Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
Proceedings IAU Symposium No. 291, 2012
J. van Leeuwen, ed.

doi:10.1017/S1743921312023393

Recycling Pulsars: spins, masses and ages

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Abstract. Although the first millisecond pulsars (MSPs) were discovered 30 years ago we still do not understand all details of their formation process. Here, we present new results from Tauris, Langer & Kramer (2012) on the recycling scenario leading to radio MSPs with helium or carbon-oxygen white dwarf companions via evolution of low- and intermediate mass X-ray binaries (LMXBs, IMXBs). We discuss the location of the spin-up line in the $P\dot{P}$–diagram and estimate the amount of accreted mass needed to obtain a given spin period and compare with observations. Finally, we constrain the true ages of observed recycled pulsars via calculated isochrones in the $P\dot{P}$–diagram.

Keywords. stars: neutron, pulsars: general, white dwarfs, X-rays: binaries

1. Introduction

Binary MSPs represent the advanced phase of stellar evolution in close, interacting binaries. Their observed orbital and stellar properties are fossil records of their evolutionary history. Thus one can use binary pulsar systems as key probes of stellar astrophysics. Although the standard recycling scenario (Alpar *et al.* 1982; Bhattacharya & van den Heuvel 1991) is commonly accepted, many aspects of the mass-transfer process and the accretion physics are still not understood in detail. Examples of such ambiguities include the accretion disk structure, the disk-magnetosphere transition zone, the accretion efficiency, the decay of the surface B-field of the neutron star and the outcome of common envelope evolution. For further details on these aspects, details in general and discussions of our results, we refer to our journal paper, Tauris *et al.* (2012).

2. The spin-up line

Some of the above mentioned simplifications become a problem when trying to probe the formation and the evolution of observed recycled radio pulsars located near the classical spin-up line for Eddington accretion in the $P\dot{P}$–diagram (e.g. as illustrated with the MSP J1823−3021A, Freire *et al.* 2011). The location of the spin-up line can be found by considering the equilibrium configuration when the angular velocity of the neutron star is equal to the Keplerian angular velocity of matter at the magnetospheric boundary ($r_{\rm mag}$) where the accreted matter enters the magnetosphere, i.e. $\Omega_\star = \Omega_{\rm eq} = \omega_c\,\Omega_{\rm K}(r_{\rm mag})$ or: $P_{\rm eq} = 2\pi(r_{\rm mag}^3/GM)^{1/2}\,\omega_c^{-1}$, where $0.25 < \omega_c \leqslant 1$ is the so-called critical fastness parameter. Introducing the magnetospheric coupling radius, $\phi \equiv r_{\rm mag}/r_{\rm Alfven}$ and the magnetic inclination angle, α we can rewrite this expression:

$$\dot{P} = \frac{2^{1/6}G^{5/3}}{\pi^{1/3}c^3}\frac{\dot{M}M^{5/3}P_{\rm eq}^{4/3}}{I}\;(1+\sin^2\alpha)\;\phi^{-7/2}\,\omega_c^{7/3} \qquad (2.1)$$

which can be plotted directly in the $P\dot{P}$–diagram. (Here M is the mass of the pulsar, $\dot{M}$ is its accretion rate and I is its moment of inertia.) In case $\sin\alpha = \phi = \omega_c = 1$ we find:

$$\dot{P} = 3.7 \times 10^{-19}\ (M/M_{\odot})^{2/3}\, P_{\rm ms}^{4/3} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}} \right) \tag{2.2}$$

where $P_{\rm ms}$ is the equilibrium spin period in units of milliseconds. We have included the plasma term in the spin-down torque using the combined model of Spitkovsky (2006) to compensate for the incompleteness of the vacuum magnetic dipole model.

