Publication Year	2018
Acceptance in OA@INAF	2020-11-09T14:48:08Z
Title	A young contracting white dwarf in the peculiar binary HD 49798/RX J0648.0-4418?
Authors	Popov, S. B.; MEREGHETTI, Sandro; Blinnikov, S. I.; Kuranov, A. G.; Yungelson, L. R.
DOI	10.1093/mnras/stx2910
Handle	http://hdl.handle.net/20.500.12386/28225
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Number	474

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **474,** 2750–2756 (2018)
Advance Access publication 2017 November 13

doi:10.1093/mnras/stx2910

A young contracting white dwarf in the peculiar binary HD 49798/RX J0648.0−4418?

S. B. Popov,[1⋆] S. Mereghetti,[2] S. I. Blinnikov,[1,3,4] A. G. Kuranov[1] and L. R. Yungelson[5]

[1] *Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky prospekt 13, 119234 Moscow, Russia*
[2] *INAF, IASF-Milano, Via E. Bassini 15, I-20133 Milano, Italy*
[3] *ITEP, B.Cheremushkinskaya 25, 117218 Moscow, Russia*
[4] *Kavli IPMU, Kashiwa, Chiba Prefecture 277-8583, Japan*
[5] *Institute of Astronomy, Russian Academy of Science, 48 Pyatnitskaya Str., 119017 Moscow, Russia*

Accepted 2017 November 6. Received 2017 October 19; in original form 2017 August 31

ABSTRACT

HD 49798/RX J0648.0−4418 is a peculiar X-ray binary with a hot subdwarf (sdO) mass donor. The nature of the accreting compact object is not known, but its spin period $P = 13.2$ s and $\dot{P} = -2.15 \times 10^{-15}$ s s^{-1} proves that it can be only either a white dwarf or a neutron star. The spin-up has been very stable for more than 20 yr. We demonstrate that the continuous stable spin-up of the compact companion of HD 49798 can be best explained by contraction of a young white dwarf with an age ∼2 Myr. This allows us to interpret all the basic parameters of the system in the framework of an accreting white dwarf. We present examples of binary evolution, which result in such systems. If correct, this is the first direct evidence for a white dwarf contraction in early evolutionary stages.

Key words: pulsars: general – white dwarfs – X-rays: binaries.

1 INTRODUCTION

HD 49798/RX J0648.0−4418 is a peculiar binary consisting of an X-ray pulsar, with spin period $P = 13.2$ s, and a hot subdwarf of O spectral type in a circular orbit with period $P_{\rm orb} = 1.55$ d (Thackeray 1970; Stickland & Lloyd 1994; Israel et al. 1997; Mereghetti et al. 2011). It is the only confirmed X-ray binary with a hot subdwarf mass donor. In fact, its X-ray emission is most likely powered by accretion of matter from the weak wind of the sdO star HD 49798 (mass-loss rate $\dot{M}_{\rm W} = 3 \times 10^{-9}$ M$_{\odot}$ yr^{-1}, Hamann 2010), although it is still unclear whether the accreting object is a white dwarf (WD) or a neutron star (NS). Its mass is well constrained by a dynamical measurement yielding 1.28 ± 0.05 M$_{\odot}$ (Mereghetti et al. 2009), which fits well both possibilities. The evolution of this system was recently studied by Brooks, Kupfer & Bildsten (2017).

The relatively low value of X-ray luminosity $L_{\rm X} \sim 2 \times 10^{32}\,(d/650\,{\rm pc})^2$ erg s^{-1} as well as the X-ray spectrum (a very soft blackbody of temperature $kT \sim 30$ eV and large emitting radius $R \sim 40$ km plus a hard power-law tail) favoured a WD interpretation (Mereghetti et al. 2009, 2011).

However, recently Mereghetti et al. (2016) were able to measure for the first time the secular evolution of the spin period by phase-connecting all the available X-ray observations spanning more than 20 yr. They discovered that the compact companion of HD 49798 is spinning-up at a rate $\dot{P} = 2.15 \times 10^{-15}$ s s^{-1} (the period derivative is negative, but here and everywhere below, we refer to its absolute value).

In the framework of accretion-driven spin-up, it is difficult to explain such a high $\dot{P}$ value for a WD. In fact, as shown in Mereghetti et al. (2016), this would require that HD 49798 be farther than ∼4 kpc, a distance inconsistent with that derived from optical/UV studies (650 ± 100 pc, Kudritzki & Simon 1978). An NS, thanks to its ∼10^5 times smaller moment of inertia, seems less problematic. However, also in the NS case, some puzzles remain, such as the large emitting area of the blackbody component, the extremely steady luminosity and spin-up rate for more than 20 yr, which are quite unusual in wind-accreting NSs, and the requirement of an NS magnetic field less than 3×10^{10} G to avoid the propeller effect (Mereghetti et al. 2016).

In this paper, we propose a completely different explanation for the spin-up of the compact companion of HD 49798, not related to accretion. We propose that the object is a young WD, still contracting and thus with a decreasing moment of inertia. In the next section, we describe the model we used to calculate the WD evolution. In Section 3, our results are presented and the age estimate for the WD is provided. In Section 4, we discuss our hypothesis and, finally, we conclude in Section 5. Through the paper, we use the notation $N_{\rm X} = N/10^X$.

⋆ E-mail: polar@sai.msu.ru

Published by Oxford University Press on behalf of the Royal Astronomical Society

2 MODEL OF WHITE DWARF EVOLUTION

Theories of the WD evolution predict the dependence of luminosity L and effective temperature T_{eff} on their age t. WDs belong to the old population of the Galactic disc, so their birthrate for the last billion years remains constant and their number within few tens of parsec from the Sun does not depend on our position relative to the spiral arms. That is why the number of WDs per unit volume in a luminosity (or T_{eff}) interval is proportional to the time they spend in this interval. This allows one to check the validity of the theory of WD evolution.

