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Discovery of spin-up in the X-ray pulsar companion of the hot subdwarf HD 49798

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ABSTRACT

The hot subdwarf HD 49798 has an X-ray emitting compact companion with a spin-period of 13.2 s and a dynamically measured mass of $1.28 \pm 0.05 M_{\odot}$, consistent with either a neutron star or a white dwarf. Using all the available *XMM–Newton* and *Swift* observations of this source, we could perform a phase-connected timing analysis extending back to the *ROSAT* data obtained in 1992. We found that the pulsar is spinning up at a rate of $(2.15 \pm 0.05) \times 10^{-15} \text{ s s}^{-1}$. This result is best interpreted in terms of a neutron star accreting from the wind of its subdwarf companion, although the remarkably steady period derivative over more than 20 yr is unusual in wind-accreting neutron stars. The possibility that the compact object is a massive white dwarf accreting through a disc cannot be excluded, but it requires a larger distance and/or properties of the stellar wind of HD 49798 different from those derived from the modelling of its optical/UV spectra.

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

1 INTRODUCTION

HD 49798/RX J0648.0–4418 is a binary system with orbital period of 1.55 d containing an X-ray pulsar with spin period of 13.2 s (Thackeray 1970; Stickland & Lloyd 1994; Israel et al. 1997; Mereghetti et al. 2011). This X-ray source is particularly interesting since it is the only known pulsar with a hot subdwarf companion.¹ Its properties are quite different from those of all the other X-ray binaries containing accretion-powered neutron stars (NSs) or white dwarfs (WDs). The X-ray emission from RX J0648.0–4418 shows two distinct features: a strongly pulsed soft thermal component, well fit by a blackbody of temperature $kT \sim 30 \text{ eV}$, and a harder tail (power-law photon index ~ 2), which accounts for most of the emission above 0.6 keV. An upper limit on the pulsar spin period derivative of $|\dot{P}| < 6 \times 10^{-15} \text{ s s}^{-1}$ (90 per cent c.l.) was derived by phase-connecting *XMM–Newton* observations obtained in 2008 and 2011 (Mereghetti et al. 2013).

The masses of the two stars in this binary system 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 (Mereghetti et al. 2009): with a mass of $1.50 \pm 0.05 M_{\odot}$, HD 49798 is among the most massive hot subdwarfs of O spectral type, while the mass of the pulsating X-ray source is $1.28 \pm 0.05 M_{\odot}$.

HD 49798 is one of the few hot subdwarfs for which evidence for a stellar wind has been reported (Hamann et al. 1981; Hamann 2010). It was thus natural to explain the relatively small X-ray luminosity of this binary (see Section 2.2) as emission powered by wind accretion on to either a WD or an NS. The WD hypothesis was favoured by Mereghetti et al. (2009) based on a simple estimate of the expected luminosity resulting from the wind parameters reported by Hamann et al. (1981) and assuming a distance of 650 pc (Kudritzki & Simon 1978).

To better understand this system, we have performed a timing analysis of all the available X-ray observations in which the 13.2 s pulsations can be detected with a high confidence level. This has allowed us to derive a phase-connected timing solution and to measure for the first time the pulsar spin-up (Section 2). On the basis of this result, in Section 3, we rediscuss the nature of the compact companion of HD 49798.

2 OBSERVATIONS AND DATA ANALYSIS

Since 2002 May to 2014 October, several observations of HD 49798 were carried out using the *XMM–Newton* satellite (see Table 1). In

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¹ A possibly similar system, BD +37°442, has been reported by La Palombara et al. (2012), but the detection of an X-ray periodicity awaits confirmation.

Table 1. Log of the *XMM-Newton* observations of RX J0648.0–4418.

Observation date	Start time MJD	End time MJD	Duration pn/MOS (ks)
2002 May 3	52397.46	52397.55	4.5/7.2
2002 May 4	52397.98	52398.06	1.4/5.6
2002 May 4	52398.56	52398.59	0.6/2.5
2002 September 17	52534.58	52534.72	6.9/11.9
2008 May 10	54596.90	54597.38	36.7/43.0
2011 May 2	55683.55	55683.76	17.0/18.5
2011 August 18	55791.88	55792.07	15.0/16.6
2011 August 20	55793.46	55793.62	11.8/14.3
2011 August 25	55798.04	55798.27	18.0/19.6
2011 September 3	55807.35	55807.54	15.0/16.6
2011 September 8	55811.10	55812.19	15.0/16.6
2013 November 10	56605.80	56606.25	37.9/39.5
2014 October 18	56948.37	56948.71	27.1/29.4

this work, we used the data collected with the three CCD cameras of the EPIC instrument. In all the observations, they were operated in Full Frame mode, which provides a time resolution of 73 ms for the pn camera and of 2.6 s for the two MOS cameras. Source counts were extracted from a circle of 30 arcsec radius around the position of HD 49798.

