X-RAY AND OPTICAL OBSERVATIONS OF THE UNIQUE BINARY SYSTEM HD 49798/RX J0648.0–4418

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ABSTRACT

We report the results of XMM-Newton observations of HD 49798/RX J0648.0–4418, the only known X-ray binary consisting of a hot sub-dwarf and a white dwarf. The white dwarf rotates very rapidly (P=13.2 s) and has a dynamically measured mass of 1.28±0.05 M⊙. Its X-ray emission consists of a strongly pulsed, soft component, well fit by a blackbody with kT_{BB} ∼ 40 eV, accounting for most of the luminosity, and a fainter hard power-law component (photon index ∼ 1.6). A luminosity of ∼ 10^{32} erg s^{-1} is produced by accretion onto the white dwarf of the helium-rich matter from the wind of the companion, which is one of the few hot sub-dwarfs showing evidence of mass-loss. A search for optical pulsations at the South African Astronomical Observatory 1.9-m telescope gave negative results. X-rays were detected also during the white dwarf eclipse. This emission, with luminosity 2×10^{30} erg s^{-1}, can be attributed to HD 49798 and represents the first detection of a hot sub-dwarf star in the X-ray band. HD 49798/RX J0648.0–4418 is a post-common envelope binary which most likely originated from a pair of stars with masses ∼ 8–10 M⊙. After the current He-burning phase, HD 49798 will expand and reach the Roche-lobe, causing a higher accretion rate onto the white dwarf which can reach the Chandrasekhar limit. Considering the fast spin of the white dwarf, this could lead to the formation of a millisecond pulsar. Alternatively, this system could be a Type Ia supernova progenitor with the appealing characteristic of a short time delay, being the descendent of relatively massive stars.

Subject headings: binaries: close – subdwarfs: individual (HD 49798) – white dwarfs – X-rays: individual (RX J0648.0–4418)

1. INTRODUCTION

Interacting binaries containing accreting white dwarfs constitute a large fraction of the population of bright Galactic X-ray emitters. These systems, including both persistent and transient sources, display a rich variety of properties, determined mainly by the strength of the white dwarf’s magnetic field and the nature of the mass donor star (see, e.g., Kuulkers et al. [2006]). Most accreting white dwarfs are found in cataclysmic variables, where accretion proceeds through Roche-lobe overflow. The mass donor in these systems is typically a main sequence star or another white dwarf, but also sub-giant and giant companion stars have been observed. Symbiotic systems, where a white dwarf accretes from the stellar wind of a massive supergiant, have also been detected as X-ray sources.

The system discussed here is the only known X-ray binary composed by a white dwarf (RX J0648.0–4418) and a hot sub-dwarf star (HD 49798). Hot sub-dwarfs are evolved low mass stars that lost most of their hydrogen envelopes and are believed to be in the helium core burning stage (for a recent review on hot sub-dwarfs see Heber [2009]). They are spectroscopically classified in different types: sdB (with effective temperature T ∼ 25,000–28,000 K), sdOB (with T ∼ 33,000–40,000 K), and sdO (with T > 40,000 K). One possible mechanism responsible for the loss of their hydrogen envelopes is non-conservative mass transfer in a binary (Podsiadlowski & Han [2004]).

Being one of the brightest hot sub-dwarfs (apparent magnitude V=8.3), HD 49798 has been the object of several studies in the optical/UV wavebands. The first spectroscopic observations led to its classification as a sub-dwarf of O6 spectral type (Jaschek & Jaschek [1963]) and showed radial velocity variations, later found to be caused by orbital motion with a period of 1.55 days (Thackeray [1970]; Stickland & Lloyd [1994]). No spectroscopic evidence for a secondary could be found, leading to the early suggestion that the companion could be a white dwarf (Thackeray [1970]). Soft X-ray emission from the direction of HD 49798 was first detected with the Einstein Observatory in 1979, but it could be studied in detail only with a ROSAT satellite observation performed in 1992. The ROSAT data showed a very soft spectrum and led to the discovery of a strong modulation with a period of 13.2 s (Israel et al. [1997]). While the periodicity clearly indicated the presence of a compact object, the poorly constrained spectral fit resulted in a large uncertainty in the X-ray luminosity, making it impossible to distinguish between a neutron star and a white dwarf.

