}	4.09	1.9×10^{-5}	0.19*	>0.7	>0.7	3
B1310+18[o]	33.16			255.8	0.00	0.36*	0.56	0.34	1
B1620−26[o]	11.08	8.16	3.0×10^{9}[b]	191.4428	0.025	0.33*	0.57	0.45	1
B1639+36B[o]	3.528			1.2591	<0.001	0.19*	>0.7	>0.7	1
J1713+074	4.57014	0.085	2.0×10^{8}	67.8	7.5×10^{-5}	0.28	0.72	0.65	5
B1718−19[o]	1004.0	1.59×10^{4}	1.28×10^{12}	0.258	0.000	0.14*	>0.7	>0.7	1
B1744−24A[a,o]	11.56	-1.9×10^{-1}	?	0.0756	0.000	0.10*	>0.7	>0.7	1
B1800−27	334.415	1.73×10^{2}	7.7×10^{10}	406.781	5.07×10^{-4}	0.36	0.64	0.18	1
B1831−00	520.95	1.43×10^{2}	8.7×10^{10}	1.8111	0.000(4)	0.20	0.80	0.80	1
B1855+09	5.362	0.1784	3.1×10^{8}	12.237	2.17×10^{-5}	0.25	0.75	0.75	1
B1908+00[o]	3.6185			0.141	$<10^{-2}$	0.02*	>0.7	0.7	2
B1953+29	6.1331	0.295	4.3×10^{8}	117.349	3.3×10^{-4}	0.31	0.69	0.59	1
B1957+20[a]	1.6074	0.168	1.66×10^{8}	0.382	$\leq5\times10^{-6}$	<0.06	?	?	1
J2019+24	3.9345	0.083	1.82×10^{8}	76.51163	1.11×10^{-4}	0.29	0.71	0.65	1
J2146−07	16.05			6.839	2.1×10^{-5}	0.51*	?	?	3
J2229+26	2.98			93.016	2.56×10^{-4}	0.30*	0.7	0.7	2
J2317+14	3.445	0.046	1.27×10^{8}	2.45	1.2×10^{-6}	0.21*	0.79	0.79	6

a= 'evaporating' companion; b= upper limit to B_s dervived from spin-up line is 7×10^{9}G; o= Globular Cluster.
B and J indicate 1950.0 and 2000.0 coordinates, respectively. The companion masses M_{cf} are consistent with the observed mass functions of the systems. Values without an asterisk (*) were estimated on the basis of evolutionary computations for Low-Mass X-ray binaries (LMXBs), as described in the text. Values with an asterisk are 50% probability estimates, derived from the mass function. The transferred amounts of mass ΔM_t and the amounts ΔM_m accreted by the neutron stars were derived from evolutionary computations, assuming an intial companion mass of 1 $M_\odot$ for the systems in the galactic disk and 0.9 $M_\odot$ for systems in globular clusters. For systems with $P_{orb} < 0.7^d$, M_{cf} is expected to be $<0.2\,M_\odot$, but no precise estimate of its value can be given. In the calculations of ΔM_m it was assumed that the neutron star was present from the start of the mass-transfer phase. *References:* 1. Taylor et al. (1993), and references therein; 2. F. Camilo (private communication); 3. Bailes et al. (1994); 4. De Bruin (private communication); 5. Foster et al. (1993); 6. Nice et al. (1993).

where P is the spin-period of the neutron star. Since only for fifteen pulsars the values of $\dot{P}$ are known, and one of these is negative – presumably due to dynamical effects in its globular cluster – B_s-values could be determined for only fourteen of the pulsars. For PSR 1620-26 the B_s-value probably is not reliable, since this pulsar has a very large $\ddot{P}$ (Thorsett et al. 1993). An upper limit to the field strength of 7×10^{9} G can, however, be derived from its spin period, using the spin-up line (cf. Bhattacharya & Van den Heuvel 1991). This limit is indicated in Fig. 1b. PSR J 2145-07 probably does not belong to the same class as the other systems, as its companion is too massive to be a helium white dwarf. It had an evolutionary history different from that of the other systems (Van den Heuvel 1994). We therefore put it in parentheses.

