1996MNRAS.283.1214J

Mon. Not. R. Astron. Soc. **283**, 1214–1226 (1996)

Magnetic and spin evolution of pulsars

M. Jahan Miri

Raman Research Institute, Bangalore 560080, India
Joint Astronomy Program, Indian Institute of Science, Bangalore 560012, India

Accepted 1996 July 30. Received 1996 June 24; in original form 1996 February 21

ABSTRACT

We explore the consequences of the model of spin-down-induced flux expulsion for the magnetic field evolution in solitary as well as in binary neutron stars. The spin evolution of pulsars, allowing for their field evolution according to this model, is shown to be consistent with the existing observational constraints in both low- and high-mass X-ray binary systems. The contribution from pulsars recycled in massive binaries to the observed excess in the number of low-field (10^{11}–10^{12} G) solitary pulsars is argued to be negligible in comparison with that of normal pulsars undergoing a 'restricted' field decay predicted by the adopted field decay model. Magnetic fields of neutron stars born in close binaries with intermediate- or high-mass main-sequence companions are predicted to decay down to values as low as $\sim 10^6$ G, which would leave them unobservable as pulsars during most of their lifetimes. The post-recycling evolution of some of these systems can, however, account for the observed binary pulsars having neutron star or massive white dwarf companions. Pulsars recycled in the disc population low-mass binaries are expected to have residual fields $\gtrsim 10^8$ G, while for those processed in globular clusters larger residual fields are predicted because of the lower field strength of the neutron star at the epoch of binary formation. A value of $\tau \sim 1$–2×10^7 yr for the mean value of the Ohmic decay time-scale in the crusts of neutron stars is suggested, based on the consistency of the model predictions with the observed distribution of periods and magnetic fields in the single and binary pulsars.

Key words: magnetic fields – binaries: general – stars: neutron – pulsars: general.

1 INTRODUCTION

Neutron stars are generally detected as either rotation-powered radio pulsars (single or in a binary, normally with another compact stellar remnant) or accretion-powered X-ray sources in binary systems. Rotation periods and surface magnetic fields assigned to neutron stars in these two different types of systems, and even in their observationally distinct subclasses, are found to span different ranges of values (see e.g. Bhattacharya & van den Heuvel 1991). The evolution of the spin periods in binary systems, accounting for the observed differences, has been explained through the effects of the interaction of the magnetosphere of a neutron star with the matter accreted from its mass-losing companion in a binary system (e.g. Pringle & Rees 1972; Illarionov & Sunyaev 1975). Certain evolutionary routes among various systems have hence been established with additional constraints on the expected ages and lifetimes of neutron stars in the various systems (e.g. Taam & van den Heuvel 1986). The evolution of the magnetic field has, therefore, not only to account for the observed differences in the field strengths of different types of sources, but also to be consistent with the requirements of the spin evolution of neutron stars in binaries. Although we are here concerned only with the decay of the total surface fields of neutron stars it is important to note that, observationally, there exists no direct and model-independent measurement of the strengths of the total magnetic fields of neutron stars (see e.g. Lamb 1992). Also, theoretically, there is no consensus regarding the origin or the structure and distribution of the fields inside these stars (see e.g. Ruderman 1987). However, the popular belief is that young pulsars possess strong magnetic fields $\gtrsim 10^{12}$ G which might, at least under some conditions that are apparently connected with a binary history of the star, decay down to values $\sim 10^8$ G (see e.g. Jones 1987; Srinivasan 1989). While the issue of the field decay in iso-

© 1996 RAS

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

lated radio pulsars has remained controversial since their discovery, the association between the presence of neutron stars in close binaries and the field decay of these stars has been generally accepted following the discovery of low-field binary and millisecond pulsars (see e.g. Srinivasan & van den Heuvel 1982; Radhakrishnan & Srinivasan 1984).

One of the models which has been proposed for the magnetic evolution of neutron stars employs the spin evolution of the star as the cause of its field evolution. The model of spin-down-induced flux expulsion (SIF model) (Srinivasan 1989; Srinivasan et al. 1990) suggests that pinning between neutron vortices and proton fluxoids in the superfluid core of a neutron star causes the magnetic flux to be expelled into the core–crust boundary as the star spins down. The core of a neutron star is believed (see Baym, Pethick & Pines 1969; Ruderman 1972) to consist mainly of neutrons in a superfluid state and protons in a superconductor state, the latter contributing only to a small fraction of the total mass. The rotating core superfluid is, furthermore, expected to be in a vortex state including $\sim 2\times 10^{16} P_s^{-1}$ vortices extending parallel to the rotation axis of the star, where P_s is the spin period in units of s. These are the entities which carry the angular momentum associated with the rotation of the core superfluid, and the total number of vortices has to decrease through their outward motion in order for the superfluid to spin down. An assumed frozen-in magnetic flux in the core of a neutron star is also believed to be confined within the cores of $\sim 10^{19} B_c$ quantized fluxoids parallel to the magnetic axis of the star, where B_c is the average field strength in the core in units of G. A reduction in the number of these flux lines implies, in turn, a reduction in the magnetic field strength in the core of a neutron star.

The proton flux tubes and the neutron vortex lines are, furthermore, expected to act as pinning sites for one another because of the associated energy barrier due to an overlap of the two structures which are both in a 'normal' state in their interior regions (Muslimov & Tsygan 1985; Sauls 1989; Srinivasan 1989). The radially outward motion of the vortices as the star spins down is, therefore, suggested to induce a field decay in the core assuming that the fluxoids are also swept out of the core along with the neutron vortices due to the effect of the pinning force. In the original model of SIF (Srinivasan et al. 1990) it was assumed, as a first approximation, that the rate of this sweeping was complete, namely the fractional change in the number of fluxoids was the same as that of the vortices. In other words, the two types of lines were assumed to move with the same radial velocity all the time. A more accurate treatment of the motion of fluxoids should, however, take into account all the other forces which might act on the fluxoids, and should also allow for the finite strength of the pinning force and hence for the possibility of the two types of lines moving with different velocities and overtaking each other. The effects of such considerations on the magnetic evolution of neutron stars have been already pointed out by Ding, Cheng & Chau (1993), although their study has been restricted to the case of a dipole spin-down phase which is applicable only to single normal pulsars. Here, we will follow the same prescription of the original SIF model by assuming that the rate of the expulsion of the magnetic flux out of the core is always equal to the spin-down rate of the star (i.e. $\dot{B}_c/B_c = -\dot{P}_s/P_s$, where a dot denotes a time derivative of the respective quantity). Although a full treatment of the coupled dynamics of fluxoids and vortices remains to be done (in particular for the spin histories experienced by recycled pulsars), the results of Ding et al. (1993) for the decay time-scales of the core magnetic fields seem to indicate that, at least in the case of binaries with lifetimes longer than the crustal decay time-scale, the final field strengths derived from such studies would not be much different from the results we find from our simplified treatment (see, however, Jones 1991).

In this paper we investigate the consequences of the model of spin-down-induced magnetic field decay for the evolution of single pulsars as well as those recycled in binary systems. The coupled evolution of spin periods and magnetic fields as predicted in this model has different bearings for the single neutron stars, which are subject only to the persistent decelerating dipole torque in contrast to those in close binaries. In the latter case, interaction of the magnetosphere with the matter accreted from the stellar wind of a companion star may result in torques of either sign and varying magnitudes which act on the neutron star at the various stages of its evolution. In Section 2, the results of our computations for the spin evolution of a neutron star during the main-sequence phase of its massive companion star are presented and general predictions of the SIF model for the birth and further evolution of recycled pulsars are then discussed, based on the assumed spin histories of the neutron stars. In Section 3, implications of the adopted field decay model for the observed properties of single 'normal' pulsars are explored, assuming the same value for the field decay time-scale in the crust of a neutron star as that used in the binary evolution calculations. In Section 4, the expected post-recycling behaviours of pulsars processed in binaries with companions of various masses are considered, while indicating specific cases corresponding to some of the observed systems. Pulsars recycled in globular clusters are, finally, shown to acquire residual fields larger than their disc-population counterparts, in agreement with observations, because of their different formation routes. Our conclusions are summarized in Section 5.

