New X-ray observations of the hot subdwarf binary
HD 49798/RX J0648.0–4418

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ABSTRACT

HD 49798/RX J0648.0–4418 is the only confirmed X-ray binary in which the mass donor is a hot subdwarf star of O spectral type and, most likely, it contains a massive white dwarf (1.28±0.05 M☉) with a very fast spin period of 13.2 s. Here we report the results of new XMM-Newton pointings of this peculiar binary, carried out in 2018 and in 2020, together with a reanalysis of all the previous observations. The new data indicate that the compact object is still spinning-up at a steady rate of (2.17±0.01) × 10^-15 s^-1, consistent with its interpretation in terms of a young contracting white dwarf. Comparison of observations obtained at similar orbital phases, far from the eclipse, shows evidence for long term variability of the hard (0.5 keV) spectral component at a level of (70±20)%, suggesting the presence of time-dependent inhomogeneities in the weak stellar wind of the HD 49798 subdwarf. To investigate better the soft spectral component that dominates the X-ray flux from this system, we computed a theoretical model for the thermal emission expected from an atmosphere with element abundances and surface gravity appropriate for this massive white dwarf. This model gives a best fit with effective temperature of T_eff=2.25×10^5 K and an emitting area with radius of ~1600 km, larger than that found with blackbody fits. This model also predicts a contribution of the pulsed emission from the white dwarf in the optical band significantly larger than previously thought and possibly relevant for optical variability studies of this system.

Key words: X-rays: binaries – white dwarfs – subdwarfs.

1 INTRODUCTION

HD 49798/RX J0648.0–4418 is the only known accreting X-ray binary in which the mass donor belongs to the class of hot subdwarf stars (Heber 2016). This binary, likely the outcome of a common-envelope stage, is relevant in the context of evolutionary models of intermediate mass stars, possibly leading to the formation of millisecond pulsars or type Ia supernovae (Wang & Han 2010; Brooks et al. 2017; Wu & Wang 2019). It is also interesting because, through the study of its X-ray emission, it offers the possibility to obtain some information on the weak stellar wind of the hot subdwarf (Mereghetti & La Palombara 2016; Krtička et al. 2019).

HD 49798/RX J0648.0–4418 is composed of a compact object spinning at P=13.2 s and a subdwarf star of O spectral type (Kudritzki & Simon 1978; Israel et al. 1997; Mereghetti et al. 2011). The orbital period, determined through optical spectroscopy since early observations of HD 49798, is 1.55 days (Thackeray 1970). The masses of the two stars are well constrained by the measurement of the optical and X-ray mass functions, the system inclination being derived from the duration of the X-ray eclipse: the compact object has a mass of 1.28±0.05 M☉ and is most likely a white dwarf, while the mass of HD 49798 is 1.50±0.05 M☉ (Mereghetti et al. 2009). The most recent parallax obtained with Gaia EDR3 corresponds to a distance of 521±14 pc (Brown et al. 2020).

Contrary to the majority of X-ray binaries, which are transient or highly variable, RX J0648.0–4418 is a persistent X-ray source: a luminosity of ∼10^32 erg s^-1 was seen in all observations, that now span almost thirty years. With a radius of ∼1R☉, HD 49798 underfills its Roche lobe, but it is one of the few hot subdwarfs with strong evidence for a stellar wind (Hamann et al. 1981; Hamann 2010). The most recent estimate, obtained through the modeling of high-resolution UV/optical spectra, yields a mass loss rate of 2.1×10^-9 M☉ yr^-1 and a wind terminal velocity of 1570 km s^-1 (Krtička et al. 2019). With these stellar wind parameters, the observed X-ray luminosity is consistent with that expected from accretion onto a massive white dwarf (Mereghetti et al. 2009, 2011).