Thanks to a long observation carried out with the XMM-Newton satellite in May 2008, we could establish that the subdwarf’s companion is a white dwarf. Its X-ray luminosity, well constrained by the high quality XMM-Newton spectrum, is much smaller than that expected from a neutron star accreting in the stellar wind.
of HD 49798. The measurement of the X-ray pulse delays induced by the orbital motion, and the discovery of the X-ray eclipse, allowed us to derive the X-ray mass function and to constrain the system’s inclination. This information, coupled to the accurately measured optical mass function, gives the masses of the two stars: $M_{sd} = 1.50 \pm 0.05 \, M_\odot$ for the subdwarf HD 49798 and $M_{WD} = 1.28\pm0.05 \, M_\odot$ for its white dwarf companion RX J0648.0–4418 (Mereghetti et al. 2009). The main parameters of this binary system are summarized in Table 1.

RX J0648.0–4418 is one of the most massive white dwarfs currently known and the one with the shortest spin period. This binary is also particularly interesting since systems of this kind, where a massive white dwarf accretes from a helium star, have been proposed as possible progenitors of type Ia supernovae (Iben & Tutukov 1994; Wang et al. 2009). Here we report a comprehensive analysis of all the XMM-Newton observations and the results of a search for optical pulsations.

2. X-RAY DATA ANALYSIS AND RESULTS

XMM-Newton performed four short observations of RX J0648.0–4418 in 2002 and a longer one in 2008 (see Table 2). To look for possible variability, the 2002 pointings were taken at different orbital phases. Based on the orbital ephemeris of the system (Stickland & Lloyd 1994), the 2008 observation was scheduled to include the orbital phase 0.75, in order to look for the presence of an X-ray eclipse. This orbital phase was not covered by previous X-ray observations.

Here we concentrate on data obtained with the EPIC instrument (0.1–12 keV), consisting of two MOS and one pn CCD cameras (Turner et al. 2001; Strüder et al. 2001). During all the observations, the three cameras were operated in Full Frame mode (time resolution of 73 ms and 2.6 s for pn and MOS, respectively) and with the medium optical blocking filter. The data were processed using SAS version 9.0.

The source photons for the timing analysis were extracted from a circular region of 30″ radius and their arrival time corrected to the Solar System barycenter and for the orbital motion using the system parameters given in Table 1. The source spectra were extracted from a slightly smaller circle (20″ radius), in order to avoid possible contamination at high energy from a source of similar brightness and harder spectrum located 70″ away from RX J0648.0–4418. The spectra were rebinned to have at least 30 counts per energy channel and to oversample by a factor 3 the instrumental energy resolution. The background spectra were extracted from nearby regions, which were on the same chip as the source and where no sources were detected. Observation B was affected by high particle background, therefore we excluded it from the spectral analysis.

2.1. Variability

The background subtracted light curves of RX J0648.0–4418 in the total (0.1–10 keV), soft (0.1–0.5 keV), and hard (0.5–10 keV) energy ranges are plotted as a function of the orbital phase in Fig. 1 (pn) and Fig. 2 (sum of the two MOS). These figures clearly show that a significant flux is detected also during the X-ray eclipse, with net count rates of $(2.8\pm0.3) \times 10^{-2}$ counts s$^{-1}$ in the pn and $(1.7\pm0.2) \times 10^{-2}$ counts s$^{-1}$ in the sum of the two MOS. The presence of X-ray emission during the eclipse is confirmed by the image shown in Fig. 3 which was accumulated selecting events in the time interval corresponding to the eclipse.

Besides the variation due to the eclipse, the light curves shown in Figs. 1 and 2 indicate the possible presence of some variability. In particular, the count rates in September 2002 (obs.D) were slightly larger than in the 2008 observation, especially at energies above 0.5 keV. This variability is confirmed by the spectral analysis described below.