To calculate an evolutionary sequence of a WD, we apply the code developed by Blinnikov & Dunina-Barkovskaya (1993, 1994). The modelling of the WD evolution is done with account of the data on the electron heat conductivity (Urpin & Yakovlev 1980; Yakovlev & Urpin 1980; Itoh et al. 1983; Nandkumar & Pethick 1984), the rate of neutrino losses (Adams, Ruderman & Woo 1963; Beaudet, Petrosian & Salpeter 1967; Dicus 1972; Munakata, Kohyama & Itoh 1985; Itoh et al. 1989), the equation of state (Yakovlev & Shalybkov 1989; Blinnikov, Dunina-Barkovskaya & Nadyozhin 1996) and Coulomb screening (Yakovlev & Shalybkov 1989) in thermonuclear reactions for the hot dense plasma.

To start the evolution for a given WD mass, we construct an artificial hydrostatic model that first allows us to get a hot WD with $T_{\mathrm{eff}} > 10^5$ K, and this WD later cools down. We have constructed a hydrostatic configuration by the method of Nadezhin & Razinkova (1986) for calculating the initial model with a much larger radius than that of the WD. We begin our runs using an implicit hydrodynamic solver, and the stellar model is quickly heated up to $T_{\mathrm{eff}} > 10^5$ K by the influence of gravitation. One can start to compare the results with the observations from the moment at which the WD cools down back to $T_{\mathrm{eff}} \approx 10^5$ K and the initial conditions become inessential.

Our cooling curves reproduce quite well the observed luminosity function of WDs. Moreover, since the cooling curves of hot WDs are sensitive to the WD mass, M_{WD}, due to sensitivity of plasma neutrino emission to density, Blinnikov & Dunina-Barkovskaya (1994) were able to derive the best-fitting mean WD mass, which was found to be higher than the value of $\sim$0.55 $\mathrm{M}_{\odot}$ usually adopted at that time (Holberg et al. 2008). However, the most recent measurements of the average WD mass are in good agreement with the original predictions of Blinnikov & Dunina-Barkovskaya (1994). A mean mass, $\langle M_{\mathrm{WD}} \rangle = 0.642\,\mathrm{M}_{\odot}$, is found in the full 25 pc WD sample by Holberg et al. (2016). This can be compared with a mean mass of $\langle M_{\mathrm{WD}} \rangle = 0.650\,\mathrm{M}_{\odot}$ found by Giammichele, Bergeron & Dufour (2012) in a 20 pc sample, and $\langle M_{\mathrm{WD}} \rangle = 0.699\,\mathrm{M}_{\odot}$ published by Limoges, Bergeron & Lépine (2015) for their 40 pc sample. Thus, the mean WD mass published by Blinnikov & Dunina-Barkovskaya (1994) two decades before these modern estimates can be considered as a blind test of the correctness of their code used in this paper. In the appendix, we present a more detailed comparison of our WD evolution code with two modern codes, based on the results obtained for different calculations in L–t and T_{eff}–t plots.

The WD moment of inertia I at each time-step is calculated according to

$$I = \frac{8\pi}{3} \int_0^R \rho r^4 \mathrm{d}r, \tag{1}$$

where R is the WD radius. The evolution of I for four values of WD masses is presented in Fig. 1.

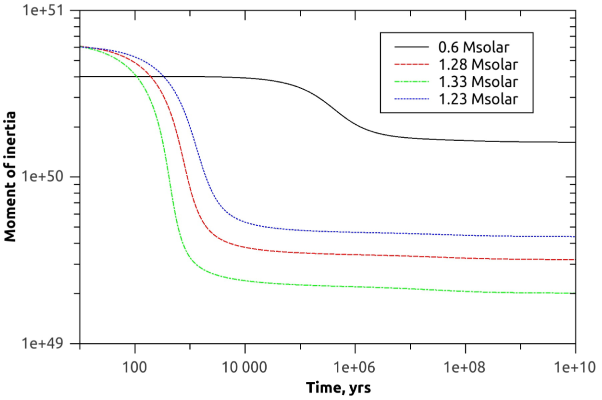

Figure 1. Evolution of moment of inertia for four WD masses: 0.6 $\mathrm{M}_{\odot}$ (black solid line), and three values representing the mass range for HD 49798 1.28 ± 0.05 $\mathrm{M}_{\odot}$ (dashed, dotted and dash–dotted colour lines).

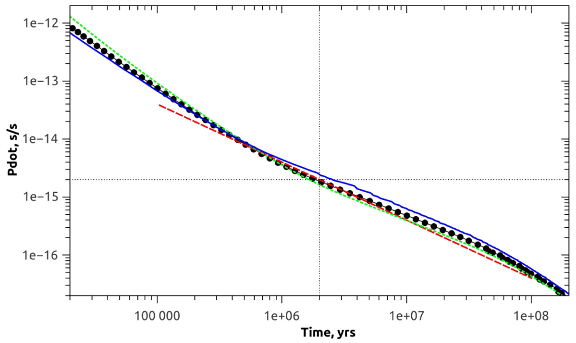

Figure 2. Evolution of $\dot{P}$ according to calculations using equation (3). Symbols correspond to the mass 1.28 $\mathrm{M}_{\odot}$. The solid line that initially goes below symbols, and then above, corresponds to 1.33 $\mathrm{M}_{\odot}$. The dotted line that initially goes above, and then below symbols, is calculated for 1.23 $\mathrm{M}_{\odot}$. The dashed diagonal line corresponds to equation $\dot{P} \propto t^{-1}$. The horizontal dotted line corresponds to the measured $\dot{P}$ of HD 49798 (Mereghetti et al. 2016) and the vertical dotted line corresponds to the age 2×10^6 yr.