HD 49798 was also observed with the ROSAT satellite on 1992 November 11. These are the data in which the pulsations were discovered (Israel et al. 1997), and they allow us to extend the baseline of our phase-connected timing solution. For the analysis reported here, we used the counts obtained with the PSPC instrument in the 0.1–0.5 keV energy range (extraction radius of 1 arcmin). Finally, we included in the timing analysis for the phase-connection also the observations carried out with the *Swift* XRT instrument in January 2013, May 2014, August 2014 and January/February 2015.

2.1 Timing analysis

The times of arrival were converted to the Solar system barycentre and corrected for the orbital motion using the parameters given in Table 2. The phases of the pulsations were derived by fitting a constant plus a sinusoid to the folded pulse profiles. For the EPIC data, we used the pn profiles in the energy range 0.15–0.5 keV, which have the largest pulsed fraction. In order to obtain a phase-connected timing solution, we fitted the pulse phases as a function of time with the function

$$\phi(t) = \phi_0 + \nu_0(t - T_0) + 0.5\dot{\nu}(t - T_0)^2, \quad (1)$$

Table 2. Parameters of the binary system HD 49798/RX J0648.0–4418.

Parameter	Value	Units
Right Ascension	6 ^h 48 ^m 4 ^s .7	J2000
Declination	−44° 18′ 58″.4	J2000
Orbital period	1.547 666(2)	d
$A_X \sin i$	9.79(19)	light-s
T^*	4361.243(15)	MJD
ν_0	0.075 848 084 6(1)	Hz
$\dot{\nu}$	$1.24(2) \times 10^{-17}$	Hz s ^{−1}
P_0	13.184 248 56(2)	s
$\dot{P}$	$-2.15(5) \times 10^{-15}$	s s ^{−1}
T_0	48937.7681361	MJD
M_X	1.28(5)	$M_\odot$
M_C	1.50(5)	$M_\odot$

where $\nu = 1/P$ is the star rotation frequency. We started by using the most closely spaced observations (Summer 2011) and gradually included in the fit the other observations, as increasingly more precise fit parameters allowed us to keep track of the number of intervening pulses. In this way, we could obtain a unique solution giving a good fit to all the considered data with the values of ν , $\dot{\nu}$ and orbital parameters reported in Table 2. The fit to the data points and the residuals are shown in Fig. 1. The highly statistically significant quadratic term in the fit corresponds to a spin-up rate of $\dot{P} = (-2.15 \pm 0.05) \times 10^{-15} \text{ s s}^{-1}$.

Based on the phase-connected timing solution, we could join all the *XMM-Newton* observations and produce the background-subtracted pulse profiles in different energy ranges shown in Fig. 2. This figure shows a striking change in the pulse profile at an energy of 0.5 keV. At lower energies, where the thermal spectral component dominates, the light curves are characterized by a single broad pulse. The pulsed fraction (defined as the amplitude of a fitted sinusoid divided by the average count rate) is 65 ± 1 per cent in the 0.15–0.23 keV range and 44 ± 1 per cent in the 0.23–0.5 keV range. Above 0.5 keV, the light curve is more complex, displaying two pulses not aligned in phase with the low-energy one and with an energy-dependent relative intensity.

2.2 Spectral analysis and luminosity

In this section, we reassess the total accretion-powered luminosity of the HD 49798 companion, exploiting all the available data and taking into account the uncertainties in the spectral parameters derived from the fits. This is particularly important since, due to the very soft spectrum, a large fraction of the luminosity might be emitted at energies smaller than ~ 0.2 keV, below the observed X-ray range. X-rays from this system are also detected during the eclipse. They are most likely emitted in the wind of HD 49798 and it is reasonable to assume that they are present during the whole orbital revolution. Therefore, it is necessary to model this component and subtract it from the non-eclipsed spectrum in order to properly estimate the bolometric luminosity of the X-ray pulsar.