2 PULSAR RECYCLING SCENARIO

2.1 Overview

A pulsar in a close binary with a main-sequence (MS) star will undergo a phase of spinning-down to a maximum period P_{max} followed by a phase of spinning-up due to interaction of its magnetosphere with the matter accreted from the stellar wind of its companion. Roche lobe overflow (RLOF) of the companion star will, at some later stage of its evolution, further decrease the spin period P_s of the neutron star (NS) bringing it from its value at the beginning of the RLOF phase P_x to a minimum equilibrium period P_{eq}, which depends on the strength of the surface magnetic field of the neutron star at that epoch B_R and the rate of accretion of matter on to the neutron star $\dot{M}_{acc}$. This minimum equilibrium period is given by $P_{eq} \sim 1.9$ (ms) $[B_R^2/\dot{M}_{acc}]^{3/7}$ where B_R is in units of 10^9 G, and $\dot{M}_{acc}$ is in units of $\dot{M}_{Edd}$ (Srinivasan & van den Heuvel 1982). In the following, the Eddington accretion rate $\dot{M}_{Edd}$ will be assumed to be applicable during the RLOF phases of all binaries of interest hence making

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

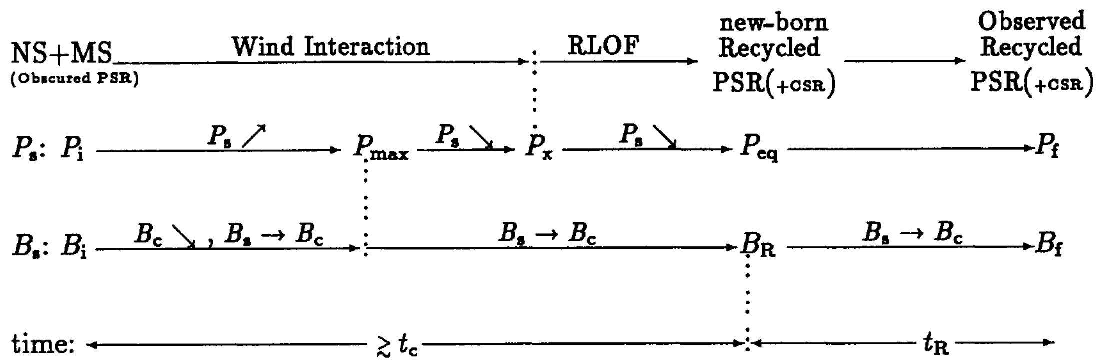

Figure 1. Schematic representation of the recycling scenario (+ SIF).

P_{eq} a function of B_R only. The above value of P_{eq} is, however, only a limit on the minimum spin period which is possible through the spin-up process; the actual value achieved is constrained also by the duration and efficiency of the RLOF phase in each case. A neutron star born with an initial period P_i and surface field strength B_i in a close binary (presumably being obscured in the wind of its companion and not detectable as a radio pulsar in most cases of interest: Illarionov & Sunyaev 1975; Bhattacharya & van den Heuvel 1991; Lipunov 1992) is, therefore, expected to start functioning later as a recycled pulsar [being either in a binary with a compact stellar remnant (CSR) or single] after a time about the MS-lifetime of its companion t_c. The subsequent evolution of a recycled pulsar will, in general, cause its period and magnetic field strength to change from the starting values P_{eq} and B_R to the final observed (after a time t_R) values P_f and B_f, respectively. The evolution of the orbital period P_{orb} of the binary system is not expected to depend on the spin or magnetic evolution of the neutron star and is determined by the amount of mass transfer within the binary as well as the mass and angular momentum losses from the system. The recycling scenario, along with the implications of the SIF model for evolution of the surface magnetic fields B_s of neutron stars in close binary systems, are summarized schematically in Fig. 1, where all the various above quantities are put in their respective positions.

2.2 Spin and magnetic evolution

Our assumptions regarding the spin and magnetic evolution of a neutron star in a close binary, based on the SIF model, were described in Jahan Miri & Bhattacharya 1994 (hereafter Paper I). The rate of transfer of angular momentum between the stellar wind and the neutron star is assumed to be equal to $\dot{M}_{acc}$ times a specific angular momentum corresponding to the difference between the co-rotation velocity with the neutron star and the Keplerian velocity around it at the radius of its magnetosphere boundary. Other rates of angular momentum transfer are, however, also tested by multiplying the above rate with an efficiency factor $\xi (\xi = 1$ for the above model). The evolution of neutron stars in binary systems with different orbital periods and for different assumed intermediate (IM) and high-mass (HM) companion stars is followed throughout the main-sequence lifetime of the companion star. The values of parameters assumed for the companion stars are listed in Table 1.

Table 1. Values of parameters for the assumed companion stars.

companion star	mass ($M_\odot$)	lifetime (yr)	mass-loss rate ($M_\odot yr^{-1}$)	wind velocity (km s^{-1})
IM	4	2×10^8	$10^{-11} - 10^{-9}$	500
HM	9	3×10^7	$10^{-10} - 10^{-8}$	600
HM	15	1.2×10^7	$10^{-10} - 10^{-6}$	700
Be-type	9	3×10^7	$10^{-10} - 10^{-8}$	200

The predicted final spin periods are plotted against orbital periods in Figs 2(a) and (b) for systems corresponding to the 'standard' and 'Be-type' massive X-ray binaries (HMXBs), respectively. The observed spin and orbital periods in HMXBs (Waters & van Kerkwijk 1989) are also indicated in each case, and show a distribution consistent with the computed curves for the case of $\tau = 10^7$ yr. However, in addition to the uncertainties arising from not knowing the exact values of the mass-loss rates, the following point must also be noted while inspecting the results in Figs 2(a) and (b): the observed standard and Be-type HMXBs are believed (e.g. Bhattacharya & van den Heuvel 1991) to relate to evolutionary stages later and earlier, respectively, than those represented by the computed curves which correspond to the end of the companion main-sequence phase. A further decrease in the oberved spin period for a Be-type source might, therefore, occur because of a decrease in the field strength before the end of the companion main-sequence lifetime (Fig. 2b). However, in an observed standard-type HMXB, the larger mass-loss rate of the supergiant companion (particularly for the disc-fed systems indicated by *pluses* in Fig. 2a) would have already resulted in a decrease in the spin period as compared to its corresponding calculated P_x value, shown in Fig. 2(a).

The results of these model computations also indicate that neutron stars that evolved in massive close binary systems are generally spun down to large spin periods with values of $P_{max}/P_i \sim 10^4$–10^5, for a given value of $P_i \sim 0.1$ s. This implies, as required in the SIF mechanism, a reduction in the magnetic fields of pulsars recycled in close binaries by 4–5 orders of magnitude, after a long enough time for the crustal field to decay. Even larger values of P_{max} are predicted for some of the binary systems considered, which would result in smaller values of $B_f \sim 10^6$ G. The generally

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

1996MNRAS.283.1214J

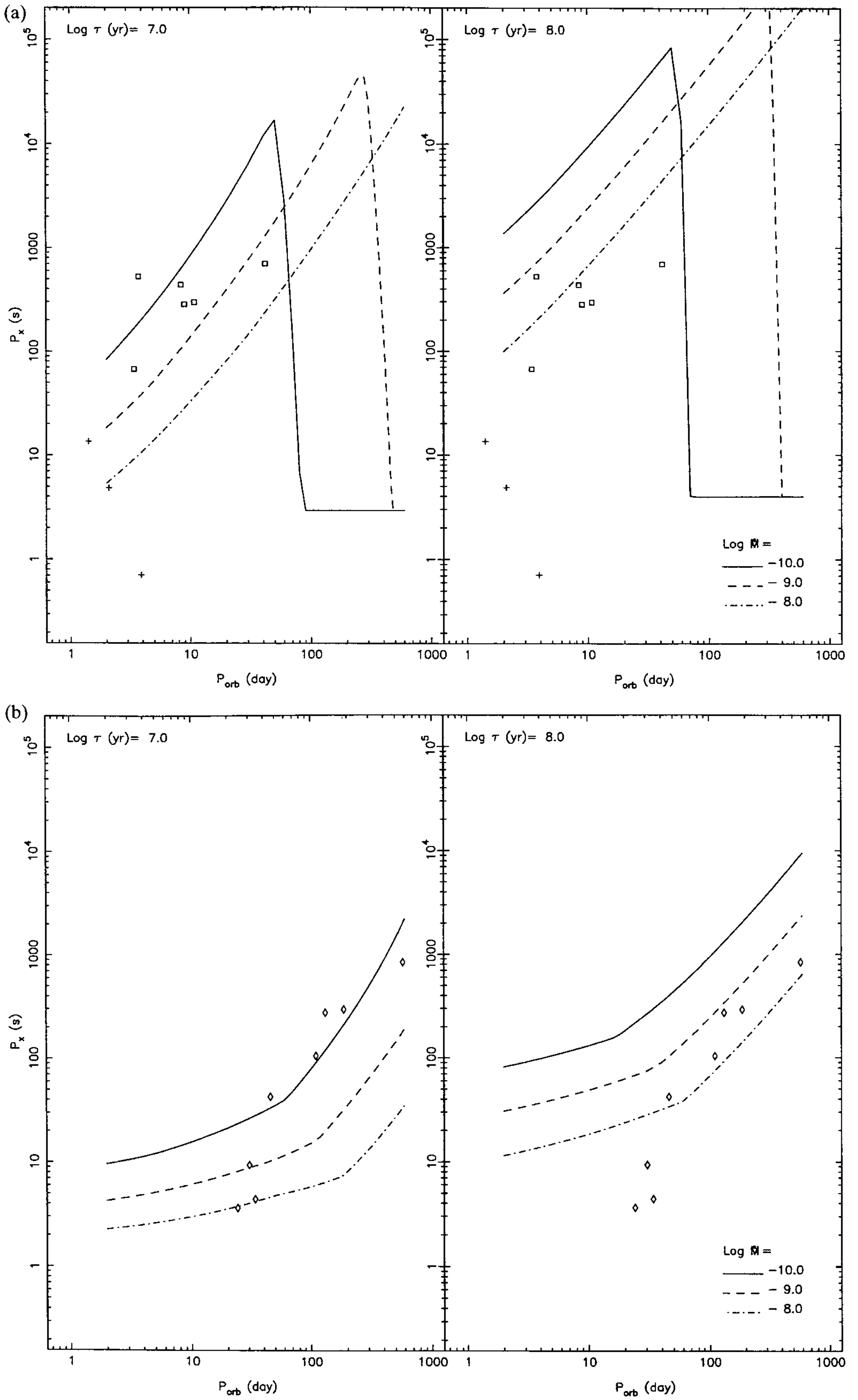

Figure 2. (a) Final spin periods of neutron stars processed in binary systems with a 9-$M_{\odot}$ main-sequence star at the end of its lifetime are plotted against the orbital periods. The two plots are for the two different values of decay time-scale in the crust, τ, as indicated. Each curve corresponds to a different value of mass-loss rate $\dot{M}$ (in units of $M_{\odot}$ yr^{-1}) for the companion star. The observed wind-fed and disc-fed 'standard' HMXBs are denoted by *squares* and *pluses*, rspectively (Waters & van Kerkwijk 1989). (b) Same as (a), but for a 9-$M_{\odot}$ Be-type companion star. The observed Be-type HMXBs are denoted by *diamonds* (Waters & van Kerkwijk 1989).