3 RESULTS

3.1 Period derivative

We use angular momentum conservation to derive $\dot{P}$ from the calculated evolution of I:

$$I_1/I_2 = P_1/P_2. \tag{2}$$

Here, all values correspond to two times separated by an interval Δt. As the WD is contracting, $I_1 > I_2$, $P_1 > P_2$. Thus, $P_1 = P_2 + \Delta P$. And finally,

$$\dot{P} = \Delta P/\Delta t = \frac{P}{\Delta t}\left(\frac{I_1}{I_2} - 1\right). \tag{3}$$

Here, we use the observed value $P = 13.2$ s, and moments of inertia are taken from the evolutionary sequences described above.

We present our results for the evolution of the period derivative in Fig. 2, where the curves refer to three values corresponding to the uncertainties in the mass of the WD in HD 49798: $M = 1.28 \pm 0.05\,\mathrm{M}_{\odot}$ (Mereghetti et al. 2009).

In Fig. 2, we also added the line $\dot{P} = 2 \times 10^{-15}$ $(t/2 \times 10^6\ \mathrm{yr})^{-1}$ s s $^{-1}$, which fits well the behaviour of $\dot{P}$ at the present epoch according to our model. This simple analytical fit allows us to estimate the second derivative of the spin period, which in this case is expected to be $\ddot{P} \approx 3 \times 10^{-29}\,(t/2 \times 10^{6}\,\mathrm{yr})^{-2}\,\mathrm{s\,s^{-2}}$. Unfortunately, the measurement of such a small value is behind the possibility of the current and near future observations.

The above results show that the observed $\dot{P}$ can be totally explained by the WD contraction. In principle, some additional spin-up could be provided by accretion. To quantitatively evaluate such a possible contribution, we consider the most favourable case for transfer of angular momentum, i.e. accretion through a disc with inner radius truncated close to the corotation radius $R_{\mathrm{co}} = (GMP^2/4\pi^2)^{1/3} = 9 \times 10^{8}$ cm. In this case, we have

$$2\pi I \dot{\nu} = \dot{M}(GMR_{\mathrm{co}})^{1/2}, \tag{4}$$

and using $\dot{M} = L(GM/R)^{-1} = 1.8 \times 10^{14} L_{32}\,\mathrm{g\,s^{-1}}$, we obtain $\dot{\nu} = 1.1 \times 10^{-19} L_{32} I_{50}^{-1} (R/3000\,\mathrm{km})^{-1}\,\mathrm{Hz\ s^{-1}}$. This corresponds to a spin-up rate $\dot{P} = 2 \times 10^{-17} L_{32}\,\mathrm{s\,s^{-1}}$, which is 2 orders of magnitude smaller than the measured value. In the case of wind accretion, the expected spin-up rate due to infalling matter would be even lower (Mereghetti et al. 2016). We finally note that the measured $\dot{P}$ has been very stable during the time of X-ray observations (more than 20 years), a situation that has never been observed in X-ray binaries where the period evolution is driven by the interaction of the rotating object with the mass accretion flow. So, we conclude that the measured spin-up is driven by the decreasing moment of inertia of the WD.

As we know the mass of the compact object and its $\dot{P}$, we can estimate its age and other parameters from the evolutionary sequence. The age is about 2 Myr for $M = 1.28\,\mathrm{M_{\odot}}$ and about 3 Myr for the upper value of the mass uncertainty (see Fig. 2). Taking into account possible uncertainties of the WD model, we can conservatively estimate the age range for the WD as $1 < \mathrm{Age} < 5$ Myr.

A WD with $M = 1.28\,\mathrm{M_{\odot}}$ might have effective surface temperature ~75 000 K and luminosity ~0.65 $\mathrm{L_{\odot}}$. The radius is ~3340 km. These values do not contradict the observed properties of the system. In fact, the optical/UV emission of HD 49798/RX J0648.0−4418 is dominated by the flux coming from the much larger sdO star, which has an effective temperature ~47 000 K and a luminosity ~$10^{4}\,\mathrm{L_{\odot}}$.

3.2 Binary evolution

The evolution of the HD 49798 binary system has been very recently studied by Brooks et al. (2017). These authors considered both possibilities, a WD or an NS, and concentrated mainly on the future evolution. In this subsection, we discuss the origin of the present day appearance of this binary.

Though both components of HD 49798 have rather extreme masses, the origin of this star may be well understood within the paradigm of formation of hot subdwarfs in close binaries due to stable (via Roche lobe overflow) or unstable (via common envelope) mass-loss (Mengel, Norris & Gross 1976; Tutukov & Yungelson 1990). Formation channels for helium subdwarfs accompanied by WDs and detailed models of their population were computed, for example, by Han et al. (2002, 2003) and Yungelson & Tutukov (2005). These models reproduce the bulk population with 'canonical' mass of subdwarfs close to $0.5\mathrm{M_{\odot}}$ and predict, as well, the existence of a 'tail' of massive ($\gtrsim 1\ \mathrm{M_{\odot}}$) objects.

A numerical example of an evolutionary scenario for the formation of a binary with parameters rather similar to HD 49798 is presented in Table 1. We applied for the modelling the binary population synthesis code BSE (Hurley, Tout & Pols 2002, September 2004 version). The crucial parameter of close binaries evolution, the efficiency α_{ce} with which the common envelope is ejected, was set to 2, whereas the binding energy of the donor envelope parameter λ was varied depending on the evolutionary stage of the star as prescribed in the BSE code. The choice of α_{ce} is justified by the circumstance that its high value allowed us to reasonably reproduce the Galactic supernovae Type Ia (SNe Ia) rate by the 'double-degenerate' scenario, as well as the observed delay time distribution for SNe Ia (Yungelson & Kuranov 2017).