At the top of Fig. 1 and in the ninth column of Table 1 we have indicated the maximum amounts of mass ΔM_m expected to have been accreted by the neutron stars in these systems. The ΔM_m values were computed by assuming that the companion started out with a mass of 1 $M_\odot$ at the beginning of the mass-transfer (LMXB) phase for systems in the galactic disk and 0.9 $M_\odot$ for systems in globular clusters, that the neutron star was present throughout this phase, that it never accreted more per unit time than the Eddington-limiting rate ($10^{-8}M_\odot$/yr, for a standard neutron star of 8 km radius) and that in phases where the mass-transfer rate was $<10^{-8}$ $M_\odot$/yr, all the transferred mass was captured by the neutron star (i.e. : no mass loss from the system). In fact, these assumptions are not expected to be completely realistic for the globular cluster sources, since these were formed by capture events (collisions) in which a sizeable part of the mass of the donor stars may have been lost from the systems. Since we have no information on how much mass was lost in this way, we will in this paper not further discuss the globular cluster systems, but from here on only concentrate on the systems in the galactic disk. The assumption of an initial donor mass of 1 $M_\odot$ for all systems, through somewhat crude, seems justified since in practically all LMXB the donors have M$\leq 1.2.M_\odot$, while systems with donors $<0.8M_\odot$ cannot have evolved into binary pulsars within a Hubble time.

It is possible that also in the disk systems only a fraction $f(<1)$ of the envelope matter of the donor star is actually accreted, and the remainder is blown out of the system. In that case the numbers at the top of Fig. 1 indicate the value of $\Delta M/f$, where ΔM is the amount really accreted by the neutron stars, i.e. $\Delta M = f.\,\Delta\, M_m$, where f is the 'accretion efficiency'. For the calculation of the ΔM_m values we had to know the evolution of the mass-transfer rate $\dot{M}_t$ as a function of time, for systems with different orbital periods. How this evolution was precisely calculated will be described elsewhere (Van den Heuvel & Bitzaraki 1994). We will now assume, for the sake of argument, that all matter that can be accreted, has indeed been accreted in the systems of Table 1 and Fig. 1, i.e.: that the accreted amounts ΔM are equal to ΔM_m, which means accretion efficiency $f = 1$. This is because the entire reasoning which follows is independent of the precise value of f, as one can easily verify. [Since heating effects in Low-Mass X-ray binaries may cause winds and mass loss from the disk, f will be <1, but it is unlikely to be far below 0.5]. The relation between field strength and ΔM, indicated by the curve in Fig. 1b, suggests that there is steep decrease in field strength with increasing amounts of matter accreted. In systems where

$\geq 0.2\, f\, M_\odot$ was accreted, the field has decayed below 5.10^9G and where more than $0.5\, f\, M_\odot$ was accreted, the field strength is below 5.10^8G.

