Binary evolution of PSR J1713+0747.

G. Lavagetto[*], F. D'Antona[†], L. Burderi[**], T. Di Salvo[*], R. Iaria[*] and N. R. Robba[*]

[*] *Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, via Archirafi n.36, 90123 Palermo, Italy.*
[†] *Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone (Roma), Italy.*
[**] *Dipartimento di Fisica, Università di Cagliari, SP Monserrato KM 0.7 09042 Monserrato (CA), Italy*

Abstract. PSR J1713+0747 is a binary millisecond radio pulsar with a long orbital period ($P_{\rm orb} \sim$ 68 d) and a very low neutron star mass ($M_{\rm NS} = 1.3 \pm 0.2\ M_\odot$). We simulate the evolution of this binary system with an accurate numerical code, which keeps into account both the evolution of the primary and of the whole binary system. We show that strong ejection of matter from the system is fundamental to obtain a mass at the end of the evolution that is within $1-\sigma$ from the observed one, but propeller effects are almost negligible in such a system, where the accretion rate is always near to the Eddington limit. We show that there are indeed two mechanisms can account for the amount of mass loss from the system: 1) Radio ejection could be triggered due to a contraction of the donor, and could account for a significant loss of mass 2) Disc instabilities can occur, and can trigger strongly super-Eddington mass transfer phases resulting in a large amount of mass lost from the system. We argue that the same mechanisms could be important in other large period binaries.

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INTRODUCTION

PSR J1713+0747 has been discovered by Foster et al. [8] during a systematic search of the sky at high Galactic latitudes with the Arecibo radio telescope. Its high flux density, shallow spectrum and pulse peak made it a natural candidate for high-precision timing, allowing for the determination of its Shapiro delay [17] and therefore of the masses of the NS and the companion. The timing parameters are reported in table 1. The companion is an helium white dwarf with an effective temperature that is firmly constrained to be lower than $T_{\rm eff} < 3800K$ [14]. Benvenuto, Rohrmann & De Vito [2] tried to determine the cooling age of the white dwarf simulating the full evolution of the binary system, assuming that the mass transfer is highly non-conservative (they assume that only 10% of the transferred matter is accreted onto the compact object, without modelling accretion or the spin evolution of the primary): they found that the present age of the white dwarf should exceed 8 Gyr for a population I companion. This coincides with the characteristic age of the pulsar, so we will adopt 8 Gyr as the lower limit on the age of the white dwarf.

Considering that the lowest mass for a neutron star precisely measured to date is 1.25 $M_\odot$ (PSR J0737-3039B, Lyne et al. 15), the mass of PSR J1713+0747 is surprisingly low, since the pulsar should have been recycled by accretion from the companion according to the standard scenario for the formation of millisecond radio pulsars [see 1].

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The evolution of this system seems therefore puzzling. Chen, Li & Wang [6] studied the evolution of the progenitor of PSR J1713+0747 and affirmed that the mass transfer in the system should have been highly non-conservative: in their semi-analytical computations, they assume that less than 1% of the transferred mass effectively accretes onto the neutron star, but they disregard the spin evolution of the primary, which is problematic if all this mass is lost from the system, and the mechanism of this large loss of mass from the system is not clear yet.

We try to improve preceding works on this system using a state-of-the-art simulation code [13] that couples the evolution of the primary under accretion with the evolution of the binary system as a whole. We confirm that the mass transfer should have been highly non-conservative, and we propose two mechanisms that could account for the whole mass and spin evolution of PSR J1713+0747.

SIMULATION PARAMETERS.

PSR J1713+0747 has a large orbital period (see 1), and thus it fits well to the evolution scenario depicted by Webbink, Rappaport & Savonije [20]: the companion star transfers mass to the neutron star (NS) once it evolves off the main sequence and, expanding its radius, fills its Roche-Lobe. As the evolution proceeds, the orbital period of the system becomes larger and larger, while the hydrogen shell is burning. When mass loss and burning completely exhaust the hydrogen envelope, the core of the donor evolves on to the white dwarf stage. The final state of the evolution of such a system depends only on the mass of the core of the companion star, which is strongly related to the orbital period of the system.

From observations we know the masses of both stars, the orbital period and the magnetic field of the primary. The initial orbital period can be determined a-posteriori as in such systems it is tightly linked to the final orbital period. As the final mass of the neutron star is very low, we make the assumption that the primary has an initial mass of 1.25 $M_{\odot}$, equal to the lowest precisely measured neutron star mass to date.

We know with a good approximation the age of the system, so we can put a limit on its evolutionary age and therefore to the initial mass of the companion: since the mass transfer begins once the companion evolves off the main sequence and the system cannot

TABLE 1. Observational data on PSR J1713+0747, taken from Splaver et al. [17].