Table 1. Scenario of formation of a binary similar to HD 49798. Evolutionary stages of stars are abbreviated as follows: MS – main-sequence, ZAMS – zero-age MS, RG – red giant, CHB – central He burning, EAGB and TPAGB – early- and thermally pulsing AGB stages, respectively, CE – common envelope, He⋆ – naked helium star (He subdwarf), HeG – helium giant.

Time (Myr)	M_1 ($\mathrm{M_{\odot}}$)	M_2 ($\mathrm{M_{\odot}}$)	Period (d)	Stage
0.0	7.0	6.75	4550.3	ZAMS
48.8	7.06	6.75	4550.3	RG+MS
49.0	7.05	6.75	4551.6	CHB+MS
53.0	6.89	6.75	4621.7	CHB+RG
53.1	6.89	6.75	4623.4	CHB+CHB
55.0	6.84	6.69	4691.9	EAGB+CHB
55.3	6.8	6.69	4657.4	TPAGB+CHB
55.7	5.96	6.84	4101.8	CE
55.7	1.28	1.47	1.48	ONe WD+He⋆
64.1	1.28	1.43	1.52	ONe WD+HeG
64.8	1.28	1.42	1.53	CE
64.8	1.28	0.83	0.15	ONe+CO WDs
467.5	1.28	0.83	0.0004	Merger

Initially, the binary is rather wide and the primary overflows its Roche lobe in the thermally pulsing asymptotic giant branch (TPAGB) stage (see Table 1 for the explanation of abbreviations related to different stages of stellar evolution). Since in this stage the star has a deep convective envelope, the mass-loss is unstable and a common envelope engulfing both components forms. The ejection of the common envelope results in the formation of an oxygen–neon (ONe) WD accompanied by a hydrogen-envelope-devoid star that burns helium in the core and may be observed as a hot helium subdwarf. Thus, the birth of the WD and the He-star is simultaneous. Helium stars more massive than $0.8\mathrm{M_{\odot}}$ expand after the core He-burning stage and then turn into 'helium giants' (Paczyński 1971). According to its position in the Hertzsprung–Russell diagram, the HD 49798 subdwarf is, likely, just in the 'transition' stage. Lifetimes of massive He-stars are extremely short and commensurate with the expected age of HD 49798. The model predicts that, after Roche lobe overflow by the expanding He-giant, a second phase of common envelope will occur. After ejection of the latter, a pair of ONe and CO WDs will be born, which will merge due to the angular momentum loss via gravitational waves radiation in about 400 Myr. The outcome of such mergers still awaits further studies.

The scenario shown in Table 1 does not reproduce exactly the parameters of HD 49798, but our only goal was just to show the viability of formation of HD 49798-like systems. Of course, a better agreement may be obtained by fine tuning of, for example, common envelope and donor binding energy parameters, which is beyond the scope of this study.

In the simulation, we assumed that the primary components follow Salpeter IMF and we used flat initial distributions for the mass ratios of components and for the logarithm of orbital separation. Then, if there are 10^{11} stars in the Galaxy and the binarity rate is about 50 per cent (see van Haaften et al. 2013, Appendix A), we roughly estimate that, currently, in the Galaxy exist

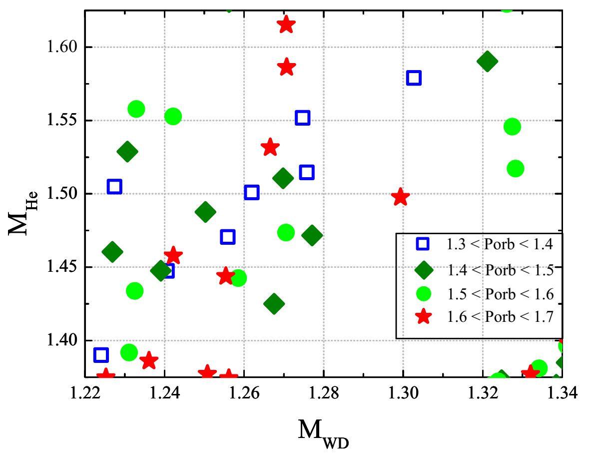

Figure 3. Masses of components and periods in model systems similar to HD 49798. The vertical axis corresponds to subdwarf mass, and horizontal axis corresponds to the mass of WD. Only systems with He-stars born less than in 5 Myr after WD are shown. The colours and symbols indicate the orbital period given in days (see the legend). Calculations are done for the common envelope parameter $\alpha_{ce} = 2$.

$\sim$25 HD 49798-like systems in which a He-star forms within 5 Myr after the WD and have masses of components and period within $\pm 0.1\ M_\odot$ and ± 0.2 d of the observed values, respectively. These systems are shown in Fig. 3. A slight relaxation of the required binary parameters ($\pm 0.2\ M_\odot$ for component masses) resulted in $\sim$500 systems in the Galaxy, so that the discovery of one of them within 650 pc is quite probable.

4 DISCUSSION

Our hypothesis of a young WD still in the contracting phase can solve the puzzle of the spin-up of the pulsar companion of HD 49798. As extensively discussed in Mereghetti et al. (2016), such a spin-up is difficult to explain in a system where the compact object accretes matter at the low rate that can be provided by the tenuous wind of the sdO mass donor. An accretion rate able to provide enough angular momentum for a WD would also yield a large luminosity, implying that the commonly adopted distance of HD 49798 (650 pc, Kudritzki & Simon 1978) has been underestimated by a factor of 10 or more, which seems very unlikely. In the case of an NS, the luminosity would fit the observations, but an unusually low magnetic field would be required.