2.2. Spectral analysis

We first analyzed the X-ray emission detected during the eclipse, by extracting the pn and MOS spectra corresponding to the orbital phase interval 0.73–0.77. The three spectra were fitted together obtaining good results either with a power law with photon index $\Gamma = 2.8 \pm 0.3$ or with a thermal bremsstrahlung with temperature $kT_{Br} = 0.55^{+0.3}_{-0.2}$ keV ($\chi^2$/dof=17.2/16 and 24.7/16, respectively). In both cases we fixed the interstellar absorption to the value $N_H = 2.7 \times 10^{19}$ cm$^{-2}$ derived from the 2008 un-eclipsed pn data. The X-rays seen during the eclipse of the white dwarf are most likely due to emission from HD 49798, but even in the case of a different origin, we expect that this emission is present at all orbital phases. Therefore we included its contribution in all the subsequent fits to the non-eclipsed RX J0648.0–4418 emission.

The 2008 out-of eclipse pn and MOS spectra were extracted excluding the orbital phase interval 0.71–0.79 and fitted jointly with different models. Single component models gave unacceptable results, while good fits could be obtained with two-component models consisting of a blackbody plus either a power law or a thermal bremsstrahlung. The best fit parameters are summarized in Table 3. The results differ slightly from those we reported earlier (Mereghetti et al. 2009) due to the inclusion in the present analysis of the eclipse component. The blackbody component, which accounts for most of the flux, is similar in both models, with temperature $kT_{BB} \sim 40$ eV and bolometric luminosity $L_{BB} \sim 8 \times 10^{31}$ erg s$^{-1}$ (for $d=650$ pc). The hard component provides an additional luminosity of $\sim 8 \times 10^{30}$ erg s$^{-1}$ (0.2–10 keV, corrected for the absorption). To check whether the uncertainties in the eclipse spectrum affect the overall results, we repeated the analysis with different bremsstrahlung temperatures of the fixed component in the range $kT_{Br} = 0.3–0.8$ keV and found that the best fit values for the non-eclipse spectra change by less than 10%.

Also the spectra of the 2002 observations rule out single component models, but, owing to their lower statistics, the best fit parameters have larger uncertainties compared to those obtained from the 2008 data. To search for possible long term spectral variations we fitted the 2002 spectra using a power-law plus blackbody model
Fig. 1.— Background-subtracted orbital light curves of RX J0648.0–4418 obtained with the pn camera in three energy ranges: 0.1–10 keV (top), 0.1–0.5 keV (middle), and 0.5–10 keV (bottom). The labels indicate the five XMM-Newton observations listed in Table 2.

Fig. 2.— Same as Fig. 1, for the sum of the two MOS cameras.

with photon index, temperature, relative normalization, and absorption fixed at the 2008 best fit values. The eclipse component was always included, with all the parameters fixed as described above. For simplicity we restricted the comparison to the pn data, which are those with the smallest statistical uncertainties. The results are shown in Figures 4 and 5 referring respectively to the observations of 2002 May (A+C) and 2002 September (D). The residuals obtained in this way (middle panel of each figure) suggest that in September 2002 only the power law component was brighter than in 2008, while in May 2002 the largest residuals are in the low-energy part of the spectrum, where the blackbody component dominates. Allowing the power law normalization to vary in the September 2002 fit, we obtained good results with a power law flux \( \sim 30\% \) higher than in 2008 (see residuals in the lower panel of Fig. 5). For the May 2002 spectrum, we kept all the power-law parameters fixed and allowed the blackbody component to change. This resulted in a best fit temperature \( kT_{BB} = 31.6 \pm 0.2 \) eV and emitting...
**TABLE 1**