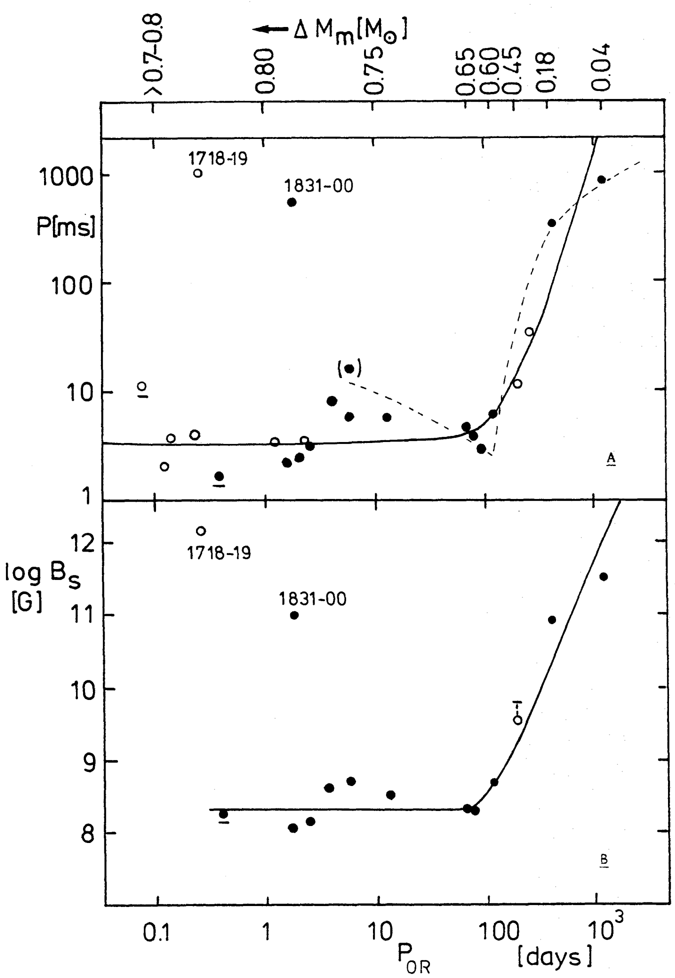

Fig. 1. (a.) The spin period (P) vs. orbital Period (P_{or}) diagram of binary radio pulsars with circular orbits and low-mass companions. Pulsars in globular clusters are indicated by open circles, those in the galactic disk with filled circles. Systems with evaporating companions are underlined (PSR 2145−075 was put in parentheses as its companion is not 'low mass'). (b.) The surface dipole magnetic field strength B_s vs. orbital period diagram for those systems for which B_s-values are available. (For 1620−26 only an upper limit is given, derived from the spin-up line). In both diagrams the curves indicate the best-fit to the observations, if the systems PSR 1831−00 and PSR 1718−19 are excluded. At the top of the figure the estimated amount ΔM_m of matter accreted by the neutron star, during the preceding Low Mass X-ray Binary Phase is indicated, assuming that the neutron star was present from the onset of the mass-transfer phase and never accreted more than the Eddington-limit rate (further explanation in the text).

Two systems, PSR 1831−00 in the galactic disk and PSR 1718−19 in the globular cluster NGC 6342, deviate very strongly from the general P vs. P_{or} and B_s vs. P_{or} relations of Fig. 1a and b. Since PSR 1718-19 may be the result of a recent capture event in its cluster, it may have accreted only very little (see above); we will therefore not discuss it any further. On the other hand, in the galactic disk system PSR 1831−00, tidal capture as a formation mechanism can be ruled out, as the probability for this process in the galactic disk is negligibly small. Therefore, assuming a normal LMXB-origin for this system, $\geq 0.7\, f\, M_\odot$ must have been transferred by the donor to its companion, since the donor cannot have started out with a mass $< 0.9\, M_\odot$ (as it would then have taken it longer than the age of the galaxy to have left the main sequence). Since, according to our calculation, throughout the mass-transfer phase in this system $\dot{M}_t$ was $< \dot{M}_{Edd}$, one would expect practically all of this mass to have been accreted by the neutron star, if this star was present in the system throughout the mass-transfer phase. According to the B_s vs. P_{or} and ΔM vs. B_s relations of Fig. 1b we then would have expected its magnetic field strength to have decreased to below $\sim 5.10^8$ G. However, its B_s value is still 0.8×10^{11} G, almost as large as that of the very wide system PSR 0820+02, in which very little mass was accreted. Adopting the field decay by accretion models, this indicates that the neutron star in PSR 1831−00 apparently accreted at most about $0.1\, f\, M_\odot$.

There is, in so far as we can see, only one way to resolve this large discrepancy between the transferred amount $\Delta M \geq 0.7\, f\, M_\odot$ and the accreted amount $\Delta M_a \leq 0.1\, f\, M_\odot$ onto the neutron star, namely that throughout most of the accretion phase the compact star in the system was a white dwarf, which only near the end of the accretion phase collapsed to a neutron star. If at the moment of its formation not more than $0.1\, f\, M_\odot$ of the envelope matter of the donor was left, the newborn neutron star could not accrete more than this amount. It might possibly be argued that PSR 1831−00 does not belong to the class of binary pulsars with helium white dwarf companions (i.e.: that it did not evolve from an LMXB), but rather to the group with massive white dwarf companions, such as PSR 0655+64, which had a different evolutionary history and may have retained stronger B-fields. However, the companion mass $\leq 0.20 M_\odot$ of PSR 1831−00, rules this out.