On the other hand, if the spin-up is caused by the secular decrease of the moment of inertia in a young contracting WD, we obtain the correct value of $\dot{P}$ for a reasonable range of masses and ages consistent, respectively, with the measured values and with the evolution of this binary. The model we used to calculate the WD evolutionary sequence is based on a set of robust assumptions. Although it does not include some refinements used in the most up-to-date models of WD evolution, this is not crucial for the purposes of this study. This is supported by recent works in which a similar technique is used to constrain the neutrino emission of hot WDs (e.g. Miller Bertolami 2014; Hansen et al. 2015, and references therein).

Secular spin-up, with $\dot{P}$ in the range $\sim 5 \times 10^{-13}$–10^{-10} s s^{-1}, has been detected in about 10 WDs in binary systems of the intermediate polar type (see, e.g. the recent compilation in de Miguel et al. 2017). These WDs have magnetic fields of about 1–20 MG and accrete from main sequence or evolved subgiant companions that are filling their Roche lobe. Accretion proceeds through a disc that is truncated at an inner radius, determined by the balance between the magnetic pressure and the ram pressure of the inflowing mass. The inner disc radius is larger by a factor from tens to hundreds than the WD radius. This is very different from the case of HD 49798 binary, where the mass donor is well within its Roche lobe[1] and the WD is accreting from the stellar wind. The spin-up rates observed in intermediate polars are fully consistent with those expected from the transfer of angular momentum to the WD caused by the mass accretion through a disc, contrary to what occurs in our system. In fact, as shown in Section 3.1, the small value of the accretion rate $\dot{M}$ and the short spin period imply a maximum spin-up rate 2 orders of magnitude below the observed value (even in the most favourable condition, i.e. an accretion disc truncated at the corotation radius).

In our interpretation, accretion at the current rate does not significantly influence the spin period evolution. Accurate measurements of the period behaviour and luminosity can help to test our hypothesis. In fact, we predict that small luminosity variations should not be accompanied by changes in $\dot{P}$. Only in the case of a major luminosity increase, which is unlikely to occur given the properties of the stellar wind of HD 49798, we would expect a noticeable effect on the spin period derivative.

As in our model the spin-up does not depend on the magnetic field of the WD, we cannot use the $\dot{P}$ value to estimate it. The only limitation comes from the evidence of stable accretion, which requires the Alfvén radius, $R_A = (\mu^2/(\dot{M}\sqrt{2GM}))^{2/7}$, to be smaller than the corotation radius. Here, $\mu = BR^3$ is the magnetic moment of the WD (B is the field at the equator). Thus, assuming $R_A = R_{co}$, the estimate of μ is

$$\mu = 2^{1/4}(GM)^{5/6}\dot{M}^{1/2}\omega^{-7/6}. \tag{5}$$

With $\dot{M} = 3 \times 10^{14}$ g s^{-1}, we obtain $\mu \sim 10^{29.5}$ G cm^3 and $B \sim 10^4$ G. As for accretion it is necessary to have $R_A < R_{co}$, we obtained a rough upper limit for B, so the field is about few kG. Note that R_A, derived here under the assumption of a dipolar field, is only a factor of a few larger than the WD radius, meaning that the magnetosphere is squeezed close to the star. More realistically, the magnetic field might have a complex geometry, with multipolar components able to channel the accretion flow in a hotspot much smaller than the WD radius, as required to explain the large pulsed fraction ($\sim$65 per cent) and emitting radius of the thermal X-ray emission (Mereghetti et al. 2016).

We followed the evolution of WDs up to ages comparable to the Galactic lifetime. After $\sim 10^8$ yr, $\dot{P}$ starts to decrease faster (approximately as $t^{-1.5}$), and reaches values $\lesssim 10^{-19}$ s s^{-1} at the age $\sim$5 Gyr. Thus, the WD cannot spin up significantly in its future due to contraction. Thus, at some point, the spin evolution of the HD 49798 companion will be driven by the angular momentum transferred through accretion.

We can also estimate the initial period of the WD taking its present day value of 13.2 s and the age of 2 Myr. Assuming that the spin period did not change much during the relatively short common envelope stage, the initial value is $P_0 = P(I_0/I) \sim 4$ min, where P and I are the current values. Thus, the compact object has been significantly spun up during its lifetime due to contraction.

The predicted value of $\ddot{P}$ due to the WD contraction is very small. It is comparable to the smallest values of the second period

---

[1] The Roche lobe radius is $\sim 3\ R_\odot$, whereas the radius of HD 49798 is $1.45 \pm 0.25\ R_\odot$ (Kudritzki & Simon 1978).

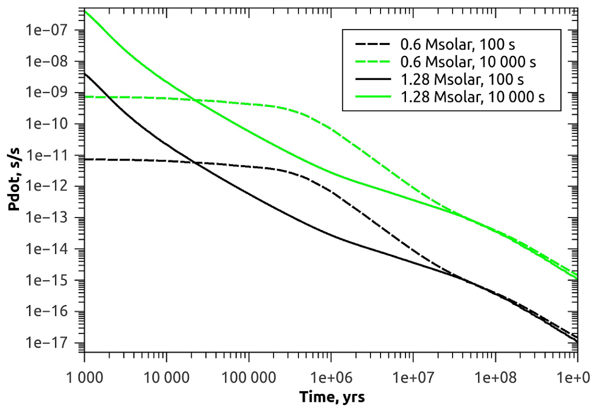

Figure 4. Evolution of $\dot{P}$. Solid lines correspond to $M = 1.28\,\mathrm{M}_{\odot}$. Dashed lines to $0.6\,\mathrm{M}_{\odot}$. Two upper (lighter and thicker, green in electronic version) lines are plotted for spin period 10^4 s, and two lower for $P = 100$ s.

derivatives in radio pulsars. Thus, it would be very difficult to measure it with X-ray observations.