Main parameters of the HD 49798/RX J0648.0–4418 binary system

| parameter         | reference |
|-------------------|-----------|
| Orbital Period $P_{\text{orb}}$ | 1.5476666±0.0000022 days (1) |
| Eccentricity $e$ | 0 (2) |
| Inclination $i$ | 79–84$^\circ$ (1) |
| Distance $d$ | 650±100 pc (3) |

| HD 49798          |          |
|-------------------|-----------|
| Mass $M_{\text{sd}}$ | 1.50±0.05 $M_\odot$ (1) |
| Effective temperature $T_{\text{eff}}$ | 46,500 K (4) |
| Magnitudes $U=6.758$, $B=8.017$, $V=8.287$ (5) |
| Surface gravity $\log g$ | 4.35 cgs (4) |
| Radius $R_{\text{sd}}$ | 1.45±0.25 $R_\odot$ (3) |
| Luminosity $L$ | $3\times10^{37}$ erg s$^{-1}$ (3) |

| RX J0648.0–4418 |          |
|-----------------|-----------|
| Mass $M_{\text{WD}}$ | 1.28±0.05 $M_\odot$ (1) |
| Radius $R_{\text{WD}}$ | 3000 km |
| Luminosity $L_X$ | $10^{32}$ erg s$^{-1}$ |
| Spin period $P$ | $13.18425\pm0.00004$ s (1) |
| Period derivative $\dot{P}$ | $-5\times10^{-13}$ s s$^{-1}$ $< \dot{P} < 9\times10^{-13}$ s s$^{-1}$ |

*a References: (1) Mereghetti et al. (2009); (2) Stickland & Lloyd (1994); (3) Kudritzki & Simon (1978); (4) Hamann (2010); (5) Landolt & Uomoto (2007).*

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**TABLE 2**

Log of the X-ray observations of HD 49798/RX J0648.0–4418.

| Obs. | Date       | start-end (MJD) | Exposure | Orbital phase | Spin period (s) | Reference |
|------|------------|-----------------|----------|---------------|-----------------|-----------|
| A    | 2002 May 03 | 52397.46–52397.55 | 4.5 / 7.2 | 0.45–0.48    | 13.18421(7)$^{(a)}$ |           |
| B    | 2002 May 04 | 52397.98–52398.06 | 1.4 / 5.6 | 0.78–0.81    | –               |           |
| C    | 2002 May 04 | 52398.56–52398.59 | 0.6 / 2.5 | 0.15–0.16    | –               |           |
| D    | 2002 Sep 17 | 52534.58–52534.72 | 6.9 / 11.9 | 0.06–0.12    | 13.1856(14)    |           |
| E    | 2008 May 10-11 | 54596.90–54597.38 | 36.7 / 43.0 | 0.56–0.87 | 13.18425(4) |           |

*(a) Joint analysis of observations A, B, and C.*
radius $R_{BB} = 42.5 \pm 1.5$ km (see residuals in lower panel of Fig. 4). Table 4 summarizes all the parameters obtained in this analysis of the 2002 observations.

### 2.3. Timing analysis

A best fit pulse period $P = 13.18425 \pm 0.00004$ s was derived for the 2008 observation by Mereghetti et al. (2009). After correcting the times of arrival to the Solar system barycenter and for the effects of the orbital motion of the system, we searched for pulsations in the 2002 observations obtaining the values reported in Table 2. No long term variations in the spin period could be inferred by comparing the 2002 and 2008 values. A linear fit gives a 90% c.l. interval $-5 \times 10^{-13} \text{ s}^{-1} < \dot{P} < 9 \times 10^{-13} \text{ s}^{-1}$ for the period derivative.

The folded light curves at soft and hard X-rays are shown in Fig. 4. No significant variations are seen by comparing the 2002 and 2008 lightcurves. On the other hand, all datasets show a clear difference between the two energy ranges. The soft band, where the blackbody component dominates, has a nearly sinusoidal profile with a pulsed fraction of 56%. Above 0.5 keV the light curve is instead characterized by two peaks, of unequal intensity and out of phase with respect to the soft pulse.

### 2.4. Phase-resolved spectroscopy

On the basis of the spectral results presented above, clearly showing the presence of two distinct components, we performed phase-resolved spectroscopy choosing different phase intervals tailored to the light curves seen in the soft and hard energy ranges. We concentrate here on the 2008 data (excluding the eclipse). The 2002 data gave fully consistent, but less constrained, results, owing to their smaller statistics. In all the phase-resolved spectral fits discussed below we included the fixed eclipse component, as was done for the phase-averaged analysis.