In Fig. 1 we have plotted equation (2.1) for different values of α, ϕ and $\omega_{\rm c}$ to illustrate the uncertainties in the applied accretion physics to locate the spin-up line. In all cases we assumed a fixed accretion rate of $\dot{M} = \dot{M}_{\rm Edd}$. The location of the spin-up line is simply shifted one order of magnitude in $\dot{P}$ down (up) for every order of magnitude $\dot{M}$ is decreased (increased). It is important to realize that there is no universal spin-up line in the $P\dot{P}$–diagram. Not only are M and α individual to each pulsar (giving rise to the width of each band), also ϕ and ω_c could be related to B, α and $\dot{M}$.
If we assume that accretion onto the neutron star is indeed Eddington limited, then the three bands in Fig. 1 represent upper limits for the spin-up line for the given sets of (ϕ, $\omega_{\rm c}$). Thus we can in principle use this plot to constrain (ϕ, $\omega_{\rm c}$) and hence the physics of disk–magnetosphere interactions from future detections of MSPs.

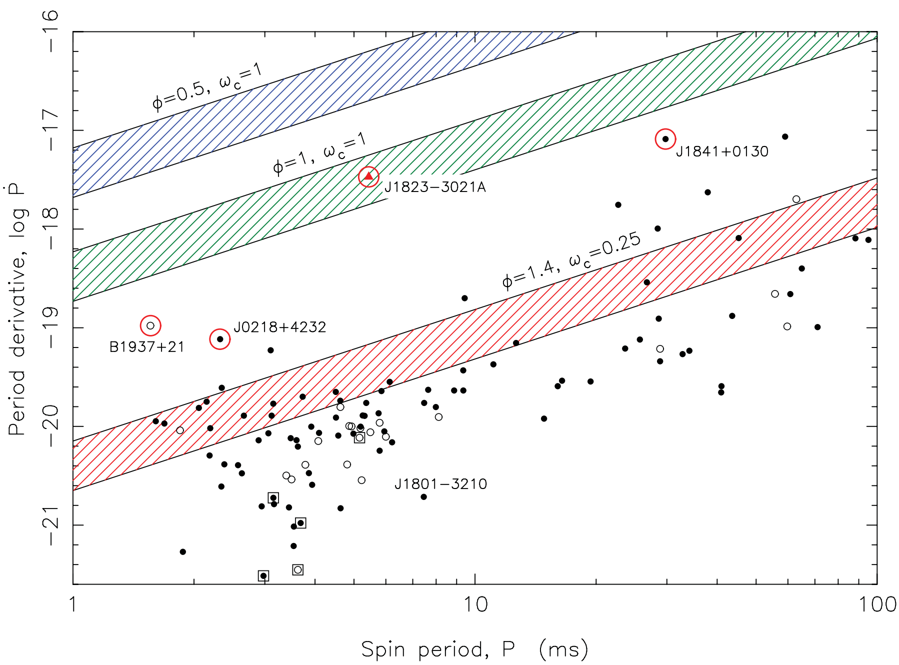

Figure 1. Calculations of three spin-up lines, shown as coloured bands, depending on the parameters (ϕ, $\omega_{\rm c}$). The upper boundary of each band (or "line") is calculated for a neutron star mass $M = 2.0\,M_{\odot}$ and $\alpha = 90°$. The lower boundary is calculated for $M = 1.0\,M_{\odot}$ and $\alpha = 0°$. The green (central) hatched band corresponds to $\phi = 1$ and $\omega_{\rm c} = 1$. The blue and red hatched bands are upper and lower limits set by reasonable choices of the two parameters (ϕ, $\omega_{\rm c}$). In all three cases the spin-up line is calculated assuming accretion at the Eddington limit, $\dot{M} = \dot{M}_{\rm Edd}$. The observed distribution of binary and isolated radio pulsars in the Galactic disk are plotted as filled and open circles, respectively. Also plotted is the pulsar J1823−3021A, located in the globular cluster NGC 6624. (Fig. adapted from Tauris *et al.* 2012.)

https://doi.org/10.1017/S1743921312023393 Published online by Cambridge University Press

When modeling the birth spins of recycled radio pulsars it is important to include the braking torque acting during the Roche-lobe decoupling phase (RLDP) when the donor star terminates its mass transfer. It has been shown that accreting X-ray MSPs may lose up to 50 % of their rotational energy during the RLDP of LMXBs (Tauris 2012).