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

accepted minimum value of $B_f \sim 10^8$ G for the residual fields, which might be true for pulsars recycled in binaries with low-mass companions and is also in good agreement with predictions of the SIF scenario for these systems (Paper I), seems, therefore, to be a selection effect imposed by the pulsar 'death'-line (Ruderman & Sutherland 1975) on the observable spin periods and magnetic fields. We note that while our results for the large values of P_{max} are based on an assumed 'propeller' spin-down mechanism, other processes responsible for a spinning down of an accreting neutron star have also been proposed which are expected to be effective in cases where the 'propeller' mechanism fails or is argued not to be very efficient (Mineshige, Rees & Fabian 1991; Illarionov & Kompaneets 1990).

The quantity P_{max} plays a special role in determining the properties and final fates of the recycled pulsars. The strength of the surface magnetic field B_R of a pulsar just after recycling as predicted in SIF is given, approximating the time interval between achieving P_{max} and P_{eq} in the binary to be $\sim t_c$, as

$$B_R \approx (B_i - B_f)\, e^{-t_c/\tau} + B_f, \tag{1}$$

where τ is the decay time-scale of the magnetic field in the crust, and B_f is the predicted final value of the field given as:

$$B_f = \left(\frac{P_{max}}{P_i}\right)^{-1} B_i. \tag{2}$$

The post-recycling evolution of the pulsar will further depend on the ratio t_{ch}/τ, where t_{ch} $[=P_s/2\dot{P}_s = 1.6 \times 10^7$ yr $(P_s/B_{12})^2]$ is the characteristic age of a pulsar with the given P_s and $\dot{P}_s$ values, and where $B_{12}^2 = 10^{15} P_s \dot{P}_s$ has been assumed, B_{12} is the surface field strength (B_s) in units of 10^{12} G, and P_s is in units of s. Assuming a ratio of $B_i/B_f = P_{max}/P_i \sim 2 \times 10^4$ to prevail for most of the recycled pulsars, two distinct classes of recycled pulsars are thus distinguished, based on the corresponding values of t_c/τ.

(1) In systems with a $t_c/\tau \gtrsim 10$ (i.e. $e^{t_c/\tau} \sim P_{max}/P_i$), the flux expelled out of the core of the neutron star into its crust would be completely decayed by the time the recycled pulsar starts its new life, and no further field decay is expected during the subsequent evolution of the recycled pulsar, namely $B_f \sim B_R$.

(2) Binaries with a $t_c/\tau < 9$, on the other hand, would be subject to further magnetic decay while functioning as a recycled pulsar. Two subclasses are, in principle, possible among these pulsars, which are expected to experience a so-called 'delayed' field decay (Srinivasan et al. 1990).

(a) If $t_{ch} < \tau$ at and around the P_{eq} from which the recycled pulsar starts off, it would initially move along a constant magnetic field path on the B_s–P_s plane. Such pulsars would eventually acquire long enough periods corresponding to values of $t_{ch} > \tau$ and their evolutionary tracks would, therefore, bend down and cross the death-line vertically.

(b) At the other extreme, in which the condition $t_{ch} \gg \tau$ is satisfied at the given P_{eq}, the evolution of the pulsar would be along a vertical path and at a constant period (equal to its P_{eq}) until its field decays to the final expected residual value. The pulsar would then evolve along a constant field track, if its downward evolution had not already crossed the death-line.

From the above discussion it is clear that the behaviour of pulsars recycled in low-mass long-lived systems is determined basically by the values of P_{max} which they have attained at some stage in their past histories. On the other hand, the dominant factor in the case of those descended from short-lived massive binaries is the Ohmic time-scale τ. The predicted behaviour of the latter systems is, therefore, expected to be more sensitive to and hence might be used along with the corresponding observational data to further constrain the assumed value of τ. In addition, we wish to emphasize that even for the population of *solitary* pulsars, the implications of the SIF scenario would be quite different from that of a purely exponential field decay. This seems to have been overlooked in the earlier applications of the SIF model to the case of solitary pulsars (Srinivasan 1991). Considerations based on the computed evolutionary behaviour and lifetimes of these pulsars prove, in fact, to be very useful in this regard, as discussed in the following Section.

3 SOLITARY PULSARS

The observed single pulsars have spin periods extending from 0.03 s up to 1–5 s which is believed to represent also the range of their spin evolution during their active lifetime as pulsars. According to the SIF model, therefore, a decay by a factor of 30–170 in the surface field is expected for these pulsars during their lifetimes, provided $t_{ch} > \tau$ when they die. Although the predicted evolution of pulsars is in the beginning similar to that of a purely exponential field decay model, the final *restricted* decay due to SIF has a distinct effect on the expected pulsar population. As is shown in Fig. 3(a), the predicted paths of pulsars on the B_s–P_s plane in general bend down (as in the exponential model) and extend vertically at an almost constant P_s, once $t_{ch} > \tau$ is satisfied. However, if the vertical path does not cross the death-line, which happens for pulsars with an assumed value of $\tau \gtrsim 10^7$ yr and $B_i(\mathrm{G}) \lesssim 10^{12.5}$, the subsequent evolution is expected to be along a track corresponding to a power-law dependence of the magnetic field on time, namely $B_s \propto t^{-1/4}$ (Srinivasan et al. 1990). During this period, the decay of the field in the crust will keep pace with the expulsion of the flux, which occurs over a time-scale equal to t_{ch}, and no further substantial field decay will occur before the pulsar dies. The low-field pulsars would, therefore, experience a restricted field decay by an order of magnitude or less during their lifetimes and will populate the region with $B_s \lesssim 10^{11.5}$ G (Fig. 3a) in the observed pulsar population. Consequently, the predicted lifetimes of these pulsars tend, on the whole, to be larger than for the exponential model or for assuming no field decay at all during a pulsar lifetime. This effect is shown in Fig. 3(b), where the computed lifetimes of single pulsars with various values of B_i according to both SIF and the free exponential model are plotted for the different assumed values of $10^6 \le \tau(\mathrm{yr}) \le 10^9$. Furthermore, the increased lifetimes of the low-field pulsars are also seen to be larger for the smaller values of τ in contrast to the behaviour expected in the exponential model (Fig. 3b). The behaviour and lifetimes of pulsars with large initial field strengths ($B_i \gtrsim 10^{12.5}$ G) are, however, the same

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

(a)