We first searched for spectral variations as a function of the pulse phase in the soft component, by extracting four spectra corresponding to two pairs of phase intervals selected on the basis of the 0.1–0.5 keV pulse profile: pulse minimum/maximum (phases 0.25–0.65/0.65–1.25), and pulse decline/rise (phases 0.4–0.4–1). All the spectra were fitted with the power-law plus blackbody model keeping $N_H$ linked to a common value. The blackbody temperatures obtained in the four spectra were all consistent with the value $kT_{BB} \approx 40$ eV found in the phase-averaged spectrum. Acceptable $\chi^2$ values were obtained by forcing a common value of $kT_{BB}$ and fitting together the minimum and maximum or the rise and decline spectra. Thus we conclude that all the variations in the low energy pulse profiles can be interpreted as a change in the intensity of the blackbody component that remains at a constant temperature.

In order to investigate the phase dependence of the hard component, we extracted three spectra corresponding to the intervals marked in Fig. 4: first peak (P1, phases $0.15–0.35$), second peak (P2, phases $0.65–0.85$), and inter-peak (IP, phases $0.35–0.65$ and $0.85–1.15$). The three spectra were fitted with a blackbody plus...
### Table 3
Results of phase-averaged spectroscopy of the 2008 observation (pn+MOS)

|                    | Blackbody + Power law | Blackbody + Bremsstrahlung |
|--------------------|-----------------------|----------------------------|
| $N_H$ (cm$^{-2}$)  | $<2.4 \times 10^{19}$ | $<1.6 \times 10^{19}$      |
| $kT_{BB}$ (eV)     | $38.9^{+1.4}_{-1.2}$  | $40.0^{+1.1}_{-1.3}$       |
| $R_{BB}^{(a)}$ (km)| $17.9^{+3.2}_{-1.5}$  | $16.3^{+1.7}_{-1.9}$       |
| $\Gamma$           |                      | 1.6±0.1                    |
| $F_{PL}^{(b)}$ (erg cm$^{-2}$ s$^{-1}$) | $(1.7±0.1) \times 10^{-13}$ | – |
| $kT_{Brem}^{(c)}$ (keV) |                          | $7.9^{+2.7}_{-1.5}$       |
| $F_{Brem}^{(c)}$ (erg cm$^{-2}$ s$^{-1}$) | – | $(1.53±0.08) \times 10^{-13}$ |
| $L_{BB}$ (erg s$^{-1}$) | 8.9$\times 10^{31}$ | 8.2$\times 10^{31}$       |
| $kT_{Ecl}^{(a)}$ (keV) | 0.55$^{(a)}$ | 0.55$^{(a)}$            |
| $F_{Ecl}^{(c)}$ (erg cm$^{-2}$ s$^{-1}$) | 4.3$\times 10^{-14}$ ($^{(e)}$) | 4.3$\times 10^{-14}$ ($^{(e)}$) |
| $\chi^2$/dof       | 151.1 / 133           | 158.7 / 133               |

*a* Blackbody emission radius at infinity, for d=650 pc.

*b* Observed flux of the power law component 0.2-10 keV.

*c* Observed flux of the bremsstrahlung component 0.2-10 keV.

*d* Bolometric luminosity of the blackbody component, for d=650 pc.