Besides the low X-ray luminosity, much smaller than that expected if the accreting object were a neutron star, there are other
arguments that support the presence of a white dwarf in this system. Most of the X-ray flux is emitted in a very soft and strongly pulsed thermal component, well fitted by a blackbody with temperature of kT ~ 30 eV and an emitting radius of ~30 km (Mereghetti et al. 2016). These dimensions are consistent with those of a hot spot on the surface of a white dwarf, but are too large for a neutron star. This emitting radius could be reconciled with a neutron star only if the X-ray emission comes from the whole (or a large part of the) star surface, but this is at variance with the very high pulsed fraction of the soft X-ray pulse profile (~65%).

The steady long-term spin-up of RX J0648.0–4418, at a rate of \( \dot{P} = -2.15 \times 10^{-15} \text{ s}^{-2} \), is difficult to explain by accretion torques (Mereghetti et al. 2016). On the other hand, Popov et al. (2018) showed that it is consistent with that caused by the radial contraction of a young white dwarf with age of a few millions years. Such a small age is in agreement with the evolutionary models that account for the properties of this binary. Finally, we note that population synthesis simulations of hot subdwarf binaries predict that those hosting white dwarfs greatly outnumber those with a neutron star (Yungelson & Tutukov 2005; Wu et al. 2018).

To continue our long term monitoring of this unique X-ray binary, we observed it with XMM-Newton in 2018 and 2020. Here we present the results of these new observations, complemented by a reanalysis of all the previous data, including the first spectral fits with a white dwarf atmosphere model applied to this system.

2 DATA ANALYSIS AND RESULTS

XMM-Newton observed RX J0648.0–4418 for ~34 ks on 2018 November 8 and for ~37 ks on 2020 February 27. We use the data obtained with the EPIC instrument, that consists of one pn and two MOS cameras (Strüder et al. 2001; Turner et al. 2001). As in all the previous observations, the pn and MOS cameras were operated in Full-Frame mode, giving time resolutions of 73 ms and 2.6 s, respectively.

To compare properly the new observations with the previous ones, we processed all the available XMM-Newton data using SAS v.16.1 and the most recent calibration files. We filtered out time intervals with high background and selected single- and double-pixels events for the pn (PATTERN<4), and single- and multiple-pixels events for the MOS (PATTERN<12). The resulting exposure times are given in Table 1. Source and background events were extracted from circular regions with radii of 30" and 60", respectively.

For the timing analysis we used also the ROSAT data obtained on 1992 November 11. We selected the counts obtained with the PSPC instrument in the energy range 0.1–0.5 keV, from a source region with radius of 1 arcmin.

For all data sets, the times of arrival of the events were corrected to the solar system barycenter using the source coordinates given in Table 2.

2.1 Timing analysis results

The source pulsations at 13.2 s are clearly visible in the 2018 and 2020 data. The spin periods measured in these new observations are consistent with those predicted by the ephemeris reported in Mereghetti et al. (2016), which were derived from a phase-coherent timing of all the data obtained before 2015. Therefore, we included the new data in the phase-coherent analysis. Briefly, this consists in deriving the time of arrivals of a fiducial phase of the pulse profile measured in the different observations and, after correcting for the effect of orbital motion, fitting them with a quadratic function \( \phi(t) = \phi_0(t) + \nu_0(t - T_0) + 0.5\nu_0(t - T_0)^2 \). The phases were determined by fitting a sinusoidal function to the 0.15-0.5 keV pulse profiles measured in time intervals of 2000 s. This procedure was done iteratively, starting from the most closely spaced observations, and progressively including the other ones, as the improved timing parameters allow to maintain phase coherence. The orbital parameters were kept fixed at the values of Table 2.

Our final solution provided a good fit (\( \chi^2 = 1.21 \) for 44 degrees of freedom (dof)) and a highly significant quadratic term with the parameters given in Table 2. The best fit and its residuals are shown in Fig. 1. This timing solution is consistent with that of Mereghetti et al. (2016), but, thanks to the longer baseline, it has smaller uncertainties on the best fit parameters.

