

Two Clocks in the PSR J0737–3039 Binary System and Their Implications for the System’s Origin and Evolution

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Abstract. As discussed elsewhere in this volume, the double pulsar system is a magnificent laboratory for gravitational physics and for studying pulsar magnetospheres. Here we consider the uses of having two clocks in the system in the context of its origin and evolution. We find that the “standard” evolutionary scenario involving spin-up of the first-born neutron star in an X-ray binary phase is consistent with the observed parameters. Equality of the spin-down ages of the two pulsars requires that the post-accretion spin period of A most likely lies in the range $16 \text{ ms} \lesssim P_{0,A} \lesssim 21 \text{ ms}$. The likely age of the system is 30 – 70 Myr.

1. Introduction

An application of the standard binary pulsar evolutionary model (e.g., Bhattacharya & van den Heuvel 1992) to the double pulsar system J0737–3039 identifies the 22.7-ms pulsar (hereafter A) as the first-born neutron star. Following an initial phase where A existed as a regular radio pulsar with a main-sequence companion, the currently observed spin parameters of A are the result of a subsequent X-ray binary phase where it acquired matter and angular momentum from the secondary star after the secondary evolved off the main sequence and overflowed its Roche lobe. By processes that are not fully understood, this mass-transfer phase also resulted in a reduction of A’s magnetic field (Shibasaki et al. 1989). Following the supernova explosion of the secondary, a second neutron star was formed which we now observe as the 2.77-s pulsar (hereafter B).

While the spin periods of both these pulsars, and the low inferred magnetic field of A relative to B¹ are consistent with this model, a further test is to compare

¹Due to the interaction of A’s wind which penetrates deep into B’s magnetosphere, some care should be taken when interpreting B’s magnetic field strength. In spite of this disruption, B is observed to be spinning down due to a steady braking torque which we model in Section 2.

the time since the spin-up phase of A ended (\mathcal{T}_A) with the time since B has been active as a radio pulsar (\mathcal{T}_B). We therefore expect $\mathcal{T}_A = \mathcal{T}_B$.

The simplest means to test this prediction is to use the characteristic ages of A and B, which are based on the observed periods and period derivatives: $\tau_A = P_A/(2\dot{P}_A)$ and $\tau_B = P_B/(2\dot{P}_B)$. Lyne et al. (2004) find $\tau_A = 2.1 \times 10^8$ yr and $\tau_B = 0.5 \times 10^8$ yr. Possible explanations for this discrepancy are: (i) the standard evolutionary scenario does not apply; (ii) as observed in other pulsars (see e.g. Kramer et al. 2003), characteristic ages are not reliable; (iii) both the model and the characteristic ages are wrong! Given the aforementioned circumstantial evidence in favour of recycling hypothesis, the simplest solution is option (ii). We now briefly investigate the implications for this case. Further details will be given in a forthcoming paper (Lorimer et al., in preparation).

2. Modeling the Spin-Down for A and B

We consider a generic pulsar spin-down model of the form

$$\dot{\Omega} = K\Omega^n, \quad (1)$$

where for a spin period P , the angular frequency $\Omega = 2\pi/P$, n is the braking index (for spin-down due to magnetic dipole radiation, $n = 3$) and K depends on the braking torque applied to the star. In the simplest case, both K and n are independent of time and equation (1) can be integrated directly. For the case $n \neq 1$, we find the ‘‘true age’’ of the pulsar

$$t_{\text{true}} = \frac{2\tau}{(n-1)} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right], \quad (2)$$

where P_0 is the initial spin period and $\tau = P/2\dot{P}$ is the characteristic age. Alternatively, if K decays exponentially with $1/e$ time scale t_{decay} , then

$$t_{\text{reduced}} = t_{\text{decay}} \ln(1 + t_{\text{true}}/t_{\text{decay}}) \quad (3)$$

is the so-called ‘‘reduced age’’. We now consider various applications of these solutions by simply equating the derived ages for the two pulsars and determining their resulting initial spins and ages. In order to distinguish between both pulsars, we use ‘‘A’’ and ‘‘B’’ subscripts where appropriate.

Case 0: spin-down due to a non-decaying magnetic dipole. We first assume that both pulsars spin down due to magnetic dipole radiation (i.e. $n_A = n_B = 3$), their braking torques do not decay (i.e. K_A and K_B are constant) and that the initial spin period of B was much smaller than currently observed (i.e. $P_{0,B} \ll P_B$). Requiring that $t_{\text{true},A} = t_{\text{true},B}$, the initial spin period of A after the spin-up phase ($P_{0,A}$) and the time since spin-up ceased (\mathcal{T}) are:

$$P_{0,A} = P_A \sqrt{1 - (\tau_B/\tau_A)} \simeq 20 \text{ ms}, \quad \text{and} \quad \mathcal{T} = \mathcal{T}_B = \tau_B \simeq 50 \text{ Myr}. \quad (4)$$

As mentioned by Lyne et al. (2004), the value for $P_{0,A}$ is consistent with the period of J0737–3039A predicted by spin-up models (e.g. Arzoumanian et al. 1999).

