

The eclipsing binary millisecond pulsar PSR B1744-24A – possible test for a magnetic braking mechanism

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Abstract. As presented by Nice et al. (2000), long-term timing of the eclipsing binary PSR B1744-24A shows that the orbital period of this system decreases with a time-scale of only ~ 200 Myr. To explain the much faster orbital period decay than that predicted by only emission of the gravitational waves (~ 1000 Myr) we propose that the orbital evolution of this system is also driven by magnetic braking. If magnetic braking is to explain the rapid decay of the orbit, then λ characterizing the effectiveness of the dynamo action in the stellar convection zone in the magnetic stellar wind formula must be equal to 1.

Key words: stars: binaries: close – stars: binaries: general – stars: mass-loss – stars: pulsars: general – stars: pulsars: individual: B1744-24A

1. Introduction

The formation and evolution of a very low-mass binary system consisting of a neutron star (millisecond pulsar) and a $0.1 M_{\odot}$ companion is not yet well understood. One of the main observational features of these systems is that they are eclipsing. One interesting eclipsing binary system, PSR B1744-24A, is in the globular cluster Terzan 5. The neutron star is an 11.56 ms pulsar in a 1.8 h orbit with a low-mass companion (Lyne et al. 1990). The duration of the eclipse in this system is very variable and is never less than one-third of the orbital period. Lyne et al. (1990) estimated that the energy flux from the pulsar at the companion surface (isotropic radiation is assumed) is $< 2 \times 10^{10} \text{ erg s}^{-1} \text{ cm}^{-2}$ which is near the critical value when the irradiation may influence the structure of a low-mass star (Podsiadlowski 1991). However, this value is at least a factor of 15 less than for another eclipsing millisecond binary pulsar system PSR B1957+20 (Fruchter et al. 1988). This small irradiative flux value and great variations in duration of the eclipse lead Lyne et al. (1990) to the conclusion that in this system Roche lobe overflow may occur.

Recent long-term timing observations of the eclipsing binary pulsar PSR B1744-24A at the VLA and Green Bank, show that the orbital period of PSR B1744-24A has decreased, with a time-scale of only $P_{orb}/\dot{P}_{orb} \sim 200$ Myr. This is five times faster

than if the orbital period decay is driven only by the gravitational wave radiation (Nice et al. 2000).

The key question of interest is: how did this system evolve?

In this short note we show that the new observational data for the orbital period decay of PSR B1744-24A may give us a unique opportunity to test the magnetic braking mechanism if the observed orbital period decay is secular.

2. General picture of low-mass binary system evolution

More than twenty years ago it was realized that to produce short orbital period low-mass binary systems (cataclysmic variables and low-mass X-ray binaries – LMXB) it is necessary to include two mechanisms for orbital angular momentum losses: gravitational wave radiation and/or magnetic braking. Low-mass unevolved stars (main-sequence stars) will fill their Roche-lobe only for orbital periods less than 12 hours and the mass transfer due to gravitational wave radiation mechanism never exceeds $\sim 10^{-10} M_{\odot}/\text{yr}$. This produces an X-ray luminosity of $\sim 10^{36}$ erg/s. Observations, however, show that many LMXBs in this orbital period range have X-ray luminosities that are one or two orders of magnitude higher.

To explain this discrepancy Verbunt & Zwaan (1981) introduced additional orbital angular momentum loss by magnetic braking which was able to drive a much higher mass-transfer rate. In view of these much higher mass transfer rates the companion will be driven out of thermal equilibrium. However magnetic braking will not work forever. As soon as the companion mass has decreased to $M \sim 0.3 M_{\odot}$ (fully convective star) an orbital period near the 3 hours, the rate of angular momentum loss by magnetic braking is expected to either vanish or to drop considerably (Spruit & Ritter 1983), causing the mass-loss rate to drop, and the secondary star subsequently relaxes to its thermal equilibrium state. The stellar radius decreases and the star detaches from its Roche lobe. During the detached phase, orbital angular momentum loss by gravitational wave radiation will continue, and when the orbital period has been reduced to 2 hours, the companion (of mass $\sim 0.3 M_{\odot}$) again fills its Roche lobe. This is the so-called standard cataclysmic variable (CV) evolutionary scenario.

In 1985 Tutukov et al. discussed what will happen with a low-mass binary if the star filling its Roche lobe is a slightly

evolved star (so-called “turn-off main-sequence star”). In this scenario the binary evolves towards very short orbital periods. Due to the chemical composition gradient, the secondary star does not become fully convective when its mass has reduced to $0.3 M_{\odot}$ and magnetic braking does not vanish. Between orbital periods of two to three hours, the mass transfer rate is very low, and apparently during this time the system may be in the “propeller” stage (Ergma & Sarna 1996). According to the standard CV evolutionary picture, the magnetic braking mechanism vanishes near an orbital period of 3 hours. However in the latter scenario, it will also work for smaller values of the orbital periods.