To search for long term variability, disentangling the effects related to the orbital phase, we produced background subtracted light curves folded at the orbital period (Fig. 2). They refer to the soft (0.2-0.5 keV) and hard (0.5-10 keV) energy bands. It can be seen that there is some evidence that the hard X-ray flux in 2020 was slightly lower than in previous observations that covered similar or-

### Table 1. Log of the XMM-Newton observations of HD 49798.

| Date          | Obs. ID       | Start (MJD) | Stop (MJD) | Exposure (pn/MOS) (ks) | Orbital phase |
|---------------|---------------|-------------|------------|------------------------|---------------|
| 2002 May 03   | 0121250301    | 52397.46    | 52397.55   | 4.57/2                 | 0.45 – 0.48   |
| 2002 May 04   | 0121250401    | 52397.98    | 52398.06   | 1.45/4                 | 0.78 – 0.81   |
| 2002 May 04   | 0121250501    | 52398.56    | 52399.39   | 0.62/5                 | 0.17 – 0.16   |
| 2002 Sep 17   | 0121250601    | 52534.58    | 52534.72   | 6.9/11.9               | 0.06 – 0.11   |
| 2008 May 10   | 0555460201    | 54596.90    | 54597.38   | 36.7/43.0              | 0.56 – 0.87   |
| 2011 May 02   | 0671240901    | 55683.55    | 55683.76   | 17.0/18.3              | 0.70 – 0.82   |
| 2011 Aug 18   | 0671241001    | 55791.88    | 55792.07   | 15.0/16.4              | 0.69 – 0.80   |
| 2011 Aug 20   | 0671241101    | 55793.46    | 55793.62   | 11.8/14.1              | 0.72 – 0.80   |
| 2011 Aug 25   | 0671241201    | 55798.04    | 55798.27   | 18.0/19.2              | 0.67 – 0.81   |
| 2011 Sep 03   | 0671241301    | 55807.35    | 55807.54   | 15.0/16.4              | 0.69 – 0.80   |
| 2011 Sep 08   | 0671241401    | 55811.10    | 55812.19   | 15.0/16.4              | 0.70 – 0.80   |
| 2013 Nov 10   | 0721050101    | 56605.80    | 56606.25   | 37.9/39.1              | 0.60 – 0.86   |
| 2014 Oct 18   | 0740280101    | 56948.37    | 56948.71   | 27.1/29.1              | 0.95 – 0.15   |
| 2018 Nov 08   | 0820220101    | 58430.46    | 58430.92   | 34.3/40.9              | 0.56 – 0.85   |
| 2020 Feb 27   | 0841270101    | 58906.31    | 58906.81   | 37.3/45.4              | 0.03 – 0.35   |
2.2 X-ray emission during the eclipse

The 2018 observation covered the orbital phases around the eclipse of the X-ray pulsar and confirms the presence of significant X-ray emission also when the compact object is occulted by its subdwarf companion, as it was seen in previous eight observations (Mereghetti et al. 2009, 2013). To investigate possible long term variability of the emission during the eclipse, we extracted EPIC-pn images (in the 0.3–4.5 keV range) in a time interval of 4300 s (the eclipse duration measured in Mereghetti et al. 2013) centered at phase 0.75 and carried out source detections using the SAS task edetect_chain. HD 49798 was detected in all the nine images, with count rates consistent with a constant value of 0.048 ± 0.002 counts s⁻¹ (χ² = 1.44 for 8 dof).

We then produced a pn and a MOS spectrum of the eclipse emission by stacking all the source spectra of the individual observations, extracted from the above orbital phase interval. These two spectra were fit simultaneously using the sum of three thermal plasma emission models (vapec in XSPEC) with abundances fixed to the most recent values found for HD 49798 (see Table 2 of Krtiĉka et al. 2019). The resulting temperatures of 0.15, 0.9, and 6 keV, and the corresponding model normalizations, were consistent with those found by Mereghetti & La Palombara (2016). Under the assumption that the X-ray flux seen during the eclipse is due to intrinsic emission from HD 49798, and thus present at all orbital phases, we included this best fit eclipse model as a fixed component in all the subsequent spectral fits discussed below.

2.3 Variability in the hard X-ray component

The 2020 observation provided the first data set with a long exposure time at orbital phases far from the eclipse, which were covered only marginally by previous XMM-Newton pointings. For a first analysis of these data and to facilitate the comparison with previous results, we adopted a blackbody plus power law model and we concentrated on a comparison with the 2014 observation, which covered similar orbital phases.