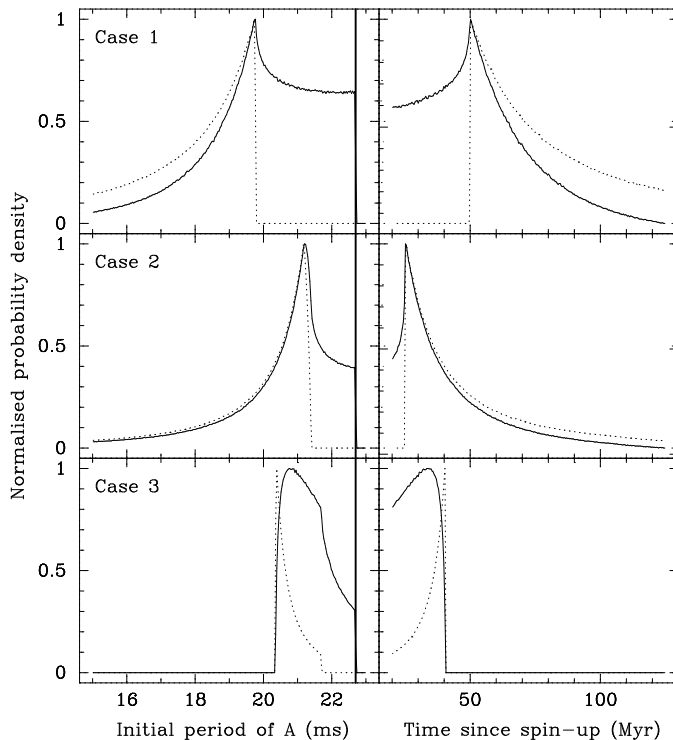


Figure 1. Simulated distributions of the post-accretion spin period of A (left panels) and the time since the end of the spin-up phase (right panels). In each case, the distributions are calculated assuming a range of initial spin periods for B (solid curves) and a negligible initial period (dotted curves). The thick vertical line shows A’s current spin period.

Case 1: no torque decay, $n_A = 3$ and $1.4 < n_B < 3.0$. A more realistic model is to relax the assumption of dipolar spin-down for B and allow its braking index to vary in the range observed for other non-recycled pulsars ($1.4 < n_B < 3.0$; see e.g. Kaspi & Helfand 2002 for a review). For a flat braking index distribution in this range, a simple Monte Carlo simulation to compute $t_{\text{true},B}$ for a large number of trials results in the distributions of $P_{0,A}$ and \mathcal{T} for the condition $t_{\text{true},A} = t_{\text{true},B}$ shown in Fig. 1. In order to show the negligible effect of B’s unknown initial spin period on the results, we performed all calculations with a flat distribution in the range $0 < P_{0,B} < P_B$ (solid lines) and for $P_{0,B} = 0$ (dashed lines). In both cases, the resulting initial spin period distribution for A peak sharply just below 20 ms. The age distribution peaks at ~ 50 Myr (i.e. τ_B).

Case 2: no torque decay, variable braking indices for A and B. Relaxing the conditions on braking indices imposed in case 1, the centre panel of Fig. 1 shows the results when n_A and n_B are drawn from flat distributions in the range $0 < n < 5$. Regardless of B’s initial spin period, the peak of the $P_{0,A}$ distribution is increased over case 1; the age distribution favours smaller ages than case 1.

Case 3: $n_A = n_B = 3$, exponential torque decay for B. The above two cases assume no decay of the braking torque. An alternative solution to the spin-down model is the case of an exponentially decaying braking torque resulting in equation (3) above. The cause of torque decay is uncertain and controversial, and thought to be due to either the decay of the neutron star’s magnetic field and/or the alignment of the spin and magnetic axes with time (see e.g. Tauris and Konar 2001). Since torque decay is not thought to be significant for recycled pulsars (Bhattacharya & van den Heuvel 1992), we consider here the case in which only the torque on B decays. In Figure 1 we show the simulated distributions resulting from the equality $t_{\text{true,A}} = t_{\text{reduced,B}}$ assuming pure magnetic dipole braking ($n_A = n_B = 3$) and a torque decay on B with a timescale $t_{\text{d,B}}$ drawn from a flat distribution between 10 and 100 Myr. The effect of such a decay is to decrease the age significantly so that the distribution peaks at around 30–40 Myr.

3. Conclusions

The two clocks in the double pulsar system J0737–3039 provide a unique means to constrain the age and birth spin periods of the two pulsars. These simple case studies demonstrate the use of the recycling model to place constraints on the post-accretion spin period of A ($P_{0,A}$) and the age since spin-up ceased (\mathcal{T}). For the spin-down models considered, we find $P_{0,A}$ to be in the range 16 – 21 ms and \mathcal{T} to be in the range 30 – 70 Myr. This is shorter than the age of 100 Myr assumed in the merger rate calculations by Burgay et al. (2003) and Kalogera et al. (2004) and hence increases the overall neutron star merger rate by 20–40%.

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