3. Model

The evolutionary sequences for the secondary star in a low-mass binary were computed using a standard one-dimensional stellar evolution code based on a Henyey-type code developed by Paczyński (1970) and adapted to low-mass main-sequence stars. For more detail about the computer program see Muslimov & Sarna (1993) and Sarna & De Greve (1994, 1996).

We compute the loss of orbital angular momentum due to gravitational radiation using the formula presented by Landau & Lifshitz (1971).

$$\frac{\dot{J}}{J_{GWR}} = -\frac{32}{5} (2\pi)^{\frac{8}{3}} \frac{G^{\frac{5}{3}} M_1 M_2}{c^5 M^{\frac{1}{3}}} P_{orb}^{-\frac{316}{3}} \quad (1)$$

where M_1 , M_2 , M and P_{orb} are the primary mass, secondary mass, total mass and orbital period of the system. We assume that the companion is being spun down by the magnetic braking and its spin and orbital rotation are synchronized at the cost of orbital angular momentum loss. We adopt the standard formula (see Mestel 1968; Mestel & Spruit 1987) for the rate of orbital angular momentum losses due to magnetic braking of the companion.

$$\frac{\dot{J}}{J_{MB}} = -5.0 \times 10^{-29} (2\pi)^{\frac{10}{3}} G^{-\frac{2}{3}} \left(\frac{k_2}{\lambda}\right)^2 \frac{M^{\frac{1}{3}} R_2^4}{M_1} P_{orb}^{-\frac{10}{3}} \quad (2)$$

where k_2 is the radius of gyration of the secondary star, $k_2 = 0.1$. This formula contains a poorly known parameter λ (~ 0.7 – 1.8) characterizing the effectiveness of the dynamo action in the stellar convection zone (Verbunt & Zwaan 1981). To take account of the angular momentum loss that accompanies mass loss during the “propeller phase”, we use a formula based on that used to calculate angular momentum loss via a stellar wind (Paczynski 1967; Sarna & De Greve 1994)

$$\frac{\dot{J}}{J_{WIND}} = f_1 f_2 \frac{M_1 \dot{M}_2}{M_2 M}, \quad \dot{M} = f_1 \dot{M}_2, \quad \dot{M}_1 = -\dot{M}_2 (1 - f_1) \quad (3)$$

where $f_1 = \frac{M_{ej}}{M_{acc}}$ and $\dot{M}_2 (\leq 0)$ is the mass-loss rate from the secondary star; $\dot{M}_1 (\geq 0)$ is the accretion rate on to the neutron star, $\dot{M} (\leq 0)$ is the rate of the total mass loss from the system; f_1 is the ratio of the mass ejected by the neutron star to that

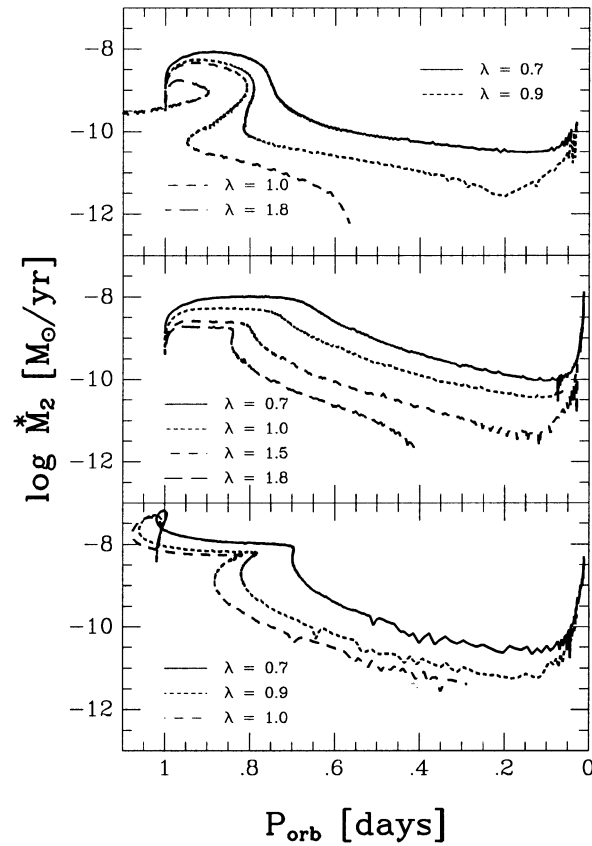


Fig. 1. The dependence of the mass loss rate as a function of orbital period for three different evolutionary sequences (A) (upper panel), (B) (middle panel), (C) (lower panel). For details see text.

accreted by the neutron star and f_2 is defined as the effectiveness of angular momentum loss during mass transfer (Sarna & De Greve 1994, 1996).

We consider the following model (similar scenarios have been discussed by Shaham & Tavani 1991; Kluźniak et al. 1992; Ergma & Sarna 1996) for the PSR B1744-24A system. The progenitor of this system is a low-mass ($< 1.5 M_{\odot}$) star + old neutron star. The secondary star fills its Roche lobe, as a “turn-off main-sequence star”. At the beginning, the mass transfer rate proceeds on a thermal time-scale and the neutron star will spin up to a millisecond period. After that, the mass transfer rate drops and the system enters the “propeller stage” and the pulsar spins down.