Separate fits to the 2014 and 2020 spectra, in the 0.3–10 keV range, gave consistent values for the blackbody component, but different best fit parameters for the power law, indicating a lower flux in 2020. Therefore, we fitted the 2014 and 2020 pn spectra simultaneously, imposing common values for all the parameters except for the power law normalization. This resulted in a good fit (χ²ν = 1.15 for 167 dof) with 0.3–10 keV fluxes of the power law component of (1.7 ± 0.2) × 10⁻¹³ erg cm⁻² s⁻¹ in 2014 and (1.0 ± 0.1) × 10⁻¹³ erg cm⁻² s⁻¹ in 2020. These flux values confirm the evidence for the variability seen in the hard X-ray light curves of Fig 2. All the other spectral parameters were consistent with those obtained from the sum of all the data taken before 2015 (Mereghetti et al. 2016), although they had larger uncertainties due to their lower counting statistics.

2.4 The soft thermal component

Since with the new observations we found no evidence for long term variability in the soft thermal component, we performed a spectral analysis using the spectra obtained by stacking all the available observations. In the following, we present the results obtained with the EPIC-pn spectra¹, corresponding to a total exposure time of 170 ks.

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¹ We checked that similar results were obtained with the MOS.
In addition to fits with the usual blackbody plus power law model, we also explored a more physically motivated scenario, replacing the blackbody component with a white dwarf atmosphere model that we computed specifically for this source.

The effects of an atmosphere on the emerging thermal radiation depend on many parameters, including elemental composition and surface gravity, but it is impossible to constrain all of them with the limited spectral resolution and narrow bandwidth of the current data. Therefore, we explored only a single model that we computed assuming a surface gravity of \( \log g = 9 \) (appropriate for this massive white dwarf) and a composition based on the abundances measured for HD 49798 (Krtička et al. 2019). This choice for the abundances is based on the hypothesis that the white dwarf surface, or at least the regions where matter accretes and that are responsible for the X-ray emission, are covered by matter coming from the companion star.

To model stellar spectra in the relevant \( T_{\text{eff}} \) and \( \log g \) ranges, non-local thermodynamic equilibrium (NLTE) model atmospheres are mandatory. Thus, we employed the Tübingen NLTE Model-Atmosphere Package (TMAP\(^2\), Werner et al. 2003, 2012) to calculate plane-parallel and chemically homogeneous atmospheres in hydrostatic and radiative equilibrium. We considered opacities of H, He, C, N, O, Fe, and Ni. The atomic data were taken from the Tübingen Model-Atom Database (TMAD) and, for Fe and Ni, calculated with our Iron Opacity and Interface program (IrOnIc), that uses a statistical approach with so-called super levels and super lines (Rauch & Deetjen 2003) based on Kurucz’s line lists\(^3\) (Kurucz 2009, 2011) and Opacity Project data\(^4\) (Seaton et al. 1994).

We adopted the abundances given by the following normalized mass fractions: H (8.045\( \times 10^{-2} \)), He (9.134\( \times 10^{-1} \)), C (2.337\( \times 10^{-4} \)), N (3.431\( \times 10^{-3} \)), O (1.239\( \times 10^{-4} \)), Fe (2.168\( \times 10^{-4} \)), and Ni (1.817\( \times 10^{-4} \)). Some examples of the model for different values of the effective temperature are shown in Fig. 3. Due to the presence of many absorption lines and edges, they deviate significantly from blackbody spectra, especially at the shortest wavelengths. This is also illustrated in Fig. 4, which presents an enlarged view of the energy range covered by our X-ray data. In this figure, the theoretical model has been convolved with the instrumental response of the EPIC pn detector, which results in a smearing of the sharp spectral features.