*e* Fixed eclipse component

All the errors are at the 90% c.l. for a single interesting parameter

### Table 4
Spectroscopy results of the 2002 observations (pn data)

|                    | May 2002 (A+C)   | September 2002 (D) |
|--------------------|------------------|--------------------|
| $N_H$ (cm$^{-2}$)  | $2.7 \times 10^{19}(a)$ | $2.7 \times 10^{19}(a)$ |
| $kT_{BB}$ (eV)     | 31.6±0.2         | 39.6(a)            |
| $R_{BB}$ (km)      | 42.5±1.5         | 16.6(a)            |
| $\Gamma$           | 1.57(a)          | 1.57(a)            |
| $F_{PL}^{(b)}$ (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$) | 1.7(a) | 2.2±0.2 |
| $L_{BB}$ (erg s$^{-1}$) | 2.2$\times 10^{32}$ | 8.4$\times 10^{31}$ |
| $kT_{Ecl}$ (keV)   | 0.49(a)          | 0.49(a)            |
| $F_{Ecl}$ (10$^{-14}$ erg cm$^{-2}$ s$^{-1}$) | 4.2(a) | 4.2(a)   |
| $\chi^2$/dof       | 41.8 / 31        | 34.7 / 34          |

*a* Fixed

*b* Observed flux of the power law component 0.2-10 keV.

All the errors are at the 90% c.l. for a single interesting parameter
power law model, keeping absorption and temperature fixed to the phase averaged values obtained with the pn ($N_H=2.7\times10^{19}$ cm$^{-2}$ and $kT_{BB}=39.6$ eV). The results are given in Table 5. The spectrum during the first peak is slightly softer than at other phases, as shown by the confidence level contours for the power law photon index and normalization plotted in Fig 7.

3. SEARCH FOR OPTICAL PULSATIONS

We observed HD 49798/RX J0648.0–4418 with the University of Cape Town CCD photometer (O'Donoghue 1993) at the 1.9-m telescope of the South African Astronomical Observatory in Sutherland on December 25 and 27, 2009. The observations were carried out in the U filter, with a time resolution of 4 and 6 seconds, respectively. The first observing run lasted 29.1 minutes, the second run lasted 60.2 minutes.

A timing analysis of the optical data did not reveal any significant signal at, or close to, the frequency of the X-ray pulsations down to a level of 1.3 mmag (December 25), and 0.6 mmag (December 27). These limits correspond respectively to a pulsed flux of $1.5\times10^{-3}$ and $0.6\times10^{-3}$ photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ at 3600 Å, several orders of magnitude above the extrapolation to the optical U band of the X-ray blackbody spectrum. Even considering the low energy extrapolation of the power law seen during Peak 1, i.e. the spectral component with the steepest slope ($\Gamma=1.9\pm0.2$), gives a 3600 Å flux of a few $10^{-6}$ photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$, well below our upper limit. However, other mechanisms not directly related to the spectral components seen in X-rays might in principle contribute in the optical/UV band, and the above limit is the best currently available in the optical band for this pulsar.

| TABLE 5 | RESULTS OF PHASE-RESOLVED SPECTROSCOPY OF THE 2008 OBSERVATION (PN DATA) |
|---------|--------------------------------------------------|
| Peak 1  | Peak 2  | Inter-peak |
| $N_H(10^{19})$ (cm$^{-2}$) | $2.7\times10^{19}$ | $2.7\times10^{19}$ | $2.7\times10^{19}$ |
| $kT_{BB}(a)$ (eV) | 39.6 | 39.6 | 39.6 |
| $R_{BB}$ (km) | 15.1±0.8 | 17.0±0.7 | 16.6±0.4 |
| $\Gamma$ | 1.9±0.2 | 1.4±0.15 | 1.39±0.15 |
| $L_{PL}^{(b)}$ (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$) | 1.55±0.25 | 2.6±0.3 | 1.2±0.2 |
| $\chi^2$ / dof | 38.4 / 28 | 43.8 / 32 | 83.7 / 62 |

$a$ Fixed
$b$ Observed flux of the power law component 0.2-10 keV.
All the errors are at the 90% c.l. for a single interesting parameter

4. THE X-RAY EMISSION FROM RX J0648.0–4418

The results of X-ray observations with XMM-Newton spanning six years indicate that the properties of RX J0648.0–4418 are rather stable. Only minor changes were seen in the spectrum, but it is not possible at this stage to attribute them to the different orbital phases of the observations or to a long term variability. The spectrum and luminosity seen with XMM-Newton are consistent with those measured with ROSAT in 1992 and Einstein in 1979, although the uncertainties in the latter data are rather large. No significant variations were seen in the spin period, pulsed fraction and shape of the pulse profile. Given that this is the only known X-ray emitting binary composed of a hot sub-dwarf and a white dwarf, it is worth examining different possibilities for the origin of the observed X-ray emission.