3. Relation between accreted mass and final spin period

Recycled pulsars obtain their fast spins via angular momentum exchange from the differential rotation between the accretion disk and the neutron star. The amount of spin angular momentum added to an accreting pulsar is given by:

$$\Delta J_{\star} = \int n(\omega, t)\, \dot{M}(t)\, \sqrt{GM(t) r_{\rm mag}(t)}\, \xi(t)\, dt \tag{3.1}$$

where $n(\omega, t)$ is a dimensionless torque. Assuming $n(\omega, t) = 1$, and $M(t)$, $r_{\rm mag}(t)$ and $\xi(t)$ to be roughly constant during the major part of the spin-up phase we can obtain a simple and convenient expression to relate the (minimum) amount of accreted mass and final equilibrium spin period (see also Alpar *et al.* 1982):

$$\Delta M_{\rm eq} = 0.22\, M_{\odot}\, \frac{(M/M_{\odot})^{1/3}}{P_{\rm ms}^{4/3}} \tag{3.2}$$

assuming a numerical factor $f(\alpha, \xi, \phi, \omega_c) = 1$ (from disk-magnetosphere interactions). Considering a pulsar with a final mass of $1.4\, M_{\odot}$ and a recycled spin period of either 2 ms, 5 ms, 10 ms or 50 ms requires accretion of $0.10\, M_{\odot}$, $0.03\, M_{\odot}$, $0.01\, M_{\odot}$ or $10^{-3}\, M_{\odot}$, respectively. Therefore, it is no surprise that observed recycled pulsars with massive companions (CO/ONeMg WD or NS) in general are much more slow rotators – compared to MSPs with He WD companions – since the progenitor of their massive companions evolved on a relatively short timescale in IMXBs or HMXBs, only allowing for very little mass to be accreted by the pulsar.

4. True age isochrones of recycled pulsars

In order to investigate if we can understand the distribution of MSPs in the $P\dot{P}$–diagram we have traced the evolution of eight hypothetical, recycled MSPs with different birth locations $(P_0, \dot{P}_0)$. In each case we traced the evolution as a function of age, t for a constant braking index $2 \leqslant n \leqslant 5$ and calculated isochrones by integration for each pulsar given that $P(t, n, P_0, \dot{P}_0)$. The results are shown in Fig. 2 together with observed data. Furthermore, we plotted two isochrones (see fat green and pink lines) calculated for ($P_0 = 1.0\,$ms, $n = 3$, $t = 1.5\,$Gyr) and ($P_0 = 7.0\,$ms, $n = 3$, $t = 12\,$Gyr), respectively, and with no restrictions on $\dot{P}_0$ (or B_0).

A number of interesting conclusions can be drawn from this diagram. The overall distribution of observed pulsars follows nicely the banana-like shape of the two fat isochrones, see also Kiziltan & Thorsett (2010), and hence pulsars are recycled with a wide range of final B-fields. Although these curves are not an attempt for a best fit to the observations it is interesting to notice that close to 90 % of all recycled pulsars (even up to P = 100 ms) are compatible with being born (recycled) with an initial spin period of $P_0 = 1-7$ ms and having ages between 1.5 and 12 Gyr. However, from a binary evolution point of view many of the $P = 20 - 100$ ms pulsars (the mildly recycled pulsars) are born with such relatively slow spins (see Section 3) and hence they need not be that old. This can, for example, be verified by cooling age determinations of their WD companion stars. Pulsars with small values of the period derivative, $\dot{P} \simeq 10^{-21}$ hardly evolve at all in