By fitting the pn spectrum with the atmosphere model plus a power law, we could not obtain a unique best fit solution. In fact, exploring the whole range of temperatures covered by our model\(^5\), we found similarly good results with effective temperatures of about 2.2 or 2.9\( \times 10^5 \) K (\( \chi^2_n = 1.26 \) and \( 1.28 \), respectively). These fits imply emitting regions more than one hundred times larger than that derived with the blackbody model (see Table 3). Another reasonably good fit, with only a slightly worse \( \chi^2_n = 1.39 \), was found for \( T_{\text{eff}} = 3.7 \times 10^5 \) K.

The reason for these multiple solutions can be qualitatively understood by examining Fig. 4: in the \( \sim 0.3-0.6 \) keV range, where the thermal emission dominates over the power law component, the atmosphere model has an average spectral slope that varies with temperature in a non monotonic way. The slope observed in the X-ray data, and well described by a blackbody of \( \sim 3.7 \times 10^5 \) K, can be well approximated by atmosphere models with different values of \( T_{\text{eff}} \), also considering the effect of changes in \( N_H \) and in the power law parameters (see best fit values in Table 3).

The best fit to the pn spectrum with an atmosphere of \( T_{\text{eff}} = 2.25 \times 10^5 \) K is shown in Fig. 5. The residuals in the fits, which lead to a \( \chi^2_n \) value slightly higher than that obtained with a blackbody, could be reduced by changing the atmosphere metal abundances and/or surface gravity (as well as by allowing some small variations in the eclipse model used to describe the contribution from HD 49798). However, besides increasing the number of free parameters, this would not lead to a unique solution and we believe that such more refined analysis should wait for the availability of future data with better spectral resolution and statistics.

\(^2\) http://astro.uni-tuebingen.de/~TMAP

\(^3\) http://kurucz.harvard.edu/atoms.html

\(^4\) http://cdsweb.u-strasbg.fr/topbase/topbase.html

\(^5\) We imposed values of \( N_H > 10^{20} \) cm\(^{-2} \) to avoid convergence of the fits to unreasonable values.
| Model       | \(N_H\) \(10^{20}\) cm\(^{-2}\) | \(T_{\text{eff}}\) 10\(^5\) K | \(R^a\) km | photon index | \(F_{\text{PL}}^0\) \(10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) | \(\chi^2/\text{dof}\) |
|-------------|-------------------------------|-----------------|----------|-------------|----------------|----------------|
| BB+PL       | 1 (fixed)                     | 3.65 \(\pm\) 0.18 | 41 \(^{+13}_{-10}\) | 1.80 \(\pm\) 0.06 | 1.18 \(\pm\) 0.05 | 1.16/116       |
| Atm+PL      | 14.3 \(\pm\) 1.5             | 2.25 \(^{+0.02}_{-0.04}\) | 1604 \(^{+207}_{-212}\) | 1.75 \(\pm\) 0.09 | 1.23 \(\pm\) 0.06 | 1.26/116       |
| Atm+PL      | 8.5 \(\pm\) 0.8              | 2.94 \(\pm\) 0.01 | 397 \(\pm\) 32 | 1.66 \(\pm\) 0.09 | 1.20 \(\pm\) 0.06 | 1.28/116       |
| Atm+PL      | 6.3 \(\pm\) 1.5              | 3.73 \(^{+0.04}_{-0.10}\) | 66 \(^{+3.20}_{-2.16}\) | 1.92 \(\pm\) 0.06 | 1.22 \(\pm\) 0.05 | 1.39/116       |

\(^a\) Emission radius for \(d=521\) pc.

\(^b\) Unabsorbed flux of power law component in the 0.3–10 keV energy range.

Figure 5. Best fit (top) and residuals (bottom) of the total pn spectrum with a power law plus atmosphere model with \(T_{\text{eff}}=2.25 \times 10^5\) K.

3 DISCUSSION AND CONCLUSIONS

Evidence for small (\(\sim 30\%\)) variability in the hard X-ray component of HD 49798 was first reported by Mereghetti et al. (2011), based on the observations of September 2002 and May 2008. Since those data were obtained at very different orbital phases, it was not clear if such variation was related to the source position in the orbit or to real long term changes in the properties of the system. The latter possibility seems favoured by our new results, which show a \(\sim 70\%\) flux variation between two observations spaced by six years, but taken at similar orbital phases. This suggests that the stellar wind from the hot subdwarf HD 49798, despite being much weaker than those of normal early type stars, might be subject to time variable inhomogeneities leading to changes in the mass accretion rate, similar to those seen in high mass X-ray binaries. The resulting luminosity variations are more prominently appearing in the harder spectral component, likely originating in shocks occurring within the accretion stream.