As $\dot{P} \propto P$ (see eq. 3) and rotation does not influence the internal structure significantly (i.e. I does not depend on P), we expect that in similar sources with young accreting WDs with more typical spin periods, the values of $\dot{P}$ can be larger. As an example, we show the evolution of $\dot{P}$ versus age for two values of P and two WD masses in Fig. 4. It is seen that WDs with a typical mass $0.6\,\mathrm{M}_{\odot}$ at ages $\sim$ few hundred thousand years can have very large period derivatives, especially for large spin periods. It is possible that the process described here is at work also in some of the cataclysmic variables, which show a secular spin-up, provided the WDs are sufficiently young. Unfortunately, this is difficult to demonstrate due to the presence of significant accretion torques, which by themselves are already able to account for the observed spin-up rates. It would be important to look for other low-luminosity X-ray pulsars with WDs with ages $\lesssim 10^8$ yr, similar to HD 49798/RX J0648.0−4418. Note that the low accretion rate in this system is due to the particular nature of the mass donor, i.e. a hot subdwarf fitting inside the Roche lobe, but endowed with a weak stellar wind. This yields a small luminosity and a very soft X-ray spectrum, properties which unfortunately hamper the detection of similar systems. Future X-ray facilities, especially all-sky surveys such as the one planned with eRosita, will hopefully provide more candidates to test our proposed scenario and further investigate the early stages of WD evolution.

5 SUMMARY

In this paper, we have proposed a novel interpretation which, contrary to explanations related to mass accretion, can naturally explain the spin-up of the compact object in the peculiar X-ray binary HD 49798/RX J0648.0−4418. We showed that the contraction of a WD with mass of $1.28\,\mathrm{M}_{\odot}$ and age of about 2 Myr can produce the observed spin-up rate of $\dot{P} = 2.15 \times 10^{-15}\,\mathrm{s\,s^{-1}}$.

If our hypothesis is correct, it could be the first direct observational evidence of a young contracting WD and gives us the unique opportunity to probe early stages of WD evolution.

ACKNOWLEDGEMENTS

SBP and AGK acknowledge support from RSF grant No. 14-12-00146. SIB is grateful to W. Hillebrandt and H.-T. Janka for support of the visit to MPA where part of this work was done. LRY was supported by Presidium of RAS Basic Research Program P-41. We also would like to thank the organizers of the conference ‘Physics of neutron stars – 2017’ in St. Petersburg, where we started to discuss this problem. This research has made use of NASA’s Astrophysics Data System.

REFERENCES

Adams J. B., Ruderman M. A., Woo C.-H., 1963, Phys. Rev., 129, 1383
Beaudet G., Petrosian V., Salpeter E. E., 1967, ApJ, 150, 979
Bergeron P. et al., 2011, ApJ, 737, 28
Blinnikov S. I., Dunina-Barkovskaya N. V., 1993, Astron. Rep., 37, 187
Blinnikov S. I., Dunina-Barkovskaya N. V., 1994, MNRAS, 266, 289
Blinnikov S. I., Dunina-Barkovskaya N. V., Nadyozhin D. K., 1996, ApJS, 106, 171
Brooks J., Kupfer T., Bildsten L., 2017, ApJ, 847, 78
de Miguel E. et al., 2017, MNRAS, 467, 428
Dicus D. A., 1972, Phys. Rev. D, 6, 941
Fontaine G., Brassard P., Bergeron P., 2001, PASP, 113, 409
Giammichele N., Bergeron P., Dufour P., 2012, ApJS, 199, 29
Hamann W.-R., 2010, Ap&SS, 329, 151
Han Z., Podsiadlowski P., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449
Han Z., Podsiadlowski P., Maxted P. F. L., Marsh T. R., 2003, MNRAS, 341, 669
Hansen B. M. S., Richer H., Kalirai J., Goldsbury R., Frewen S., Heyl J., 2015, ApJ, 809, 141
Holberg J. B., Sion E. M., Oswalt T., McCook G. P., Foran S., Subasavage J. P., 2008, AJ, 135, 1225
Holberg J. B., Oswalt T. D., Sion E. M., McCook G. P., 2016, MNRAS, 462, 2295
Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897
Israel G. L., Stella L., Angelini L., White N. E., Kallman T. R., Giommi P., Treves A., 1997, ApJ, 474, L53
Itoh N., Mitake S., Iyetomi H., Ichimaru S., 1983, ApJ, 273, 774
Itoh N., Adachi T., Nakagawa M., Kohyama Y., Munakata H., 1989, ApJ, 339, 354
Kudritzki R. P., Simon K. P., 1978, A&A, 70, 653
Limoges M.-M., Bergeron P., Lépine S., 2015, ApJS, 219, 19
Mengel J. G., Norris J., Gross P. G., 1976, ApJ, 204, 488
Mereghetti S., Tiengo A., Esposito P., La Palombara N., Israel G. L., Stella L., 2009, Science, 325, 1222
Mereghetti S., La Palombara N., Tiengo A., Pizzolato F., Esposito P., Woudt P. A., Israel G. L., Stella L., 2011, ApJ, 737, 51
Mereghetti S., Pintore F., Esposito P., La Palombara N., Tiengo A., Israel G. L., Stella L., 2016, MNRAS, 458, 3523
Miller Bertolami M. M., 2014, A&A, 562, A123
Munakata H., Kohyama Y., Itoh N., 1985, ApJ, 296, 197
Nadezhin D. K., Razinkova T. L., 1986, Nauchnye Informatsii, 61, 29
Nandkumar R., Pethick C. J., 1984, MNRAS, 209, 511
Paczyński B., 1971, Acta Astron., 21, 1
Salaris M., Althaus L. G., García-Berro E., 2013, A&A, 555, A96
Stickland D. J., Lloyd C., 1994, The Observatory, 114, 41
Thackeray A. D., 1970, MNRAS, 150, 215
Tutukov A. V., Yungelson L. R., 1990, Sov. Astron., 34, 57
Urpin V. A., Yakovlev D. G., 1980, Sov. Astron., 24, 126
van Haaften L. M., Nelemans G., Voss R., Toonen S., Portegies Zwart S. F., Yungelson L. R., van der Sluys M. V., 2013, A&A, 552, A69
Yakovlev D. G., Shalybkov D. A., 1989, Astrophys. Space Phys. Rev., 7, 311
Yakovlev D. G., Urpin V. A., 1980, Sov. Astron., 24, 303
Yungelson L. R., Kuranov A. G., 2017, MNRAS, 464, 1607
Yungelson L. R., Tutukov A. V., 2005, Astron. Rep., 49, 871