Hence, we first analysed all the *XMM-Newton* data in which the eclipse was present (8 observations in 2008, 2011 and 2013). We stacked together all the EPIC-pn data of the eclipses for a total exposure of ~ 30 ks, and we did the same for the EPIC-MOS1 and MOS2 data. We fitted together the resulting pn and MOS spectra with the sum of three MEKAL components (Mewe, Gronenschild & van den Oord 1985) with temperatures of 0.1, 0.6 and 4 keV and abundances fixed at those of HD 49798 (Mereghetti & La Palombara 2015). This model was then included as a fixed component in all the fits of the non-eclipsed X-ray emission described below.

We then summed all the *XMM-Newton* data (from 2002 to 2014) excluding the time intervals corresponding to the pulsar eclipse. This resulted in a total exposure of ~ 90 ks. These stacked spectra (one for each camera) were fitted with a blackbody plus power-law model, including as a fixed component the eclipse model. The resulting best-fitting values of the spectral parameters are given in Table 3. Varying the model parameters within their 3σ c.l. regions (see Fig. 3), we found that the bolometric flux of the blackbody component is constrained within the range $(3\text{--}5) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. The flux of the power-law component depends on the considered energy range, but it is at most $\sim 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (corrected for the interstellar absorption), even considering the wide energy range 0.01–10 keV. Therefore, the power-law component gives only a minor contribution to the total flux and we can conclude that the

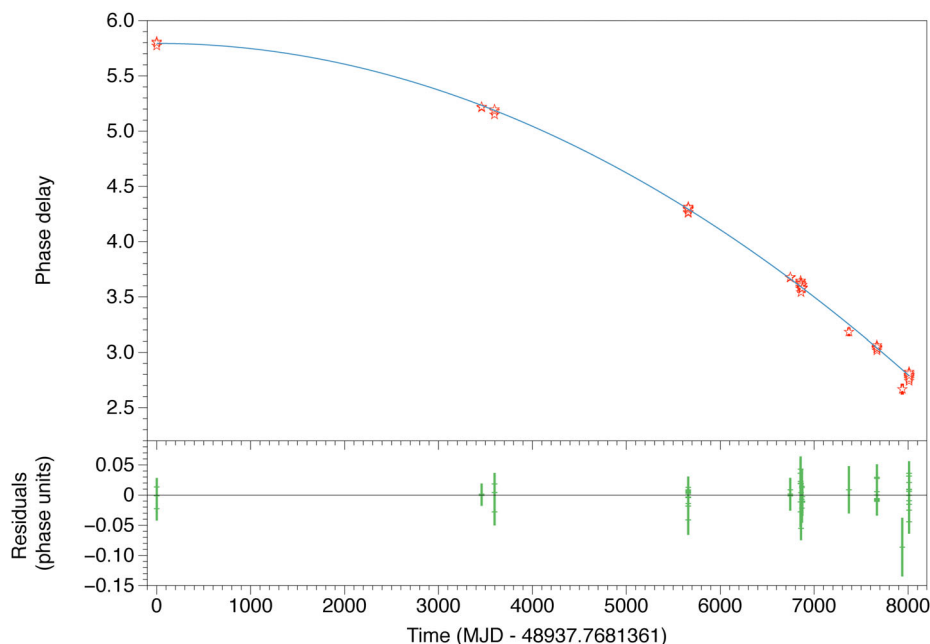


Figure 1. Phases of the pulses (in units of cycles) fitted with a quadratic function (top panel) and residuals from the best fit (bottom panel).

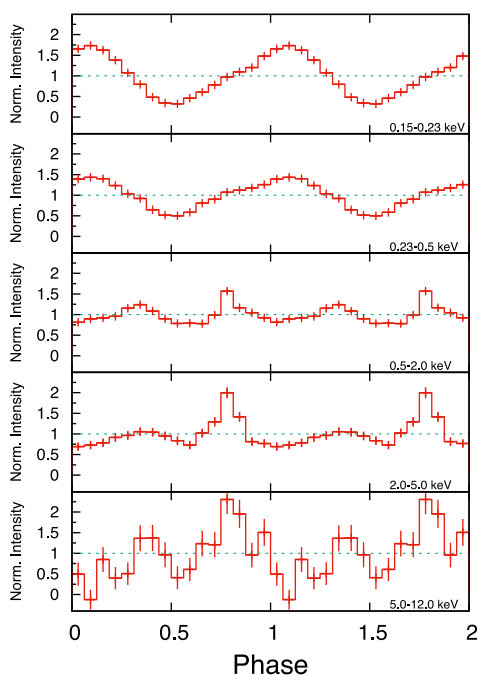


Figure 2. Folded light curves in different energy ranges obtained by summing all the *XMM-Newton* observations (pn+MOS). The estimated background contribution has been subtracted and the profiles have been normalized to the average count rate.

total accretion-powered luminosity, L_X , is in the range $(2 \pm 0.5) \times 10^{32} (d/650 \text{ pc})^2 \text{ erg s}^{-1}$.

