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

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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 \(^{-1}\), prove that it can be only either a white dwarf or a neutron star. The spin-up has been very stable for more than 20 years. 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 \( \sim 2 \) Myrs. 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 on early evolutionary stages.

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

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 \( P_{\text{orb}} = 1.55 \) days (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 \( \dot{M}_W = 3 \times 10^{-9} \) 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 \( 1.28 \pm 0.05 \) M\(_\odot\) (Mereghetti et al. 2009), which fits well both possibilities. The evolution of this system was recently studied by Brooks et al. (2017).

The relatively low value of X-ray luminosity \( L_X \sim 2 \times 10^{32} \) (d/650 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 years. They discovered that the compact companion of HD 49798 is spinning-up at a rate \( \dot{P} = 2.15 \times 10^{-15} \) 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 \( \sim 4 \) kpc, a distance inconsistent with that derived from optical/UV studies (650±100 pc, Kudritzki & Simon 1978). A NS, thanks to its \( 3 \times 10^5 \) times smaller moment of inertia, seems less problematic. However, also in the NS case, some puzzles remain, such as, e.g., the large emitting area of the blackbody component, the extremely steady luminosity and spin-up rate over more than 20 yrs which are quite unusual in wind-accreting neutron stars, and the requirement of a NS magnetic field lower than \( 3 \times 10^{10} \) 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 Sec. 3 our results are presented and the age estimate for the WD is provided. In Sec. 4 we discuss our hypothesis and, finally, we conclude in Sec. 5. Through the paper we use the notation $N_X = N/10^7$.

2 MODEL OF WHITE DWARF EVOLUTION

Theories of the WD evolution predict the dependence of luminosity $L$ and effective temperature $T_{\text{eff}}$ on their age $t$. White dwarfs belong to the old population of the Galactic disk, 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 $T_{\text{eff}}$) 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 modeling 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 et al. 1963; Beaudet et al. 1967; Di curis 1972; Munakata et al. 1985; Itoh et al. 1989), the equation of state (Blinnikov et al. 1996; Yakovlev & Shalybkov 1989) 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 which first allows us to get a hot WD with $T_{\text{eff}} > 10^6$ 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 $T_{\text{eff}} > 10^5$ 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 $T_{\text{eff}} \approx 10^5$ 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, $M_{\text{WD}}$, 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 $\sim 0.55 M_\odot$ usually adopted at that time (Holberg et al. 2008). However, the most recent measurements of the average WD masses are in good agreement with the original predictions of Blinnikov & Dunina-Barkovskaya (1994). A mean mass, $\langle M_{\text{WD}} \rangle = 0.642 M_\odot$, is found in the full 25 pc WD sample by Holberg et al. (2016). This can be compared with a mean mass of $\langle M_{\text{WD}} \rangle = 0.650 M_\odot$ found by Giammichele et al. (2012) in a 20 pc sample, and $\langle M_{\text{WD}} \rangle = 0.699 M_\odot$ published by Limoges et al. (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 the current 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 $T_{\text{eff}} - t$ plots.

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

$$I = \frac{8\pi}{3} \int_0^R \rho r^4 dr,$$

(1)

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

3 RESULTS

3.1 Period derivative

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

$$I_1/I_2 = P_1/P_2.$$

(2)

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

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

(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: $M = 1.28 \pm 0.05 M_\odot$ (Mereghetti et al. 2009).

In Fig. 2 we also added the line $P = 2 \times 10^{-15} \times (t/2 \times 10^9 \text{yrs})^{-1} \text{ s}^{-1}$, which fits well the behavior of $P$ in 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...
emission of HD49798/RXJ0648.0–4418 is dominated by the 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.

3.2 Binary evolution

The evolution of the HD49788 binary system has been very recently studied by Brooks et al. (2017). These authors considered both possibilities, a WD or a 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 HD49788 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 et al. 1976; Tutukov & Yungelson 1990). Formation channels for helium subdwarfs accompanied by WDs and detailed models of their population were computed, e.g., by Han et al. (2002, 2003); Yungelson & Tutukov (2005). These models reproduce the bulk population with “canonical” mass of subdwarfs close to 0.5 M⊙ and predict, as well, the existence of a “tail” of massive (⩾ 1 M⊙) objects.