Spin period	4.570136525082781(6) ms
Orbital period	67.8251298718(5) d
Orbital separation	32.34242099(2) lts
Companion mass	0.28(3) $M_{\odot}$
Chacterisic age	8 Gyr
Magnetic moment	1.9×10^{26} G cm^3
Mass function	0.0078962167
Inclination angle	72(2)
NS Mass	1.3(2) $M_{\odot}$

be older than our galaxy ($\sim$ 13 Gyr), and the mass transfer should have ended at least 8 Gyr ago, the maximum main sequence age of the companion of PSR J1713+0747 is $\sim 5 \times 10^9$ yr in this case, meaning that the initial companion mass should exceed $\sim 1.3 M_\odot$ if we assume a metallicity Z=0.02 and an helium abundance of Y=0.28.

The spin period of the neutron star at the end of the accretion process can also be derived: the initial spin period P_i can be evaluated from the actual spin period P_f assuming pure magnetodipole braking: we obtain that the spin preiod at the onset of the pulsar phase should have been lower than 1.4 ms.

RESULTS

We simulated evolutionary tracks for the progenitor of PSR J1713+0747 using the binary evolution code ATON-SE [13]. If no matter could be ejected from the system once it is transferred from the companion to the accretion disk, apart from the matter accreting at super-Eddington rates, we find a final mass for the NS of 1.76 $M_\odot$ (see 2), incompatible with the experimental data at 2.3 σ. As the accretion rate in this system stays very high, $\sim 10^{-8}$ $M_\odot/yr$ (see figure 1), there is no chance that the onset of a "propeller" regime [11] can be triggered.

In order to reproduce the mass and spin of the observed system, we will consider two ejection mechanisms: the onset of a radio ejection phase and the triggering of highly super Eddington mass transfer phases due to disk instabilities.

Radio ejection

During the secular evolution leading to the pulsar stage, there is a phase of detachment due to the temporary contraction of the donor, as described by D'Antona et al. [7] (see figure 1). This can trigger a "radio ejection" phase [3, 4], which can alter the orbital evolution of the system, shortening it significantly, and can also cause the ejection of a large part of transferred mass. Generally speaking, radio ejection can be triggered whenever some instability in the mass transfer causes a sudden drop in the instantaneous mass accretion rate. Radio ejection remains active if, after the detachment, the mass transfer rate is kept below a given threshold [3]:

$$\dot{M} \leq 0.068 P_{\mathrm{orb,d}}^{25/51} M^{-107/102} \mu_{26}^{40/17} P_{\mathrm{spin},-3}^{-80/17} u(M, M_2)^{25/102}, \tag{1}$$

where $P_{\mathrm{orb,d}}$ is the orbital period of the system in days, M is the mass of the NS in solar masses, μ_{26} is the magnetic dipole moment in units of 10^{26} G cm^3, $P_{\mathrm{spin},-3}$ is the spin period in milliseconds, and $u(M, M_2)$ is

$$u(M, M_2) = \left[1 - 0.462 \sqrt[3]{\frac{M_2}{M + M_2}}\right]^3 (M + M_2) \tag{2}$$

where M_2 is the mass of the companion in solar masses. Radio ejection is triggered at the detachment phase: as can be seen in figure 1, the mass accretion rate remains below

TABLE 2. Binary parameters for the evolutionary tracks.

	P_i[*]	P_f[†]	M_p[**]	M_{wd}[‡]	P_s[§]
Conservative	5.8	66.3	1.76	0.292	0.9
Radio ejection	9.1	69.5	1.52	0.295	1.00
Disk instability	5.8	63.9	1.38	0.293	1.54

[*] Orbital period at the beginning of the evolution(d)

[†] Final orbital period (d)

[**] Mass of the primary at the end of the accretion process ($M_\odot$)

[‡] Mass of the companion at the end of the accretion process ($M_\odot$)

[§] Spin period of the NS at the end of the accretion phase. (ms)

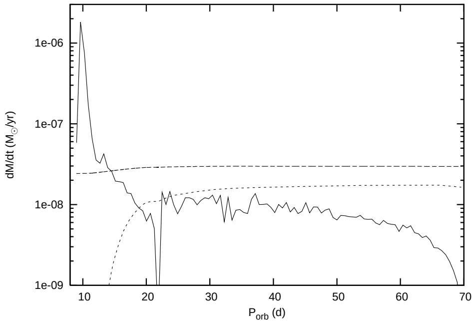

FIGURE 1. Accretion rate versus the orbital period of the system when radio ejection is active. The dashed line indicates the Eddington limit corresponding to the mass of the NS, and the dotted line indicates the critical mass transfer rate for the onset of the radio ejection mechanism. In this case, the dotted line remains above the mass transfer rate after the end of the detachment phase, and therefore radio ejection is active.

the critical mass accretion rate and therefore any further accretion is inhibited. When radio ejection is triggered an additional strong angular momentum loss is introduced, as matter is ejected near the inner Lagrangian point. As the final period of the binary depends mainly on the mass of the core of the donor, the mass transfer should have begun when the companion was slightly more evolved than in the conservative case to allow the system to attain the observed orbital period. The results of the evolution are summarized in table 2. In all, we find tha radio ejection can produce a system that is compatible with the observed one at 1.1 σ, and about half of the transferred mass is ejected from the system.