3 DISCUSSION

Our discovery of a long-term spin-up confirms that the pulsar companion of HD 49798 is accreting mass. From the observed value $\dot{\nu} = 1.24 \times 10^{-17} \text{ Hz s}^{-1}$, we can estimate the amount of specific

Table 3. Spectral results (errors at 90 per cent c.l. for a single parameter).

Parameter	Value	Units
N_H	$< 8 \times 10^{20}$	cm^{-2}
kT_{BB}	31 ± 1	eV
R_{BB}^a	$39.6^{+5.7}_{-4.8}$	km
Photon index	1.88 ± 0.08	
K_{PL}^b	$(1.75 \pm 0.08) \times 10^{-5}$	$\text{ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$

Notes. ^aBlackbody emission radius for $d = 650 \text{ pc}$.

^bPower-law flux at 1 keV.

angular momentum which is accreted by the compact object, which, using the relation $L_X = G\dot{M}M/R$, can be written as

$$j = \frac{2\pi\dot{\nu}IGM}{L_X R}, \quad (2)$$

where M , R and I are the mass, radius and moment of inertia of the compact object and $\dot{M}$ is the mass accretion rate. In the case of a WD (for which we assume $I = 10^{50} \text{ g cm}^2$, $R = 3000 \text{ km}$, $M = 1.28 M_\odot$), we obtain

$$j_{\text{WD}} = 2.2 \times 10^{19} \left(\frac{L_X}{2 \times 10^{32} \text{ erg s}^{-1}} \right)^{-1} \text{ cm}^2 \text{ s}^{-1}, \quad (3)$$

while for an NS ($I = 10^{45} \text{ g cm}^2$, $R = 12 \text{ km}$, $M = 1.28 M_\odot$), we have

$$j_{\text{NS}} = 5.5 \times 10^{16} \left(\frac{L_X}{2 \times 10^{32} \text{ erg s}^{-1}} \right)^{-1} \text{ cm}^2 \text{ s}^{-1}. \quad (4)$$

These values should be compared with the specific angular momentum that can be provided by the inflow of the accreting matter. Estimates of the specific angular momentum in the case of wind accretion are subject to many uncertainties because the properties of the flow of the matter gravitationally captured by the compact object moving through the wind of the companion are not well known. Estimates have been made by different authors (see, e.g. Illarionov & Sunyaev 1975; Shapiro & Lightman 1976; Wang 1981; Ruffert 1997) under some simplifying hypothesis which might not apply

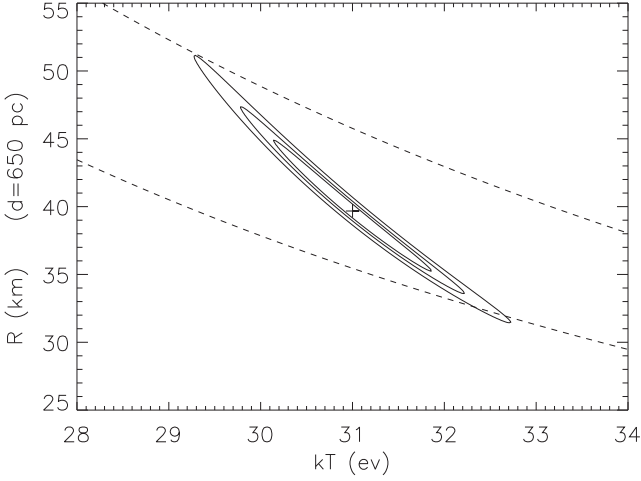


Figure 3. Confidence level contours (1, 2 and 3σ) for the blackbody temperature and radius of emitting area (assuming a distance of 650 pc). The two dashed lines correspond to bolometric luminosities of $2.5 \times 10^{32} \text{ erg s}^{-1}$ (upper curve) and $1.5 \times 10^{32} \text{ erg s}^{-1}$ (lower curve).

in our case. However, we can take as a reasonable upper limit the value $j_w \sim \Omega R_G^2$, where Ω is the orbital angular velocity and R_G is the Bondi–Hoyle accretion radius ($R_G = 2GM/V_{\text{REL}}^2$, where V_{REL} is the relative velocity between the compact object and the stellar wind). In the case of HD 49798, we have

$$j_w = 5.4 \times 10^{16} \left(\frac{V_{\text{REL}}}{1000 \text{ km s}^{-1}} \right)^{-4} \text{ cm}^2 \text{ s}^{-1}, \quad (5)$$

which, compared to equation (3), shows that, in this simple wind-accretion scenario, it is difficult to obtain the observed spin-up rate if the compact object is a WD.