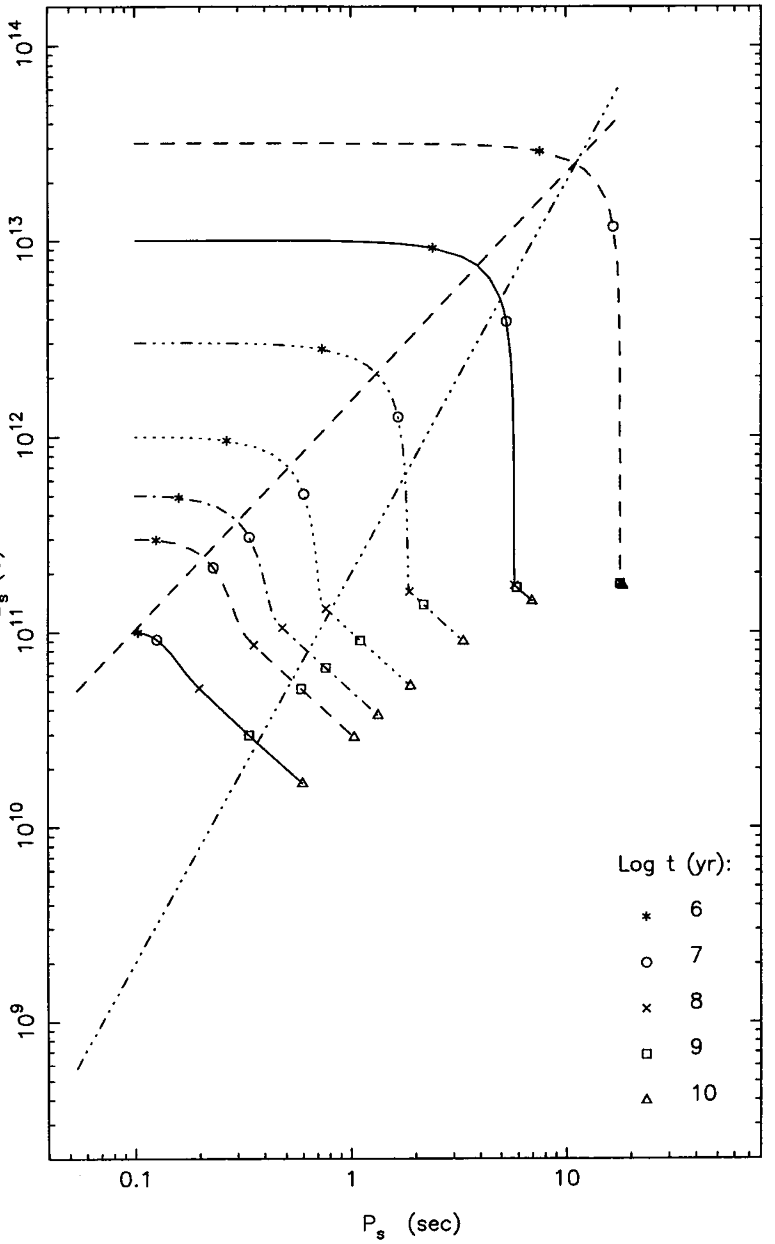

Figure 3. (a) Spin and magnetic field evolution of solitary pulsars born with the different assumed initial field strengths and a given initial period (=0.1 s) are shown, according to predictions of the spin-down-induced flux expulsion scenario. Positrons of the neutron stars at various ages are marked on each track, and the spin-up and death-lines are also shown. A value of $\tau = 10^7$ yr has been assumed. (b) Expected active lifetimes of pulsars for the different assumed initial field values B_i as predicted based on the spin-down-induced flux expulsion scenario (SIF) and the purely exponential field decay model (Exp.). Results for the different assumed values of the Ohmic time-scale τ are shown in each panel by the different curves.

for both models since they evolve along similar tracks until they cross the death-line.

3.1 Injection

The predicted evolutionary behaviour and enhanced lifetimes of pulsars which undergo a 'restricted' field decay might account for the so-called 'injection' in the 'current' of pulsars which has been recently associated with the birth events of recycled pulsars (Deshpande, Ramachandran & Srinivasan 1995). The 'current' of pulsars on the B_s–P_s plane, due to the spin down of the star, from a bin of width ΔP_s at given values of P_s and B_s, is defined as $J(B_s, P_s) = (1/\Delta P_s)\Sigma_i \dot{P}_{s_i}$, where the sum extends over all pulsars in the Galaxy that fall into the bin (Narayan & Vivekanand 1981; Phinney & Blandford 1981). A discontinuity showing a significant increase in the current at $P_s \sim 0.5$ s implies an 'injection' of a large number of pulsars into the population at this spin period (Vivekanand & Narayan 1981). The arguments, based on the analysis of the 'current' of pulsars, that the low-field pulsars have not evolved from the extreme left and along constant field lines on the B_s–P_s plane (Srinivasan

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

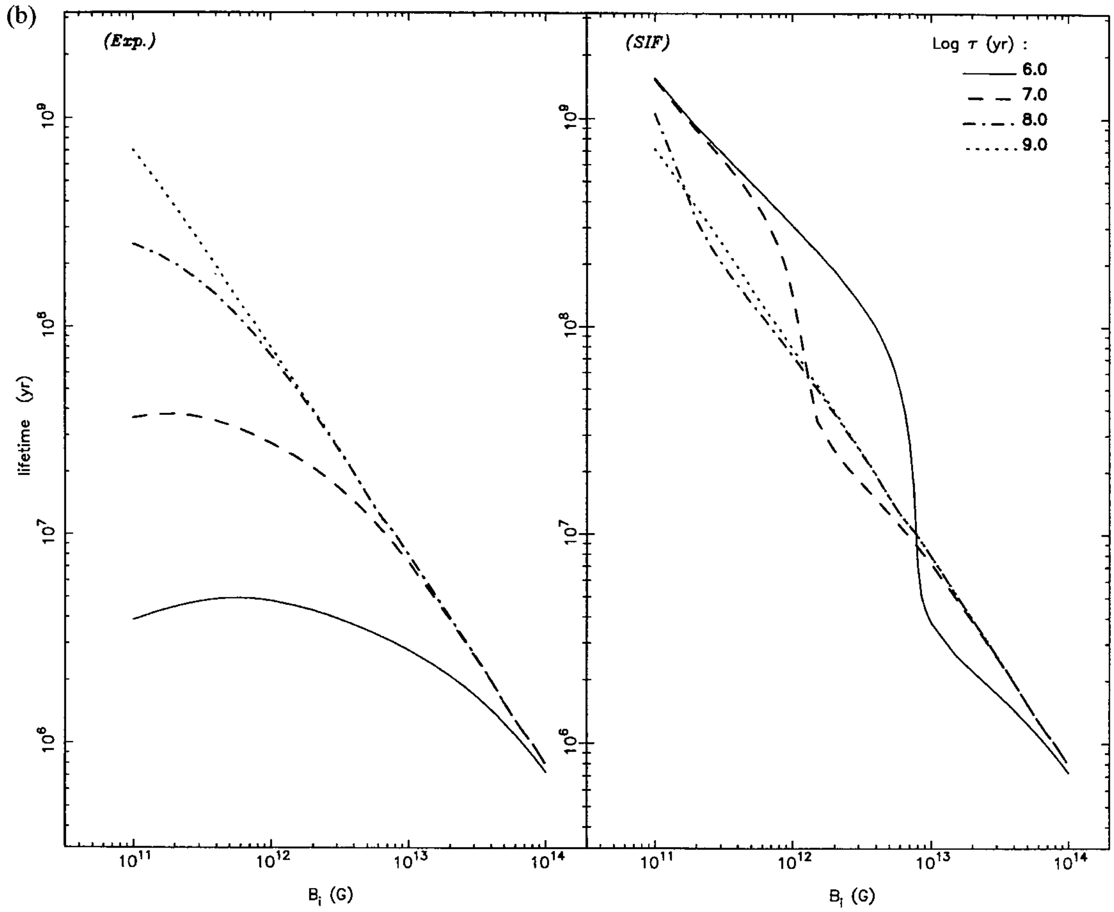

Figure 3 – *continued*

1991) would, however, also be consistent with the suggested downward motion (Fig. 3a) during their initial field decay. Also, the fact that members of this subset of pulsar population are found to have high altitudes above the galactic plane would still be explained in terms of their high ages, as in the recycling interpretation (Srinivasan 1991). On the other hand, a value of $\tau \lesssim 10^7$ yr, which is preferred here because it results in a larger jump in the expected lifetimes (Fig. 3b), is indeed a necessary requirement for the recycling of binary pulsars to account for the injection at the region of $B_s \lesssim 10^{11.5}$ G. This is because these pulsars are believed to be recycled in binaries with massive companions which have lifetimes of only a few times 10^7 yr, while they are also expected to have experienced a reduction by a factor of ~ 10 in their field strengths. Moreover, the newborn recycled pulsar is expected to further experience a fast decay in its magnetic field along a vertical track (with a time-scale $\sim \tau$) due to its earlier spin-down history. The recycled pulsars injected in the low-field long-t_{ch} region are, therefore, expected to spend much less time there than the single old pulsars which have experienced a restricted field decay and would be subject to a much slower field decay (with a time-scale $\sim t_{ch}$). The expected contribution from single old pulsars to the observed sample of pulsars in the 'injection' region has, therefore, to be weighted by a factor of t_{ch}/τ in comparison with that resulting from the recycled pulsars. In any case, even though the 'restricted' field decay interpretation can, presumably, account for the origin of all low-field pulsars without assuming any contribution arising from recycling in massive binaries, the reverse does not seem to be permissible. One cannot invoke the SIF model of field decay and also explain 'injection' as being the result of pulsars recycled in massive systems without allowing for at least a major fraction of the injection at low-field region to be the result of old single pulsars.

3.2 Population synthesis

Statistical studies of the single pulsar population have resulted in estimates for the value of the field decay time-scale ranging from $\lesssim 10^7$ yr up to $\gtrsim 10^8$ yr (e.g. Narayan & Ostriker 1990; Bhattacharya et al. 1992). In all of these studies the pulsar surface magnetic field has, however, been assumed to decay 'freely' with an exponential or a power-law time dependence. Although a similar exercise has to be repeated in order to see how the results of such studies would be modified for the case of the SIF model of field decay, the following argument seems to be supported by the implications of the earlier studies. The above Monte Carlo simulations of the observed properties of pulsars which have preferred values of $\tau \gtrsim 10^8$ yr are, however, expected to imply a lower value of $\tau \sim 10^7$ yr if a sample of pulsars with initial long periods and low field strengths is further included in the adopted population (Bhattacharya et al.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

1992). Similar low values of the decay time-scale have been inferred from those studies in which a second generation of pulsars (assumed to be born at large heights above the galactic plane and with low initial magnetic fields) has been also considered in addition to the pulsars born in the galactic plane (Narayan & Ostriker 1990). The restricted field decay predicted in the SIF model for an assumed value of $\tau \sim 10^7$ yr would, on the other hand, have the effect of increasing the population of long-lived low-field single pulars, as discussed earlier. Simulation of a single disc population of pulsars with an assumed value of $\tau \sim 10^7$ yr might, therefore, be expected to be consistent with the statistical properties of the observed pulsars if magnetic fields are assumed to evolve according to the SIF model.