Disk instability

Chen et al. [6] proposed that, as the system has a large orbital period, the accretion disk undergoes the cycle-limit instability [5], and therefore the accretion rate exceeds for most time the Eddington limit. This leads to the ejection of a significant part of the accreting matter. We confirm their result: according to our simulations, the progenitor of PSR J1713+0747 could have been subject to this instability [see 19, 9] and therefore can have become transient. However, with their modelization only up to $0.008M_\odot$ are accreted onto the NS, but this accreted mass would be sufficient only to spin the NS up to ~ 30 ms, a spin period much longer than the one observed today. We tried therefore to find a different parametrization for the mass transfer in this system. We follow the theory of accretion in X-ray transients developed by King [10]. The disc becomes unstable as soon as the disc temperature at its outer edge (due mainly to X-ray irradiation by the central source) falls below the hydrogen ionisation temperature, 6500 K: the disc is unstable if its X-ray luminosity is

$$\log L_X \leq 34.8 + 1.6 \log_{10} R_{10} \text{ erg s}^{-1}, \tag{3}$$

where R_{10} is the radius of the accretion disc in units of 10^{10} cm [19]. We assume that for every outburst cycle the mass transfer rate decays exponentially:

$$\dot{M} = \dot{M}_{\max} e^{-t/\tau} \tag{4}$$

where the accretion rate at the beginning of the outburst is [10]

$$\dot{M}_{\max} = 8.5 \times 10^{-10} R_{10}^{7/4} \text{ M}_\odot/\text{yr} \tag{5}$$

and the decay time is $\tau = 2.3 R_{10}^{5/4}$ d. We simulated a system which can reproduce quite well the final orbital period and the final masses of the two stars: the initial orbital period is smaller this time, as the matter is ejected due to super-Eddington accretion and hence with the specific orbital angular momentum of the primary (which is very small compared to the mean specific orbital angular momentum). The system becomes transient after the orbital period is larger than 8.5 d and we get $\dot{M}_{\max} \sim 10^{-6} M_\odot/yr$, $\tau \sim 1$ yr, and a recurrence time that varies between 10^2 and 10^3 yr. In our simulations we assume that the super-Eddington part of the accreting matter is expelled from the system with the angular momentum of the primary: when the disc instability is triggered, most of the accreting matter is ejected from the system, but this does not affect significantly the binary evolution which is therefore very similar to the conservative one. We obtain that the final mass of the NS is $\sim 1.38 M_\odot$, very close to the best value for the measured mass, and merely large enough to allow the NS to spin up to ~ 1.5 ms (see table 2).

DISCUSSION AND CONCLUSIONS

We showed that our simulation code can produce models consistent with the observed data only if the mass transfer is highly non-conservative. On the other hand, the high accretion rate guarantees that the accretion disk is truncated at (or very near to) the surface of the NS. For this reason almost all of the transferred matter cannot be ejected due to "propeller" effects; this grows the NS to a mass of at least 1.76 $M_\odot$.

As we have shown, radio ejection is able to eject a significant fraction of the accreting matter from the system, thus reducing the mass of the NS to within almost 1σ from the observational result. Also, using standard prescriptions for the disc instability [10], we are able to produce a system with a mass well within 1σ from the measured value and with a spin period that is very near to the required one: this mechanism gave us another viable explanation to the evolution of the system.

Strong ejection mechanisms that do not originate from the canonical disc-magnetic field interaction in the vicinity of the NS should play an important role in the evolution of the system, although we should keep in mind that experimental error on the mass measurement is still uncomfortably large. However, we hope that a longer observational timebase and employment of new instruments will allow to narrow the error bars in the future: Splaver et al. [17] predict that this will happen in a few years. Also, more observational data are obviously needed in order to understand if such a non-conservative mass transfer is a common feature of large period binaries, as implied by the apparent inverse relation between the pulsar mass and the orbital period of the binary suggested by Nice et al. [16]: this relation fits well with the mechanisms we proposed, as both are more easily triggered in large period binaries than in compact binaries. In any case, we should stress that it is fundamental to include the spin evolution of the compact object into the simulations to follow accurately the evolution of the binary system as a whole.

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