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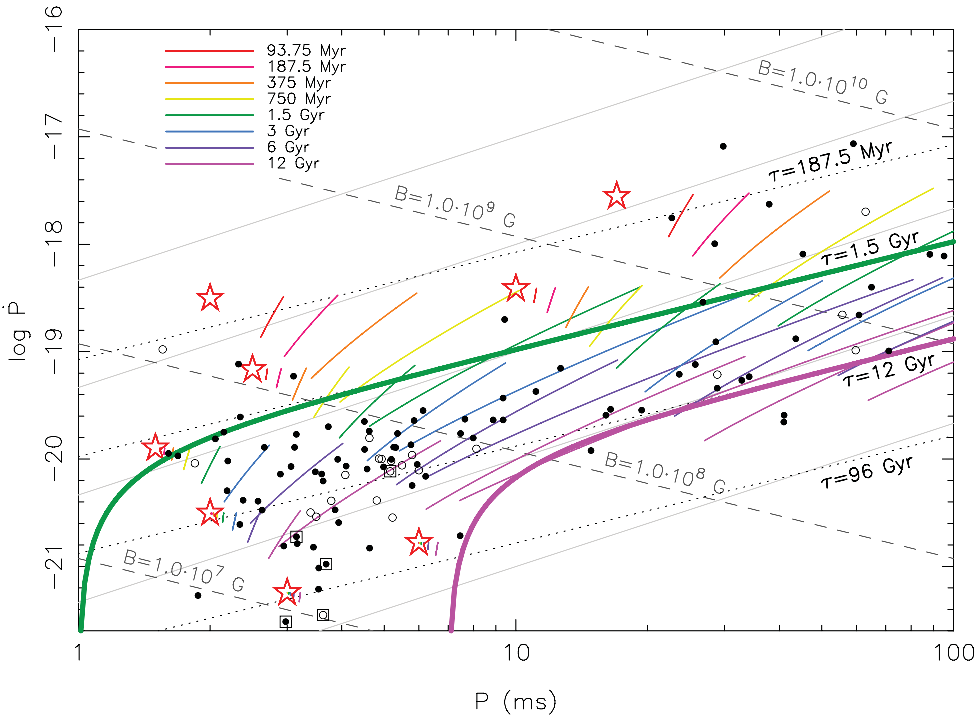

Figure 2. Isochrones of eight hypothetical recycled pulsars born at the locations of the red stars. The isochrones were calculated for different values of the braking index, $2 \leqslant n \leqslant 5$. Also plotted are inferred B-field values (dashed lines) and characteristic ages, τ (dotted lines). The thin gray lines are spin-up lines with $\dot{M}/\dot{M}_{\rm Edd} = 1,\ 10^{-1},\ 10^{-2},\ 10^{-3}$ and 10^{-4} (top to bottom, and assuming $\sin\alpha = \phi = \omega_{\rm c} = 1$). In all calculations we assumed a pulsar mass of $1.4\,M_\odot$. It is seen how the banana shape of the two fat isochrones (see text) fits very well with the overall distribution of observed pulsars in the Galactic disk. Binary pulsars are marked with solid circles and isolated pulsars are marked with open circles, using data from the *ATNF Pulsar Catalogue* and corrected for kinematic (Shklovskii) effects. (Fig. adapted from Tauris *et al.* 2012.)

the diagram over a Hubble time. This trivial fact is important since it tells us that these pulsars were basically born with their currently observed values of P and $\dot{P}$ (first pointed out by Camilo *et al.* 1994). Hence, some pulsars with characteristic ages of $\tau \simeq 100$ Gyr could in principle have been recycled very recently – demonstrating the unreliability of τ as a true age indicator. It is also interesting to notice PSR J1801−3210 (discovered by Bates *et al.* 2011) which must have been recycled with a relatively slow birth period, $P_0 \sim 7$ ms despite its low B-field $< 10^8$ G, see Fig. 1 for its location in the $P\dot{P}$–diagram.

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