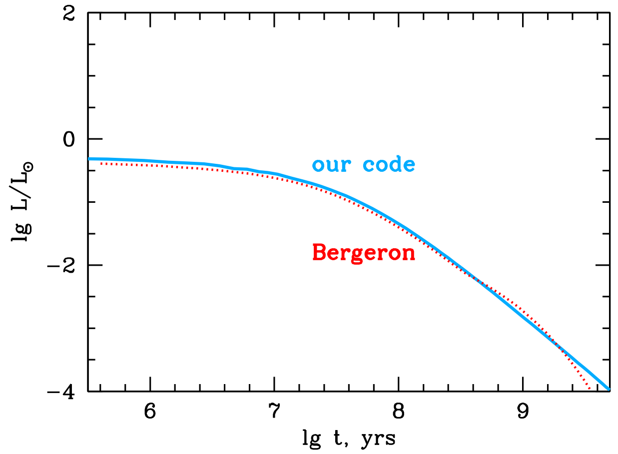

Figure A1. Evolution of luminosity L of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of Bergeron et al. (thin red dotted line).

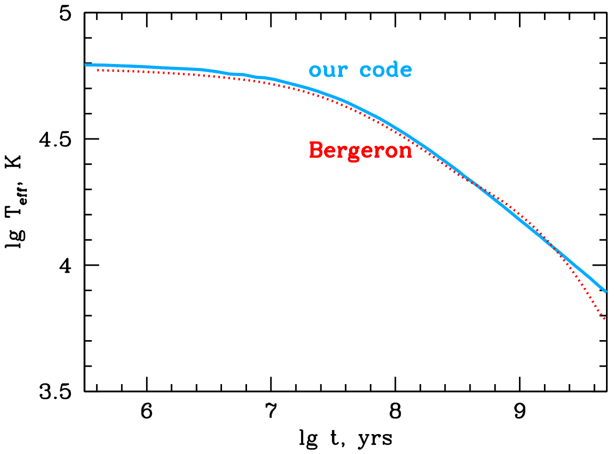

Figure A2. Evolution of effective temperature T_{eff} of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of Bergeron et al. (thin red dotted line).

APPENDIX A: CODE VALIDATION

To calculate the WD cooling, we used the code described by Blinnikov & Dunina-Barkovskaya (1993, 1994). In this appendix, we compare the results of our code with those obtained with a couple of more recent simulations of WD cooling.

A1 Comparison with Bergeron's code

First, we use models from P. Bergeron's website.[2] Some of those models are described by Fontaine, Brassard & Bergeron (2001), see new details in Bergeron et al. (2011).

We have used the evolutionary sequence `CO_1200204`, which corresponds to a mass $M = 1.2\,M_\odot$ and initially 'thick' H and He layers with $q_{\mathrm{H}} = 10^{-4}$ and $q_{\mathrm{He}} = 10^{-2}$, where q is a fraction of the total mass. It has a mixed C/O core composition (50/50 by mass fraction mixed uniformly).

For our code, we used a very similar model with $M = 1.2\,M_\odot$, with outer layers $M_{\mathrm{H}} = 1.4 \times 10^{-4}\,M_\odot$ and $M_{\mathrm{He}} = 2.6 \times 10^{-2}\,M_\odot$ (the same H and He envelopes we used for our models of the WD companion of HD 49798).

Since zero epochs in both simulations are arbitrary, we plot here our results shifting them slightly along the time axis, and starting at the moment closest to the first Bergeron's output, when his $T_{\mathrm{eff}} = 59\,280$ K.

Fig. A1 demonstrates the agreement of luminosity, and Fig. A2 demonstrates that of effective temperature between the two codes. As described in Blinnikov & Dunina-Barkovskaya (1994), our code has relevant physics when a WD is hot enough, $T_{\mathrm{eff}} > 1.2 \times 10^4$. Nevertheless, our curves are in reasonable agreement with Bergeron's code even at late epochs.

There is a tiny difference in radii in Fig. A3 in comparison with our results. This small discrepancy, at the level of 1 per cent, is probably caused by different masses of H and He envelopes, chemical composition, equations of state, etc., but the behaviour of $R(t)$ is the same in both cases. Thus, this difference does not significantly influence our conclusions.

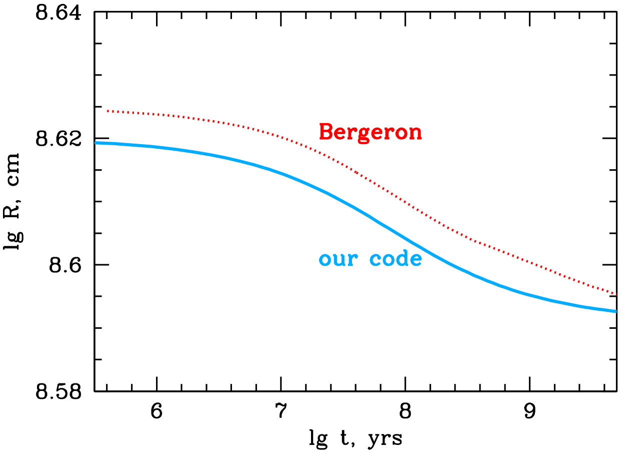

Figure A3. Evolution of radius R of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of Bergeron et al. (thin red dotted line).