The new XMM-Newton data reported here show that the pulsar in HD 49798/RX J0648.0–4418 has continued also after 2014 its regular spin-up at the same rate of \(\dot{P} = -2.17 \times 10^{-15}\) s\(^{-1}\). As discussed in Mereghetti et al. (2016), the mass accretion rate in this system is insufficient to cause this rapid spin-up if the compact object is a white dwarf. On the other hand, such a remarkably steady spin-up rate is difficult to explain for a neutron star subject to wind accretion: changes in the torque, resulting from variations in the stellar wind gravitationally captured by the compact object, should affect its spin period. However, no changes in \(\dot{P}\) were seen, despite the observed long term variability. These results support the interpretation of the spin-up in terms of the secular contraction of a white dwarf of few Myr age, as proposed by Popov et al. (2018).

Most of the X-ray luminosity of RX J0648.0–4418 is emitted in a soft thermal component, probably originating on the white dwarf surface. The large size of the emitting area, inferred from blackbody fits, has been one of the arguments used to disfavour a neutron star interpretation. Here we presented the first attempt to describe this soft component with a more physical model, accounting for the presence of an atmosphere and assuming that the white dwarf is covered by helium-rich material accreted from its companion star. Fitting with this model plus a power law, we obtained reasonably good results, although the temperature could not be uniquely constrained. Remarkably, these fits result in significantly larger emission radii than those derived with the blackbody model, implying that the thermal component originates from a large fraction, or even from the totality, of the star surface.

Another relevant implication of these fits is that the contribution of the thermal emission in the UV/optical bands is much larger than that expected by the extrapolation of the best fit blackbody model. For example, for the best atmosphere fit with \(T_{\text{eff}}=2.25 \times 10^5\) K gives an optical flux about three orders of magnitude larger than that of the blackbody. We cannot exclude that models with slightly different compositions could give an even larger flux at long wavelengths, when fitted to the X-ray data. This emission might produce detectable pulsations in the optical band, if it is modulated as strongly as in the soft X-ray band. Previous searches for optical pulsations at the spin period of 13.2 s provided an upper limit of \(6 \times 10^{-4}\) photons cm\(^{-2}\) s\(^{-1}\) \(\AA\)\(^{-1}\) at 3600 Å (Mereghetti et al. 2011). The extrapolation of the best fit atmosphere model is only about one order of magnitude below this upper limit, suggesting that more sensitive searches could lead to the detection of optical pulsations or to useful constraints in case of null results.

4 SUMMARY

Thanks to new XMM-Newton observations of HD 49798/RX J0648.0–4418 carried out in 2018 and 2020, we could extend its phase-connected timing solution, now spanning a time interval of almost thirty years, without finding any evidence of variations in the spin-up rate, despite the long term variability in the flux of the hard X-ray component reported here for the first time.

We computed a specific white dwarf atmosphere model for this system, adopting appropriate composition and surface gravity values, and used it to describe the soft X-ray component, that was tra-
ditionally fitted with a blackbody. Our analysis showed that, in order to fully exploit the potential diagnostics of physical models of this type, data with higher spectral resolution are needed, as can be provided by future experiments like XRISM (XRISM Science Team 2020) and Athena/XIFU (Barret et al. 2018). On the other hand, this first attempt indicates that atmosphere models lead to lower temperatures and much larger emission regions compared to blackbody fits. Interestingly, our best fit results imply that the pulsed thermal component emitted from the compact object gives a contribution in the optical/UV bands much larger than predicted by the blackbody. This opens promising prospects for future searches of optical pulsations and, more in general, for the investigation of variability in the optical band, where the contribution from the bright and hot HD 49798 is dominant.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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