4 RECYCLED PULSARS

4.1 Low-mass progenitors

It was shown in Paper I that simulations of the evolution of magnetic fields and spin periods of neutron stars in close binaries as predicted in SIF can successfully reproduce the observed distribution of B_f versus P_{orb} for pulsars recycled in binary systems with wide orbit low-mass companions (LMBPs). The list of six objects which were used to test the results of these computations (table 1 in Paper I) is now augmented by another three newly discovered similar systems, namely PSR J1643 − 1224, J1455 − 3330, and B1800 − 27 (Johnston et al. 1995; Lorimer et al. 1995b) which have properties still consistent with the results of our computations (Paper I). As discussed earlier, the evolution of pulsars recycled in binary systems with lifetimes much larger than τ (namely LMBPs) are determined only by their earlier acquired P_{max} values. Hence it might seem unnecessary to inspect the properties of pulsars recycled in low-mass systems in order to infer any constraint on the value of τ, provided that a value of $\tau >$ few $\times 10^9$ yr is not considered to be relevant at all. However, even in the case of these binaries it turns out that the predicted behaviour of the recycled pulsars does depend on the assumed value of τ through its effect on the value of P_{max}. A value of $10^8 \lesssim \tau \lesssim 10^9$ yr was hence inferred from the results of model computations for low-mass systems (Paper I). Nevertheless, values as low as $\tau \sim 10^7$ yr could also produce acceptable results for the simulations of LMBPs provided a more efficient spin-down mechanism, with values of $\xi \gtrsim 10$, is considered (see the results presented in Section 4.3, below, for the case with assumed $B_i = 10^{12.5}$ G, $\tau = 10^7$ yr and $\xi = 100$) in contrast to $\xi = 1$ adopted in Paper I. Large values of $\xi > 1$ might in fact be expected to be the case because the rate of angular momentum transfer during a 'propeller' phase corresponding to the assumed value of $\xi = 1$ is, as was noted in Paper I, the least efficient one among the models discussed in the literature (Wang 1981). The larger values of ξ do not, however, have much effect on our results for the values of P_{max} in the case of binaries with massive companion stars (discussed below).

A further observational constraint on the coupled spin–magnetic evolution of neutron stars in low-mass systems is provided by the observed spin periods in LMXBs. In Fig. 4 the predicted distribution of P_x versus P_{orb} in these systems according to SIF and also the exponential model are shown, separately. The values of P_x (spin periods at the *beginning* of the X-ray phase in LMXBs) as predicted in the exponential model are seen to be very small ($\lesssim 10$ s) for values of the Ohmic decay time-scale $\tau \lesssim 10^8$ yr. Larger values of $P_x \gtrsim 100$ s could be reproduced in the exponential scenario only with an assumed large value of $\tau \gtrsim 10^{8.5}$ yr. Although there is not much observational data available on the spin periods in LMXBs, a value as large as 114 s has been already observed for GX 1 + 4 (Nagase 1989). Such an observed value for the *present* spin period in an LMXB source implies that the upper limit for the actual values of P_x is much larger than ~ 100 s (values which are difficult to accommodate in the exponential model with any reasonable value of τ). The SIF model does, however, predict such large values of P_x for various choices of the value of the decay time-scale in the range $10^7 \lesssim \tau(\mathrm{yr}) \lesssim 10^9$, as shown in Fig. 4.

4.2 Massive progenitors

The adopted masses and lifetimes for the intermediate- and high-mass stars, based on the stellar evolution results of Schaller et al. (1992) for solar metallicities, are given in Table 2. We note, however, that longer lifetimes for massive stars, which are predicted because of a different treatment of the convection problem and the opacity in the stars (e.g. Bressan et al. 1993), would imply a somewhat larger upper limit on the acceptable values of τ inferred from the following considerations.

There are, at present, two observed binary pulsars with massive compact companions (neutron stars) which have magnetic fields $\gtrsim 10^{11.5}$ G and periods both smaller and larger than the corresponding P_{eq} values. These are expected to be the second-born neutron stars in the binary systems, and hence part of the population of normal pulsars. Similarly, binary pulsars with B_s and P_s values consistent with those of normal pulsars but with a white dwarf (WD) companion are not, in general, required to be recycled. A late (case B or C, as it is called) mass transfer to a white dwarf from its evolved (He or carbon core-burning, respectively) IM companion star could result in the formation of a pulsar via accretion-induced collapse of the WD. Further evolution of the companion to a WD might, however, be so rapid that the neutron star could not be spun up to the required value of P_{eq}. Binary evolution calculations have shown that a neutron star may in fact be born in a binary even *after* the birth of its white dwarf companion (Dewey & Cordes 1987; Pols et al. 1991).

On the other hand, pulsars like PSR B1913 + 16, PSR B1534 + 12, and any other binary or single pulsar with a similar period ($P_s \sim 0.06$ s) and similar or lower fields ($B_s \lesssim 10^{10.5}$ G) imply a recycling history in a binary with a companion having a lifetime $t_c \sim (3–6) \times \tau$. The post-recycling evolution of such pulsars would be, in general, first along vertical tracks on the B_s–P_s plane while the field decays on a time-scale $\sim \tau$ down to its final value (equation 2), and would then be followed by a horizontal path. A value of $P_{eq} \sim 0.01$ s corresponding to $B_R \sim 10^{10}$ G is predicted (equation 1) to be the lowest possible value achieved in binaries with HM-companions for an assumed value of $\tau \sim (1–2) \times 10^7$ yr [preferred by the result in Figs 2(a) and (b)] and the adopted range of lifetimes for HM-stars. However, lower values of B_R and hence P_{eq} might be also be expected for these systems considering the possibility of a

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

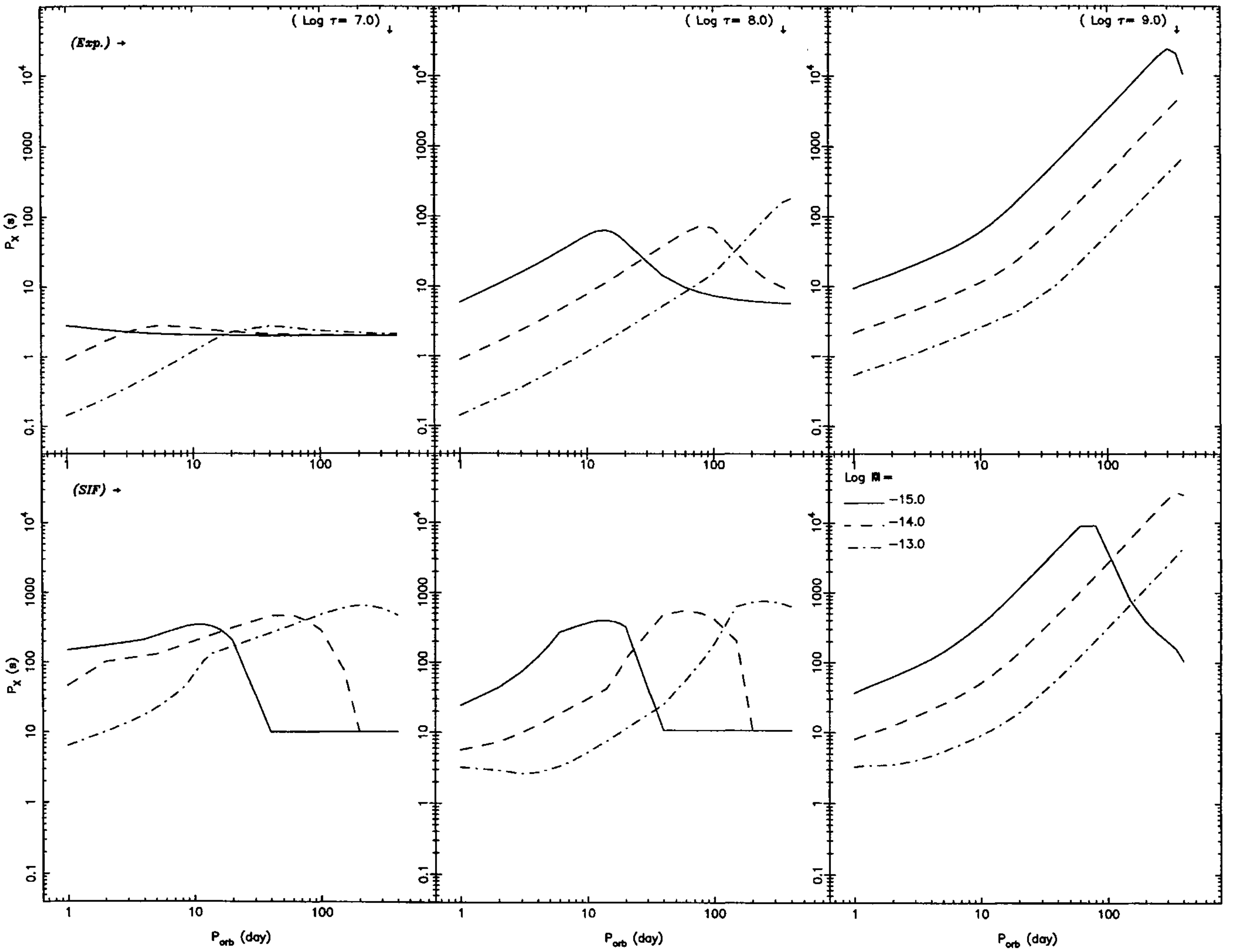

Figure 4. Spin periods of neutron stars at the beginning of the LMXB-phase versus orbital periods as predicted in the spin-down-induced flux expulsion scenario (the bottom row marked SIF) and in the purely exponential field decay model (the top row marked Exp.). Each two panels in the same column correspond to a different assumed value of τ (in units of yr) as indicated. Each curve corresponds to a different value of mass-loss rate $\dot{M}$ (in units of $M_{\odot}$ yr^{-1}) for the companion star.