As an example we calculated several evolutionary sequences: (I) $M_2 = 1 M_{\odot}$, $M_1 = 1.4 M_{\odot}$, $P_i(\text{RLOF}) = 1$ day; (II) $M_2 = 1.5 M_{\odot}$, $M_1 = 1.4 M_{\odot}$, $P_i(\text{RLOF}) = 1.02$ days ($P_i(\text{RLOF})$ is initial orbital period when the secondary star fills its Roche lobe). In Fig. 1 (a, b, c) the mass-loss rate versus orbital period is presented for the following cases: (A) sequence (I), $f_1 = f_2 = 0$, (B) sequence (I), $f_1 = f_2 = 1$, (C) sequence (II), $f_1 = f_2 = 1$. At first, the mass exchange rate is rather high (proceeds on the thermal time-scale of the secondary star) and during this phase, the old neutron star will spin-up. Latter \dot{M} decreases and near an orbital period of ~ 2 – 4 hours, the mass accretion rate has its

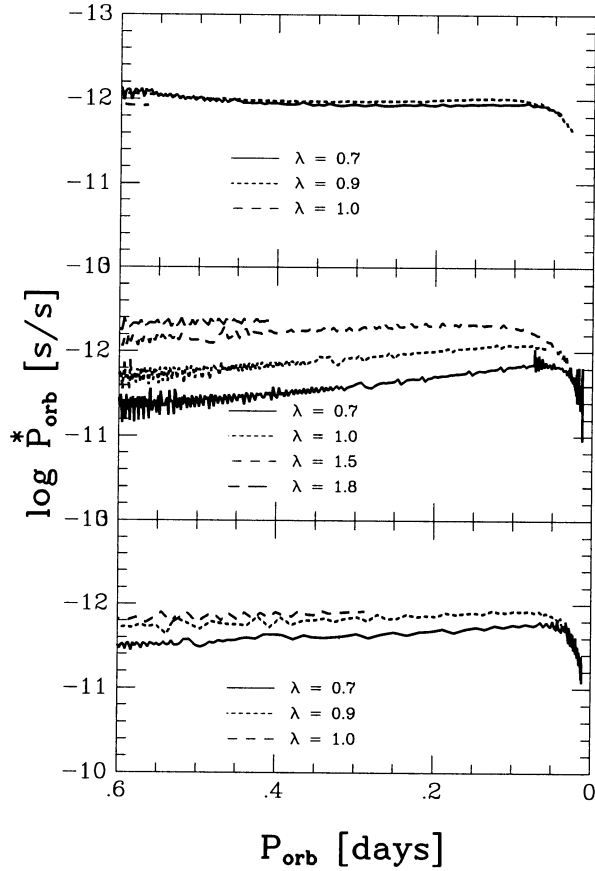


Fig. 2. The evolution of the orbital period derivative with the orbital period. Other details the same as for Fig. 1

minimum value. Depending on the value of the surface magnetic field strength, the system may or may not be in the “propeller phase”. How does the value of λ influence the orbital evolution of the binary system? For example for sequence (A) and for $\lambda=1.8$, the final orbital period is larger than the initial and for $\lambda=1.0$ a short period binary system with low-mass helium white dwarf and millisecond pulsar is formed ($P_{orb} \sim 13$ hours). Only for $\lambda < 1$ does the system evolve towards very short orbital periods (Fig. 1).

In Fig. 2, a, b, c the variation of \dot{P}_{orb} versus orbital period is shown for the same cases as presented in Fig. 1 a, b, c. As is clearly seen in this figure, orbital period changes depend on the value of λ . In Table 1 we present \dot{P}_{orb} and orbital period decay time-scale $\tau = P_{orb}/\dot{P}_{orb}$ values for various λ when the orbital period is equal to 1.8 hours. The evolutionary time-scale obtained by Nice et al. (2000) is 200 Myr. From Table 1 we can see that a λ close to 1 agrees well with the observed value for PSR 1744-24A. The calculated mass of the secondary $\sim 0.15 M_{\odot}$ near a period 1.8 h also agrees well with the observed value (Lyne et al. 1990).

4. Conclusion

If the observed orbital period decay is secular and our suggestion is correct that the orbital evolution of PSR 1744-24A is driven

Table 1.

Case	λ	$\dot{P}_{orb}/10^{-12}$ [ss^{-1}]	τ [Myr]
(A)	0.7	1.16	174
(A)	0.9	1.10	184
(B)	0.7	2.44	83
(B)	1.0	0.83	244
(B)	1.2	0.69	292
(B)	1.5	0.60	337
(C)	0.7	1.77	114
(C)	0.9	1.21	167

by magnetic braking then this may be the first case when the orbital period decay by a magnetic braking mechanism has been measured. According to our model calculations the best fit to the observed orbital period decay is obtained when λ is near to one. Which means that the value proposed by Smith (1979) $\lambda=1.78$ underestimates, that and proposed by Skumanich (1972) $\lambda=0.73$ slightly, overestimates the magnetic braking efficiency.

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