A numerical example of an evolutionary scenario for the formation of a binary with parameters rather similar to HD49788 is presented in Table 1. We applied for the modeling the binary population synthesis code BSE (Hurley et al. 2002, September 2004 version). The crucial parameter of close binaries evolution, the efficiency \( \alpha_{ce} \) with which the common envelope is ejected, was set to 2, while the binding energy of the donor envelope parameter \( \lambda \) was varied depending on the evolutionary stage of the star as prescribed in the BSE code. The choice of \( \alpha_{ce} \) is justified by the circumstance that its high value allowed us to reasonably reproduce the Galactic SNe Ia rate by the “double-degenerate” scenario, as well as the observed delay time distribution for SNe Ia (Yungelson & Kurnov 2017).

Initially, the binary is rather wide and the primary over-

Table 1. Scenario of formation of a binary similar to HD 49788. Evolutionary stages of stars are abbreviated as follows: MS – main-sequence, ZAMS – zero-age MS, RG – 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) | \( M_1 \) (M⊙) | \( M_2 \) (M⊙) | Period (days) | 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            | 0.83           | 0.15         | ONe+CO WDs |
| 467.5     | 1.28            | 0.83           | 0.0004       | Merger |
In which a He-star forms within 5 Myr after the WD and currently, in the Galaxy exist. The binarity rate is about 50% (see van S. B. Popov, S. Mereghetti, S.I. Blinnikov, A.G. Kuranov, L.R. Yungelson. Calculations are done for the common envelope parameter symbols indicate the orbital period given in days (see the legend). Masses of components and periods in model systems similar to HD 49798. The vertical axis corresponds to subdwarf mass, and horizontal – to the mass of WD. Only systems with He-stars born less than in 5 Myr after WD are shown. The colors and symbols indicate the orbital period given in days (see the legend). Calculations are done for the common envelope parameter $\alpha_{ce} = 2$.

flows its Roche-lobe in the 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 about 0.8 $M_\odot$ expand after the core He-burning stage and then turn into “helium giants” (Paczynski 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 1 Gyr. 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, e.g., 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 masses of components and for the logarithm of orbital separation. Then, if there are 1011 stars in the Galaxy and the binary rate is about 50% (see van Haarfsen et al. 2013, Appendix A), we roughly estimate that, currently, in the Galaxy exist ~ 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 $\pm0.1 M_\odot$ and $\pm0.2$ day of the observed values, respectively. These systems are shown in Fig. 3. A slight relaxation of the required binary parameters ($\pm0.2 M_\odot$ for component masses) resulted in ~ 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 ten or more, which seems very unlikely. In the case of a 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 ~ $5 \times 10^{-13} – 10^{-10}$ s$^{-1}$, has been detected in about ten 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 disk which is truncated at an inner radius, determined by the balance between the magnetic pressure and the ram pressure of the inflowing mass. The inner disk 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 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 disk, 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 two orders of magnitude below the observed value (even in the most favorable condition, i.e. an accretion disk truncated at the corotation radius).

1 The Roche-lobe radius is $\sim 3 R_{\odot}$, while the radius of HD 49798 is $1.45 \pm 0.25 R_{\odot}$ (Kudritzki & Simon 1978).
In our interpretation, accretion at the current rate does not significantly influence the spin period evolution. Accurate measurements of the period behavior and luminosity can help to test our hypothesis. In fact, we predict that small luminosity variations should not be accompanied by changes in $P$. 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 $P$ value to estimate it. The only limitation comes from the evidence of stable accretion, which requires the Alfvén radius, $R_A = (\mu^2/(M\sqrt{2G\dot{M}})^{1/7})$, 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 $R_A = R_{\text{co}}$ the estimate of $\mu$ is:

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

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 $R_A < R_{\text{co}}$, 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 hot spot much smaller than the WD radius, as required to explain the large pulsed fraction ($\sim 65\%$) 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 $\sim 10^9$ yrs $P$ starts to decrease faster (approximately as $t^{-1.5}$), and reaches values $\lesssim 10^{-15}$ at the age $\sim 5$ Gyrs. So, 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 Myrs. 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. So, the compact object has been significantly spun-up during its lifetime due to contraction.