The case of a wind-accreting NS is more favourable, but still a rather small value of V_{REL} is necessary to provide enough angular momentum (see equations (5) and (4)). Furthermore, a small value of V_{REL} might be inconsistent with the observed luminosity. In fact, the accretion rate can be estimated from the relation

$$\dot{M} = \dot{M}_w \left(\frac{R_G}{2a} \right)^2, \quad (6)$$

where a is the orbital separation and $\dot{M}_w$ the wind mass-loss rate from the companion star. The properties of the wind of HD 49798 have been derived by Hamann (2010), who obtained $\dot{M}_w = 3 \times 10^{-9} M_\odot \text{ yr}^{-1} = 2 \times 10^{17} \text{ g s}^{-1}$ and an asymptotic wind velocity $V_\infty = 1350 \text{ km s}^{-1}$. The luminosity corresponding to equation (6) is

$$L_{\text{NS}} = 1.3 \times 10^{34} \left(\frac{\dot{M}_w}{10^{17} \text{ g s}^{-1}} \right) \left(\frac{V_{\text{REL}}}{1000 \text{ km s}^{-1}} \right)^{-4} \text{ erg s}^{-1}, \quad (7)$$

which is much larger than the observed value.

In view of these difficulties, we consider in the following the case of disc accretion. If the accretion occurs through a Keplerian disc, the spin-up rate is given by

$$2\pi I \dot{\nu} = \dot{M} \sqrt{GMR_M}. \quad (8)$$

R_M is the magnetospheric radius, which can be expressed by

$$R_M = \xi \left(\frac{\mu^4}{GMM^2} \right)^{1/7}, \quad (9)$$

where μ is the magnetic dipole moment ($\mu = BR^3/2$) and ξ a parameter of the order of unity.

Using these equations, we can derive the minimum magnetic field B required to provide the observed spin-up rate. The minimum field is different in the case of a WD and of an NS:

$$B_{\text{WD}} > 1.4 \times 10^9 \xi^{-7/4} \left(\frac{\dot{M}}{10^{15} \text{ g s}^{-1}} \right)^{-3} \text{ G} \quad (10)$$

$$B_{\text{NS}} > 6.9 \times 10^{10} \xi^{-7/4} \left(\frac{\dot{M}}{10^{11} \text{ g s}^{-1}} \right)^{-3} \text{ G}. \quad (11)$$

In order to have accretion and spin-up, R_M must be smaller than the corotation radius, $R_{\text{COR}} = (GMP^2/4\pi^2)^{1/3} = 9 \times 10^8 \text{ cm}$. This condition yields an upper limit on B , which again is different in the WD and NS case:

$$B_{\text{WD}} < 4 \times 10^4 \xi^{-7/4} \left(\frac{\dot{M}}{10^{15} \text{ g s}^{-1}} \right)^{1/2} \text{ G} \quad (12)$$

$$B_{\text{NS}} < 6.3 \times 10^9 \xi^{-7/4} \left(\frac{\dot{M}}{10^{11} \text{ g s}^{-1}} \right)^{1/2} \text{ G}. \quad (13)$$

The above requirements for a minimum (equations (10) and (11)) and a maximum magnetic field (equations (12) and (13)) can be satisfied only if

$$\dot{M} > 2 \times 10^{16} \text{ g s}^{-1}, \quad \text{in the case of a WD}, \quad (14)$$

$$\dot{M} > 2 \times 10^{11} \text{ g s}^{-1}, \quad \text{in the case of an NS}. \quad (15)$$

We can thus conclude that, in case of disc accretion, it is possible to obtain the observed spin-up rate both in the WD and NS case, provided that the accretion rate is large enough. In Section 3.1, we will discuss whether this requirement is consistent with the observed X-ray flux and the implications for the nature of the compact object.

3.1 Nature of the compact companion star

As discussed above, in the case of a WD companion, it is very difficult to obtain the observed spin-up rate, unless an accretion disc is formed. This is more likely to happen if the mass donor is (nearly) filling its Roche lobe. The Roche lobe in this system has a radius $R_{\text{RL}} \sim 3 R_\odot$. Kudritzki & Simon (1978) estimated that the radius of HD 49798 is $R_{\text{HD}} = 1.45 \pm 0.25 R_\odot$, based on a distance $d = 650 \text{ pc}$. However, a larger distance is required in the WD interpretation (see below) and, considering that the estimated radius scales linearly with d , it is then possible that $R_{\text{HD}} \sim R_{\text{RL}}$.