Table 2. Adopted values of parameters for massive stars.

star	mass ($M_{\odot}$)	lifetime (yr)
IM	$2.5-7$	$7\times10^{8}-5\times10^{7}$
HM	$\gtrsim 9$	$\lesssim 3\times10^{7}$

temporary reduction in the Ohmic decay time-scale of the crustal field due to the compression of a large amount of magnetic flux into a narrow region at the bottom of the crust. Such an enhanced field compression might be expected to occur, in the context of the SIF scenario, only for the case of massive binaries in which the short spin-down time-scales could result in flux expulsion out of the core at a rate faster than its assumed rate of diffusion in to the upper regions of the crust. Compression of the current-carrying layers of the crust, with the effect of a reduction in the length-scale of the field distribution, has been considered to occur also as a result of the matter accreted on to the neutron star (Konar, Bhattacharya & Urpin 1995). Such an accretion-induced field decay for the crustal fields of neutron stars is not, however, expected to have any significant effect for the predictions of SIF in the case of long-lived low-mass systems. This is because the accretion of a substantial amount of matter in these systems occurs, during the RLOF phase, only after the crustal fields have already decayed down to very negligible values. Short decay time-scales ($\sim 5\times10^{6}$ yr) associated with a compressed flux in the high-density region at the bottom of the crust have also been suggested, based on the effect of a magnetic buoyancy force. A Hall drift is expected to occur because of the buoyancy force with a radial component that would deposit the flux into the outer regions of the crust where it would be subject to a more rapid Ohmic diffusion (Jones 1988).

The inferred field strengths of the observed binary pulsars in double neutron star recycled systems (such as PSR B1913 + 16) are, on the other hand, ~ 2 orders of magnitude smaller than those usually assumed for HMXBs (which are presumably their immediate progenitors, e.g. Bhatta-

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

charya & van den Heuvel 1991 and Verbunt 1993). The normal Ohmic decay of the field in the crust for any given value of $\tau \gtrsim 10^6$ yr clearly cannot be the effective mechanism for such a reduction in the surface fields, since the assumed transition from the X-ray phase to the birth of the recycled pulsar is expected to occur over a period $\lesssim 10^6$ yr. A short-term enhanced field decay occurring at the final stages of the X-ray phase in HMXBs discussed earlier might, however, account for the apparently large differences in magnetic fields of the neutron stars at these successive phases of their binary evolution. Alternatively, one might argue that the observed double neutron star systems have descended from a possibly low-field sub-class of HMXBs which might not show any regular pulsation in their observed X-ray emissions. In fact, field strengths as low as $\sim 10^9$ G have been suggested for some of the *pulsating* HMXB sources (Vela X-1: Ruderman 1987). Hence, while the low-field HMXBs could be considered the progenitors of recycled pulsars similar to PSR B1913+16, the strong-field pulsating HMXBs would be expected to result in recycled pulsars which would first show up in the 'injection' region (cf. Section 3.1). The latter objects will evolve rapidly along vertical tracks which extend in most cases down below the death-line. The apparent inconsistency in the strength of the magnetic fields in the two classes of objects should be treated cautiously, since the existing estimates of the *dipolar* fields of neutron stars in HMXBs are subject to large uncertainties. The direct observational measurements based on the frequencies of the observed cyclotron X-ray absorption lines in some of these sources reflect, in principle, only the *local* field strengths in the X-ray emission region, which need not be the same as the dipolar field of the star (Flowers & Ruderman 1977; Srinivasan & van den Heuvel 1982). The spin behaviour of an accreting neutron star is, on the other hand, used to estimate its *dipolar* field based on the predictions of the accretion torque theory (Ghosh & Lamb 1979). Uncertainties in the theory and in simultaneously measuring the spin-up or spin-down rates and the accretion luminosities (as required in the theory) lead to large uncertainties in the inferred values for the magnetic fields (Ruderman 1987; Lamb 1989). The two possibilities discussed for the magnetic history of a recycled pulsar similar to PSR B1913+16, namely a short-term enhanced field decay or a low-field HMXB progenitor, are invoked in the different evolutionary routes considered for the recycled pulsars in Tables 3 and 4.

Neutron stars recycled in binaries with IM companion stars (IMBPs) are predicted (equation 1), for the assumed values of τ and lifetimes of the companion star, to achieve values of P_{eq} corresponding to $10^9 < B_R < 10^{10}$ G, namely in the region which is sometimes referred to as the 'gap' in the B_s–P_s plane (see e.g. Kulkarni 1995). The subsequent evolution of these pulsars would be decided (see equation 2) by the value of P_{max} that they had attained earlier, which in turn would depend on the properties of their progenitor binary systems. The results of our model computations for the case of a 4-$M_\odot$ companion star show that binaries with smaller orbital periods (in the range of interest for a case-B RLOF mass transfer which is believed to occur in these systems) and/or larger stellar wind rates would give rise to smaller values for P_{max}. Pulsars recycled in such binaries would consequently live with no further substantial decay in their magnetic fields after recycling, given a low enough mass for the companion star and hence a long enough time for their initial fields to decay. Such an evolutionary history, with a value of 30 ms $\lesssim P_{eq} \lesssim$ 190 ms, might be assumed for PSR B0655+64. Larger values of P_{max} which are predicted for the wider binaries would imply (given a value of $t_c \lesssim 10^8$ yr) a behaviour for the recycled pulsar similar to that of the descendants of binaries with HM companion stars (see above). PSR J2145−0750 and also possibly PSR J1022+1001 (Camilo et al. 1996) might be considered as examples of the latter type of evolution in IMBPs. A value of 10 ms $\lesssim P_{eq} \lesssim$ 16 ms, and a subsequent downward evolu-

Table 3. Observationally distinct recycling routes.

X-ray source		Recycled system	Route
	Large B_x	$B_f \sim 10^{12}$ G	1
Pulsating	$\sim 10^{12}$ G		2
	Low B_x	$B_f \lesssim 10^{11}$ G	3
Non-pulsating	$\lesssim 10^{11}$ G		4

Table 4. The requirements and results of the different routes.

	Assuming			Implications for			
Route	t_c/τ	B_R/B_i	τ (yr)	Companion star	Post-recycling*	1913+16	0655+64
			10^8	HM; IM	Z	NO	NO
1	$\lesssim 3$	$\gtrsim 0.1$					
			10^7	Higher mass HM	V	NO	NO
			10^8	Lower mass IM	Z then V	NO	NO
3 and 4	3–10	$\lesssim 0.1$					
			10^7	Lower mass HM; IM	Z then V then Z	YES	YES
	Transient	$> 10^{-4}$	10^7; 10^8	HM; IM	V then Z	YES	YES
2	reduced τ						
		$\lesssim 10^{-4}$	10^7; 10^8	HM; IM	Z	NO	NO

*Z and V denote horizontal and vertical evolution on the B_s–P_s plane, respectively.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

tion on the B_s–P_s plane, is consistent in both cases with their observed properties as well as with the model predictions. Also, the observed larger P_{orb} in the latter two pulsars, as well as the smaller companion mass in the case of PSR J2145 − 0750, as compared to the orbital period, and the companion mass, of PSR B0655 + 64, are in agreement with the above criteria for occurrence of the two types of post-recycling evolution in IMBPs (to the extent that the initial orbital periods and companion masses of their progenitor systems can be ascertained). Furthermore, the predicted post-recycling evolution of IMBPs down vertical tracks might also explain the lack of observed (disc population) pulsars corresponding to the 'gap' region on the B_s–P_s plane, although it is generally expected that the region should be occupied by IMBPs. The problem has recently been further highlighted, since considerations based on the frequency and survival probability of progenitor binaries of IMBPs as compared to LMBPs has led to the conclusion that the observed number of IMBPs is much lower than the expected value (Kulkarni 1995). This is because recent theoretical considerations of binary stellar evolution in progenitors of these systems predict that, contrary to an earlier belief, their spin-up RLOF phases are long and efficient enough to spin the accreting neutron stars in these systems up to millisecond periods (Bhattacharya 1996). Possible explanations suggested for the lack of observing many IMBPs, including the one invoked here, relate to the following.

(1) The lack of observing the corresponding progenitors of such pulsars in their accretion-powered X-ray phase. This might itself be the result of (i) an instability in the associated RLOF mass transfer which would make their X-ray phases extremely short and inefficient (van den Heuvel 1994) such that a recycled pulsar would not be born, or (ii) the fact that an X-ray binary is not formed in the first place because of an instability in the first mass transfer episode in the progenitor binary, namely before the formation of the neutron star, due to the large mass ratio of the binary components (Rathnasree 1993).