A2 Comparison with BASTI code

The same $1.2\,M_\odot$ model computed with our code has been compared with another independent simulation done by Salaris, Althaus & García-Berro (2013), who used the BaSTI code.[3]

We have used tables in the BASTI website that contain data on the L and T_{eff} evolution for a $1.2\,M_\odot$ WD. The specific model is `COOL120BaSTIfinaleDAnosep`, which refers to a $M = 1.2\,M_\odot$ DA WD without separation of phases at ion crystallization stages.

Since the data on the BASTI website contain earlier epochs we have shifted our output to higher temperatures, accordingly.

In late stages (Figs A4, A6), the discrepancy is rather large (since our code is developed only for hot WDs), but for epochs that are interesting for us (Figs A5, A7) in this paper, the agreement of our results with this modern code is just perfect.

We conclude that there are no doubts on the validity of the approximations used in our approach to model the WD in the binary system HD 49798/RX J0648.0−4418.

---

[2] http://www.astro.umontreal.ca/∼bergeron/CoolingModels/

[3] A Bag of Stellar Tracks and Isochrones, see http://basti.oa-teramo.inaf.it/index.html

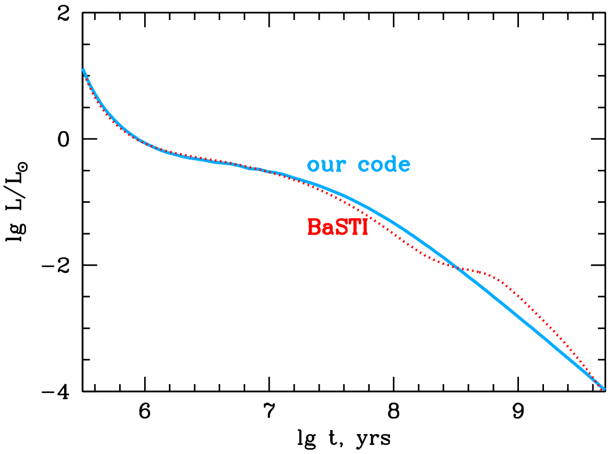

Figure A4. Long time-scale evolution of luminosity L of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of BASTI (thin red dotted line).

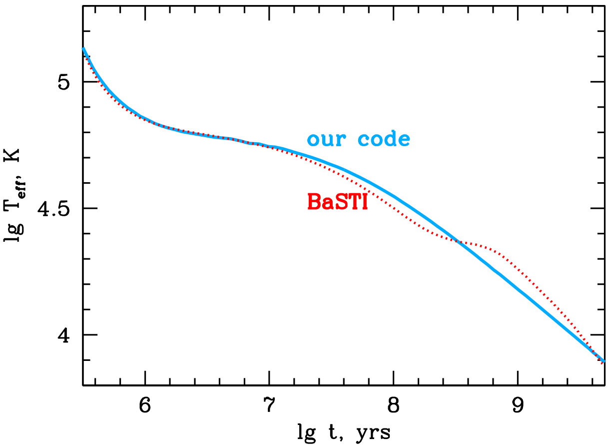

Figure A6. Long time-scale evolution of effective temperature $T_{\rm eff}$ of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of BASTI (thin red dotted line).

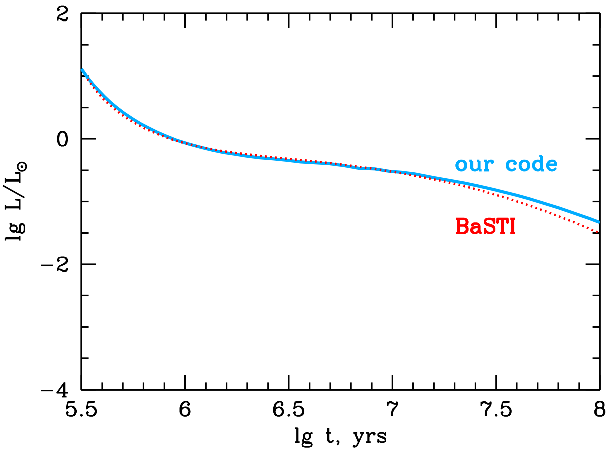

Figure A5. Evolution of luminosity L of a $1.2\,M_\odot$ WD according to our code (thick blue solid line) and that of BASTI (thin red dotted line) on short time-scale.

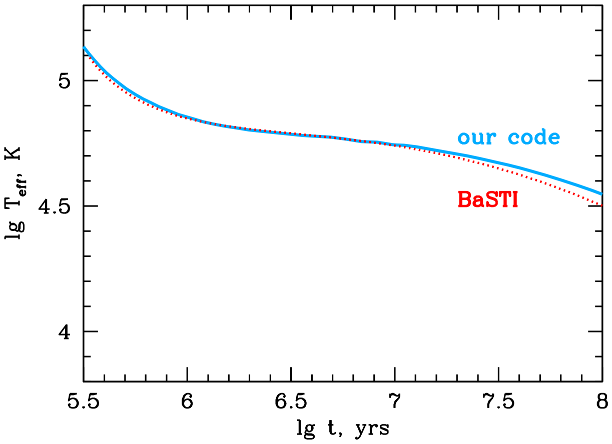

Figure A7. Evolution of effective temperature $T_{\rm eff}$ of a $1.2\,M_\odot$ WD according to our code (thick blue dashed line) and that of BASTI (thin red dotted line) on the short age scale.

This paper has been typeset from a TEX/LATEX file prepared by the author.