The predicted value of $\dot{P}$ due to the WD contraction is very small. It is comparable to the smallest values of the second period 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 $\dot{P}$ vs. age for two values of $P$ and two WD masses in Fig. 4. It is seen that WDs with a typical mass $0.6 M_\odot$ 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 variable 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 $\lesssim 10^8$ yrs, 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.

![Figure 4. Evolution of $\dot{P}$. Solid lines correspond to $M = 1.28 M_\odot$. Dashed lines to 0.6 $M_\odot$. 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.](image-url)

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 $M_\odot$ and age of about 2 Myrs can produce the observed spin-up rate of $\dot{P} = 2.15 \times 10^{-15}$ 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.

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REFERENCES

Adams J. B., Ruderman M. A., Woo C.-H., 1963, Physical Review, 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, Astronomy Reports, 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, preprint, (arXiv:1708.06798)

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., Podsadiiowski P., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449
Han Z., Podsadiiowski P., Maxted P. F. L., Marsh T. R., 2003, MNRAS, 341, 669
Hansen B. M. S., Richer H., Kalirai J., Goldsbury R., Heyl J., 2015, ApJ, 809, 141
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., 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., 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
Paczynski B., 1971, Acta Astron., 21, 1
Salas M., Allhau L. G., Garcia-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, Soviet Ast., 34, 57
Urpin V. A., Yakovlev D. G., 1980, Soviet Ast., 24, 126
Yakovlev D. G., Shalybkov D. A., 1989, Astrophysics and Space Physics Reviews, 7, 311
Yakovlev D. G., Urpin V. A., 1980, Soviet Ast., 24, 303
Yungelson L. R., Kuranov A. G., 2017, MNRAS, 464, 1607
Yungelson L. R., Tutukov A. V., 2005, Astronomy Reports, 49, 871
de Miguel E., et al., 2017, MNRAS, 467, 428
van Haften 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

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 et al. (2001), see new details in Bergeron et al. (2011).

We have used the evolutionary sequence C0.1200204, which corresponds to a mass $M = 1.2M_\odot$ and initially “thick” H and He layers with $q_H = 10^{-4}$ and $q_{He} = 10^{-2}$, 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 $M = 1.2M_\odot$, with outer layers $M_{H} = 1.4 \times 10^{-4}M_\odot$ and $M_{He} = 2.6 \times 10^{-5}M_\odot$ (the same H and He envelopes we used for our models of the WD companion of HD49798).

Since zero epochs in both simulations are arbitrary, we

\(^2\) http://www.astro.umontreal.ca/~bergeron/CoolingModels/
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 $T_{\text{eff}} = 59280$ K.

Figure A1 demonstrates the agreement of luminosity, and Fig. A2 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, $T_{\text{eff}} > 1.2 \times 10^4$. 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%, is probably caused by different masses of H and He envelopes, chemical composition, equations of state, etc., but the behavior of $R(t)$ is the same in both cases. Thus, this difference does not significantly influence our conclusions.

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 et al. (2013), who used the BaSTI code.

We have used tables at the BaSTI website which contain data on the $L$ and $T_{\text{eff}}$ evolution for a 1.2$M_\odot$ WD. The specific model is COOL120BaSTIfinal extradAnosep, which refers to a $M = 1.2M_\odot$ DA white dwarf 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.

On late stages (Figs. A4, A6) the discrepancy is rather large (since our code is developed only for hot WDs), but for epochs which 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.

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

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Figure A4. Long time scale evolution of luminosity $L$ of a $1.2M_\odot$ 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 $1.2M_\odot$ WD according to our code (thick blue solid line) and that of BaSTI (thin red dotted line) on short time scale.
Figure A6. Long time scale evolution of effective temperature $T_{\text{eff}}$ of a $1.2M_\odot$ WD according to our code (thick blue solid line) and that of BaSTI (thin red dotted line).

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