(2) Selection effects such as (i) their lower expected radio luminosities in comparison with the millisecond pulsars, and (ii) Doppler smearing of the pulsed signal because of the high orbital acceleration of the pulsar being in a tight orbit with a relatively massive companion (Kulkarni 1995; see, however, Camilo et al. 1996).

(3) The downward vertical evolution (on a time-scale $\sim\tau$) predicted in SIF for some IMBPs, although they are also expected to first appear in the 'gap' region. The very large values of $t_{ch} \gg \tau$ at the corresponding P_{eq} and B_R where the recycled pulsar starts its new life would, however, imply that it will spend very little time in the 'gap' region. Furthermore, because of the larger values of P_{max}/P_i for IMBPs as compared to LMBPs (the result of higher stellar wind rates in IM stars), their fields should decay down to values of $B_f \lesssim 10^7$ G, which is smaller than that predicted for LMBPs. Consequently, most of the pulsars recycled in binaries with IM stars are expected to cross the standard pulsar death-line before arriving at their final residual field values.

The suggested downward evolution of recycled pulsars would also allow for the wedge-shaped region between the 'Hubble'-line ($t_{ch}=10^{10}$ yr) and the 'death'-line to be populated. This is in contrast to the usual assumption that a value of $B_f \sim 10^8$ G is the minimum residual field, and also that recycled pulsars would evolve with essentially no further field decay after recycling. However, the short time-scale of the assumed downward vertical evolution of the recycled pulsars, in contrast to the much larger values of the characteristic ages in that region, would imply a low probability of observing pulsars in this phase of their evolution, as was argued earlier for the 'gap' region. In addition, the pulsar death-line has been suggested to have a smaller slope in the region of $B_s \lesssim 10^9$ G, based on additional constraints on the e^+e^- pair creation in the vacuum gap invoked in the polar cap theories of radio emission mechanism of pulsars (Phinney & Kulkarni 1994; Rudak & Ritter 1994; Bjornsson 1996; see also Chen & Ruderman 1993). The modification of the death-line will have the effect of reducing the area of the wedge-shaped region between the death-line and the Hubble-line and hence reducing the expected number of the recycled puslars in that region. Nevertheless, at least one pulsar has been already observed which lies in this region, namely PSR J2317 + 1439, with a $P_f=3.443$ ms and a $B_f=10^{7.96}$ G (Camilo, Nice & Taylor 1993). The observed properties of this pulsar can be accounted for in the standard scenario only by assuming a low accretion rate $\dot{M}_{acc} \lesssim 10^{-2}\dot{M}_{Edd}$ during the RLOF phase of the progenitor LMXB. Similarly, the observed recycled pulsars which are believed to be much younger than implied by their characteristic ages (Lorimer et al. 1995a; Camilo, Thorsett & Kulkarni 1994) might be also accounted for in terms of their rapid downward evolution discussed here.

To summarize, a value of $\tau \sim (1–2) \times 10^7$ yr is suggested for the mean crustal Ohmic decay time-scale based on the implications of the SIF scenario for the observed distribution of single and binary pulsars (descendants of massive binaries). Given such a value of τ, pulsars recycled in binaries with *high-mass* companions are expected to evolve further along *vertical* tracks on the B_s–P_s plane, while those processed in *low-mass* systems would follow *horizontal* evolutionary paths. The intermediate-mass companions are predicted to result in recycled pulsars which will have an intermediate behaviour between the above two extremes. The results for a larger assumed value of $\tau \sim 10^8$ yr might be also consistent with the observations as far as the evolution of *binary pulsars* is concerned. Such a value of τ would, however, leave the origin of the observed excess in the number of low-field solitary pulsars unexplained. Evolution of HMBPs and IMBPs as discussed here is further summarized in Tables 3 and 4, where a comparison is also made between the results expected for the two assumed values of $\tau \sim 10^7$ yr and 10^8 yr. Four possible evolutionary routes are distinguished in Table 3 depending on the values of two observable quantities, namely the strength of the magnetic field in the X-ray phase B_x and its value in recycled pulsars B_f. Route 2 differs from the others (1, 3, and 4) in that a large drop in the field strength (by a factor of $\gtrsim 10^2$) is assumed to occur *at* the transition from a progenitor HMXB phase to the descendant recycled pulsar. Routes 3 and 4, in contrast, consider the consequences of assuming low-field HMXB progenitors for HMBPs and IMBPs. The requirements for the realization of each route for the two different values of τ and the expected post-recycling evolu-

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

tion of the neutron star, as well as the possible types of its companion star, are then shown in Table 4. In particular, the possibility of producing recycled pulsars similar to PSR B1913 + 16 and PSR B0655 + 64 are also indicated in each case. As can be seen from Table 4, while both values of τ are permitted in the case of an enhanced field decay at the end of the X-ray phase (route 2), a choice of $\tau \sim 10^7$ yr has, beside its success in explaining the origin of the low-field single pulsars, the further merit of being acceptable even without invoking such a rapid field decay. Short time-scales of $\lesssim 10^7$ yr for the field decay of pulsars have been indeed suggested by different observational investigations (Gunn & Ostriker 1970; Lyne, Manchester & Taylor 1985; Narayan & Ostriker 1990). Also, theoretical studies of the field decay in the crust of neutron stars, being subject to uncertainties regarding the correct value of the electrical conductivity of the crustal matter, as well as the effects of the unknown geometry and boundary conditions of the field distribution, have resulted in a large range of values for the decay time-scale, which nevertheless extends to values as low as a few Myr (Flowers & Ruderman 1977; Muslimov & Tsygan 1985; Jones 1987, 1988; Wendell 1988; Sang & Chanmugam 1990).

4.3 Globular cluster pulsars

The suspected 'gap' in the B_s–P_s plane which does not accommodate any disc-population observed pulsars is *not*, however, devoid of pulsars recycled in globular clusters. The difference can be traced, in the context of the SIF scenario, to the different formation mechanisms which are generally assumed for the progenitor low-mass binaries in the two environments. While for the disc-population systems the neutron star is believed to be born in the binary itself, in the case of globular clusters the binary formation is explained mainly as a result of exchange and/or capture processes. At the time of capture and formation of a binary the neutron star is, therefore, expected to be an old dead pulsar (with an age > few × 10^9 yr) and have a surface field strength ~ 2 orders of magnitude smaller than at birth (Fig. 3a). The spin and magnetic evolution of such a neutron star in a binary with a low-mass star will, however, be different from that of a young pulsar with a much stronger field. This is because a lower field strength implies a smaller size magnetosphere during the spin-down interaction phase and hence the conditions for a spin-up phase would be reached at a smaller value of P_{max} corresponding to a larger value of B_f. Fig. 5 shows the computed values of B_f versus P_{orb} for the different assumed initial conditions, corresponding to the disc population low-mass binaries and those in globular clusters. Initial values (with respect to the subsequent binary evolution) of the magnetic fields and spin periods appropriate for the old neutron stars at the time of binary formation in globular clusters are assumed to be $10^{10.5} \lesssim B_i(\mathrm{G}) \lesssim 10^{11}$ and $1 \lesssim P_i(\mathrm{s}) \lesssim 5$, based on the results of the single pulsar evolution in Fig. 3(a). For comparison, the results for the assumed initial values of $B_i = 10^{12.5}$ G and $P_i = 0.1$ s are also shown, as a typical case of the disc-population systems. The final field strengths for the globular cluster systems are predicted to have values in the range $10^9 \lesssim B_f(\mathrm{G}) \lesssim 2 \times 10^{10}$ as indicated by the two curves in Fig. 5 corresponding to the limiting values of the assumed range of initial conditions.

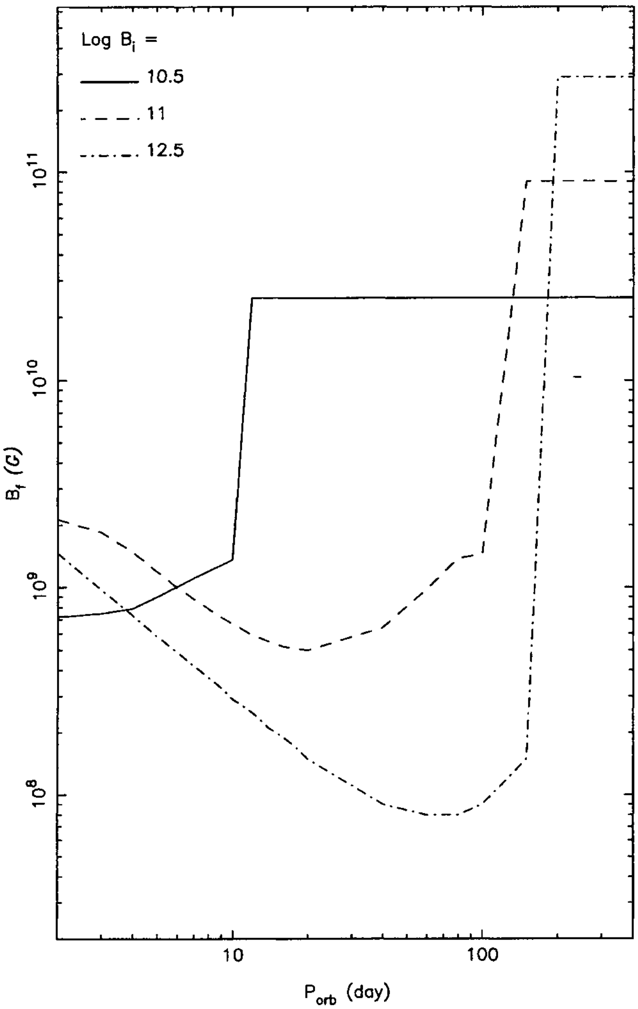

Figure 5. Final values of the surface magnetic field strengths of neutron stars evolved in low-mass binaries with various orbital periods and for the different assumed initial magnetic field strengths which are appropriate to the globular cluster (the *full* and the *dashed* lines) and disc population (the *dash-dotted* line), systems. Values of $\dot{M} = 10^{-14}$ $\mathrm{M_\odot}$ yr^{-1}, $\xi = 100$, and $\tau = 10^7$ yr have been assumed.