The constraints on the magnetic field strength (equations (10) and (12)) are compatible with the values observed in weakly magnetized WDs (Ferrario, de Martino & Gänsicke 2015). For example, a magnetic field of $\sim 200 \text{ kG}$ would be sufficiently large to produce the required torque, yet giving $R_M < R_{\text{COR}}$. However, the luminosity corresponding to the minimum mass accretion rate given by equation (14) can be reconciled with the value derived in Section 2.2 only if the source distance is larger than $\sim 4 \text{ kpc}$ (unless the radiative efficiency of the accretion flow is particularly small or most of the accretion-powered luminosity is emitted in the unobserved far-UV range).

The distance of 650 pc, commonly adopted in the literature, was derived from the equivalent width of the Ca interstellar lines in the spectrum of HD 49798 (Kudritzki & Simon 1978) and, considering the Galactic latitude of this star ($b = -19^\circ$), it could be underestimated. The revised parallax of HD 49798, obtained with *Hipparcos*

(1.2 ± 0.5 mas), corresponds to a distance of 830 pc. However, this parallax measurement has a relatively small statistical significance and a distance up to 5 kpc is within the 2σ error.

If the compact companion of HD 49798 is an NS, the condition on the minimum accretion rate derived from the torque requirement (equation (15)) predicts an X-ray luminosity $L_X > 3 \times 10^{31}$ erg s $^{-1}$, consistent with the observations. The NS dipole field is constrained by equations (11) and (13), which, for example, lead to $2 \times 10^7 < B_{\text{NS}} < 3 \times 10^{10}$ G for $\dot{M} = 1.5 \times 10^{12}$ g s $^{-1}$ ($L_X = 2 \times 10^{32}$ erg s $^{-1}$). This field is rather low when compared to those usually found in accreting pulsars in high mass X-ray binaries (e.g. Revnivtsev & Mereghetti 2015) and might be related to the particular evolution leading to an NS with a hot subdwarf companion (Iben & Tutukov 1993). Another remarkable aspect of this X-ray binary is the stability of the spin-up rate, maintained for a time period longer than 20 yr. All the known accreting NSs in (high-mass) X-ray binaries show variations in their spin-period derivative (see, e.g. Chakrabarty et al. 1997, and references therein) and, to our knowledge, for none of them it has been possible to obtain phase-connected timing solutions spanning such a long time interval of steady spin-up.

Finally, we note that the large radius of the emitting area derived from the blackbody spectral fit, $R_{\text{BB}} \sim 40$ ($d/650$ pc) km, is also puzzling. Even allowing for the uncertainties in the best-fitting parameters (Fig. 3), this value is larger than the radius of an NS, while the high pulsed fraction suggests that the thermal emission originates from a relatively small fraction of the star.

4 CONCLUSIONS

By phase-connecting *XMM-Newton*, *Swift* and *ROSAT* observations spanning more than 20 yr, we have obtained the first measure of the spin-period derivative of the X-ray pulsar in the HD 49798/RX J0648.0–4418 binary system. Although the measured spin-up rate of 2.15×10^{-15} s s $^{-1}$ is rather large for an accreting WD, the lack of a precise distance measurement does not allow us to completely rule out this possibility and safely identify the compact object in this system with an NS.

The WD interpretation requires the presence of an accretion disc. This implies that the hot subdwarf is (nearly) filling its Roche lobe and/or that the distance and wind properties of HD 49798 are different from those derived from the optical/UV observations.

However, also the possibility that the compact companion of HD 49798 is an NS is not without problems. If confirmed, it would indicate a binary with properties very different from those of all the other known NS X-ray binaries. This could be related to the peculiar nature of the mass-donor star in this system, characterized by a stellar wind much weaker and with a different composition than those of ordinary OB stars.

A precise measurement of the distance, as will be obtained with the *Gaia* astrometric satellite, will make it possible to assess the nature of the compact object in HD 49798/RX J0648.0–4418. For example, a WD would be strongly disfavoured if the distance is smaller than ~ 4 kpc. In the meantime, it is worth to investigate better the properties of HD 49798 by applying state-of-the-art atmospheric and wind models to multiwavelength spectroscopic data of this unique star.

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