Another alternative model, suggested by Phinney and Kulkarni (1994) is that, following the SN-explosion the neutron star of 1831−00 was shot into its normal companion, due to a large kick velocity, such that this companion was almost destroyed, and only a small remnant, $< 0.20 M_\odot$, was left. In that case the pulsar would be young. This model, however, can work only if the neutron star in PSR 1831−00 was formed by AIC, and not by a normal type II SN of a star $\geq 6 - 8 M_\odot$, for the following reason. The fact that the companion was not completely destroyed in the common-envelope phase after the neutron star was shot into it, implies that at that time the companion already had a compact degenerate core (otherwise the neutron star would have spiralled into its center, destroying the star, cf. Taam and Bodenheimer 1992). The mass of this remnant is so small, that it must be a helium white dwarf. This implies that the progenitor of the companion had a mass $\leq 2.3M_\odot$, and at the time of the explosion had left the main-sequence. This takes $> 4.10^8$yrs for stars $\leq 2.3M_\odot$. Since stars $\geq 6M_\odot$ live $< 5.10^7$yrs, this rules out massive-star core-collapse as a formation process for 1831−00 and only the AIC possibility remains. Thus PSR 1831−00 is the first neutron star for which we now appear to have strong evidence that it was formed by the accretion-induced collapse of a white dwarf.

We notice that an alternative interpretation of Fig. 1a and b might still be possible in terms of a model in which the magnetic fields of neutron stars spontaneously decay on a relatively short timescale ($\tau_d \sim 10^7$ yr) when they are strong ($B_s \sim 10^{12}\,G$), but stop decaying spontaneously when the B_s-values have decreased below $\sim 10^9\,G$. This schematic decay model was the first one suggested to explain the large number of millisecond pulsars with field strengths in the range $(1-5)10^8\,G$ (Bhattacharya & Srinavasan 1986; Van den Heuvel et al. 1986). Although such a type of evolution of the field is nowadays considered less likely, it still cannot be excluded. It will be immediately clear that with such a field-decay model all binary neutron stars in Fig. 1 with $B_s > 10^9$ G must have been made by accretion-induced collapse during the mass-transfer phase itself (since otherwise they must have ages $\sim 10^{10}$yrs, like their companions, and their fields would have decayed to the 'bottom' range $(1-5)\times 10^8$ G). Interestingly, more than six years ago De Kool & Van Paradijs (1987) calculated for the above-described spontaneous field-decay model, with a bottom-value and AIC, the expected relation between spin period and orbital period for binary radio pulsars with wide and circular orbits, like the ones in Fig. 1. The thin-dashed line in Fig. 1a shows their predicted relation (for $\tau_d = 10^7$ yr between $B_s = 10^{12}$ G and $5.10^8\,G$, and $\tau_d = 10^{10}$ yr for $B_s \leq 5.10^8\,G$). For systems with $P_{or} \geq 10^d$ it fits quite well, even though this is a schematic model. Since in this model all these neutron stars were formed by AIC, we thus conclude that, independent of whether spontaneous magnetic-field decay or field decay by accretion is adopted, PSR 1831−00 should have formed by accretion-induced collapse.

It is not inconceivable that in most of the systems in Table 1 the neutron stars have formed by AIC. Especially in the wider systems ($P > 200^d$) this is a very attractive model, since the mass transfer rates in their progenitor systems are so large ($\sim 10^{-7}M_\odot$/yr) that they will trigger steady nuclear burning on the surface of a white dwarf (cf. Van den Heuvel et al. 1992, and references therein). This makes the masses of these white dwarfs grow steadily, such that they may collapse to a neutron star. Natural progenitor systems of these wide binary pulsar systems are therefore the symbiotic stars (which consist of a low-mass giant and a white dwarf) which exist in abundance in the Galaxy.

Finally, we note that an alternative explanation for the strong field of PSR 1831−00 suggested by Ruderman (priv. comm.) is that of field evolution by 'plate tectonics' (Chen and Ruderman 1993). With this model one expects the numbers of strong- and weak-field stars among old post-accretion neutron stars to be roughly equal. Since we observe in the galactic disk that only one old system out of twelve has a strong field, the probability that this would occur in the 'plate tectonics' model is only 0.0025. Therefore we consider this explanation for the strong field of PSR 1831−00 as quite unlikely.

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