The observed values of surface fields of the observed recycled pulsars in globular clusters which fall in the range $10^{8.5} \lesssim B_s(\mathrm{G}) \lesssim 10^{10.5}$ are, therefore, expected to represent the final residual field strengths of the pulsars, corresponding to the values of P_{max} which they had attained earlier. Their subsequent evolution would hence be along constant field lines.

5 CONCLUSION

The spin-down-induced flux expulsion model of magnetic field decay in neutron stars (with an assumed value for the decay time-scale of the magnetic field in the crusts of neutron stars $\sim 10^7$ yr) bears the following implications.

(1) The observed single pulsars as a whole can be explained as being a single population born with similar initial conditions. The detected 'injection' in the current of pulsars and the associated low-field high-latitude pulsars

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

1996MNRAS.283.1214J

could be accounted for by the evolution of some of the larger-field pulsars undergoing a 'restricted' field decay that results in an increase (by a factor of $\gtrsim 10$) in their active lifetimes.

(2) Spin periods as large as $P_s \sim 10^3$ s for neutron stars in LMXBs are predicted by the spin-down-induced model of field decay, while spin periods $\gtrsim 10$ s are not expected based on the purely exponential decay model.

(3) Post-recycling evolution of many pulsars processed in binary systems with HM and IM companion stars would be along vertical tracks on the B_s–P_s plane, while those with LM companions will follow horizontal paths.

(4) Recycled pulsars might populate the region between the Hubble- and death-lines on the B_s–P_s plane, although the rapid downward evolution predicted for such pulsars makes the chance of observing them very small.

(5) A value of $B_f \sim 10^8$ G is not an absolute minimum value for the residual field of neutron stars. Pulsars recycled in close binaries might attain smaller final magnetic field strengths of $B_f \gtrsim 10^6$ G, although they will be observable as radio pulsars only if appropriate electrodynamic conditions apply.

(6) Recycled pulsars in globular clusters are predicted to have a similar history and future as those recycled in disc-population low-mass systems, except for their higher residual field values (which are a result of their *lower* magnetic fields when they are captured in a binary with their low-mass companions).

ACKNOWLEDGMENTS

I wish to thank D. Bhattacharya for reading an earlier draft of the manuscript and for discussions which helped to improve this work. I am also grateful to F. Camilo and G. Srinivasan for their detailed and useful comments and corrections.

REFERENCES

Baym G., Pethick C., Pines D., 1969, Nat, 223, 673
Bhattacharya D., 1996, in van Paradijs J., van den Heuvel E. P. J., Kuulkers E., eds, Proc. IAU Symp. 165, Compact Stars in Binaries. Kluwer, Dordrecht, p. 243
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1
Bhattacharya D., Wijers R. A. M. J., Hartman J. W., Verbunt F., 1992, A&A, 254, 198
Bjornsson C.-I., 1996, ApJ, in press
Bressan A., Fagotto F., Bertelli G., Chiosi C., 1993, A&AS, 100, 647
Camilo F., Nice D. J., Taylor J. H., 1993, ApJ, 412, L37
Camilo F., Thorsett S. E., Kulkarni S. R., 1994, ApJ, 421, L15
Camilo F., Nice D. J., Shrauner J. A., Taylor J. H., 1996, ApJ, 469, in press
Chen K., Ruderman M., 1993, ApJ, 402, 264
Deshpande A. A., Ramachandran R., Srinivasan G., 1995, JA&A, 16, 53
Dewey R. J., Cordes J. M., 1987, ApJ, 321, 780
Ding K. Y., Cheng K. S., Chau H. F., 1993, ApJ, 408, 167
Flowers E. F., Ruderman M. A., 1977, ApJ, 215, 302
Ghosh P., Lamb F. K., 1979, ApJ, 250, 750
Gunn J. E., Ostriker J. P., 1970, ApJ, 160, 909
Illarionov A. F., Kompaneets D. A., 1990, MNRAS, 247, 219
Illarionov A. F., Sunyaev R. A., 1975, A&A, 39, 185
Jahan Miri M., Bhattacharya D., 1994, MNRAS, 269, 455 (Paper I)
Johnston S., Manchester R. N., Lyne A. G., Kaspi V. M., D'Amico N., 1995, A&A, 293, 795
Jones P. B., 1987, MNRAS, 228, 513
Jones P. B., 1988, MNRAS, 233, 875
Jones P. B., 1991, MNRAS, 253, 279
Konar S., Bhattacharya D., Urpin V. A., 1995, in Kapahi V. K., Dadhich N. K., Swarup G., Narlikar J. V., eds, Proc. 6th Asia-Pacific Regional Meeting of the IAU (supplement to JA&A, vol. 16, Indian Academy of Sciences). p. 249
Kulkarni S. R., 1995, in Fruchter A. S., Tavani M., Backer D. C., eds, ASP Conf. Ser. 72, Millisecond Pulsars: A Decade of Surprises. Astron. Soc. Pac., San Francisco, p. 79
Lamb F. K., 1989, in Ogelman H., van den Heuvel E. P. J., eds, Proc. NATO ASI 262, Timing Neutron Stars. Kluwer, Dordrecht, p. 649
Lamb D. Q., 1992, in Tanaka Y., Koyama K., eds, Frontiers of X-ray Astronomy. Universal Academy Press, Tokyo, p. 23
Lipunov V. M., 1992, Astrophysics of Neutron Stars. Springer, Heidelberg, p. 263
Lorimer D. R., Festin L., Lyne A. G., Nicastro L., 1995a, Nat, 376, 393
Lorimer D. R. et al., 1995b, ApJ, 439, 933
Lyne A. G., Manchester R. N., Taylor J. H., 1985, MNRAS, 201, 503
Mineshige S., Rees M. J., Fabian A. C., 1991, MNRAS, 251, 555
Muslimov A. G., Tsygan A. I., 1985, Ap&SS, 115, 43
Nagase F., 1989, PASJ, 41, 1
Narayan R., Ostriker J. P., 1990, ApJ, 352, 222
Narayan R., Vivekanand M., 1981, Nat, 290, 571
Phinney E. S., Blandford R., 1981, MNRAS, 194, 137
Phinney E. S., Kulkarni S. R., 1994, ARA&A, 32, 591
Pols O. R., Coté J., Waters L. B. F. M., Heise J., 1991, A&A, 241, 419
Pringle J. E., Rees M. J., 1972, A&A, 21, 1
Radhakrishnan V., Srinivasan G, 1984, in Hidayat B., Feast M. W., eds, Proc. 2nd Asia-Pacific Regional Meeting in Astronomy (Bandung 1981). Tira Pastaka, Jakarta, p. 423
Rathnasree N., 1993, MNRAS, 260, 717
Rudak B., Ritter H., 1994, MNRAS, 267, 513
Ruderman M. A., 1972, ARA&A, 10, 427
Ruderman M., 1987, in Pacini F., ed., Proc. NATO ASI 195, High Energy Phenomena around Collapsed Stars. Kluwer, Dordrecht, p. 145
Ruderman M. A., Sutherland P. G., 1975, ApJ, 196, 51
Sang Y., Chanmugam G., 1990, ApJ, 363, 597
Sauls J. A., 1989, in Ögelman H., van den Heuvel E. P. J., eds, Proc. NATO ASI 262, Timing Neutron Stars. Kluwer, Dordrecht, p. 457
Schaller G., Schaerer D., Meynet G., Maeder A., 1992, A&AS, 96, 269
Srinivasan G., 1989, A&AR, 1, 209
Srinivasan G., 1991, Ann. N. Y. Acad. Sci., 647, 538
Srinivasan G., van den Heuvel E. P. J., 1982, A&A, 108, 143
Srinivasan G., Bhattacharya D., Muslimov A. G., Tsygan A. I., 1990, Curr. Sci., 59, 31
Taam R. E., van den Heuvel E. P. J., 1986, ApJ, 305, 235
van den Heuvel E. P. J., 1994, in Nussbaumer H., Orr A., eds, Proc. Saas-Fee Advanced Course 22, Interacting Binaries. Springer-Verlag, Heidelberg, p. 263
Verbunt F., 1993, ARA&A, 31, 93
Vivekanand M., Narayan R., 1981, JA&A, 2, 315
Wang Y.-M., 1981, A&A, 102, 36
Waters L. B. F. M., van Kerkwijk M. H., 1989, A&A, 223, 196
Wendell C. E., 1988, ApJ, 333, L95

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System