The upper limit on the white dwarf secular spin-down ($\dot{P}<9\times10^{-13}$ s$^{-1}$), implies a rotational energy loss $I_{WD} \approx 2 \times 10^{-33}$ erg s$^{-1}$ (for a moment of inertia $I_{WD} = 10^{50}$ g cm$^2$). This is sufficiently high to power the observed luminosity of $\sim 10^{32}$ (d/650 pc)$^2$ erg s$^{-1}$, with an efficiency similar to that seen in rotation-powered neutron stars. Even if no convincing examples have been discovered, the existence of white dwarf analogues of rotation-powered neutron stars is an intriguing possibility (see, e.g., Usoskin 1998). Among isolated white dwarfs, even the one with the fastest rotational velocity (RE J0317–853, P=726 s, Vennes et al. 2003) can develop a maximum potential drop along open field lines of only $\Delta V = \frac{\Omega^2}{c^2} B^2 R^3 / c^2 \approx 7 \times 10^9$ (726 s/P)$^2$ (B/660 MG) (R/5000 km)$^3$ V, despite its high magnetic field (B=170–660 MG). This should be compared with the much higher value $\sim 10^{15}$–$10^{17}$ V typically reached in radio pulsars. White dwarfs in binary systems can rotate much more rapidly. After RX J0648.0–4418, the next fastest rotators are found in the dwarf nova W Sge (P=28.87 s, Patterson et al. 1998) and in the intermediate polar AE Aqr (P=33 s, Patterson 1979). Their magnetospheres can, in principle, accelerate particles to high energies, but still few orders of magnitude below that reached in radio pulsars. A value $\Delta V \sim 10^{14}$ V could be attained in RX J0648.0–4418, but only in the case of a strong magnetic field, which, as we discuss below, seems rather unlikely. The possible detection of pulsed hard X-rays (10–30 keV) in AE Aqr has been interpreted as evidence for non-thermal processes powered by the white dwarf rotational energy (Terasawa et al. 2008), implying an efficiency of $\sim 0.1\%$. AE Aqr spins-down at a rate of $5.6\times10^{-14}$ s$^{-1}$, most likely as a result of the magnetic propeller effect. Its K-type main sequence companion transfers mass trough Roche-lobe overflow, but the accretion stream is disrupted by the magnetic field of the white dwarf and most of the mass is ejected (Wynn et al. 1997). AE Aqr exhibits a hard X-spectrum and strong rapid variability at all wavelengths, contrary to RX J0648.0–4418 which shows a nearly constant flux, dominated by a thermal-like component. The significant differences, except for the short spin-period, between these systems disfavor the presence of a rotation-powered mechanisms in RX J0648.0–4418.

We believe that accretion provides a much more plausible and natural explanation for the X-ray emission observed from RX J0648.0–4418. The Roche lobe of HD 49798 has a radius $R_L \sim a (0.38+0.2 \log (M_{sd}/M_{WD})) = 3.2$ $R_\odot$, where $a=5.5 \times 10^{11}$ cm is the orbital separation. The sub-dwarf, with a radius $R_{sd}= (1.45\pm0.25) R_\odot$ (Kudritzki & Simon 1978), is significantly smaller than its Roche-lobe. Therefore, accretion can only occur via stellar wind capture. Hot sub-dwarfs have rel-

$^3$ Assuming a dipole field
at large distances from the white dwarf, channeling the starts to dominate the motion of the accreting matter in many cataclysmic variables of the polar and intermediate polar classes. In these systems, the magnetic field in RX J0648.0–4418 is similar to what is observed with the observed value. A more precise estimate of \( \dot{M} \) has been obtained thanks to a recent analysis of the optical/UV spectra based on improved wind models (Hamann 2010), but, as a first approximation, it can be described by a thermal bremsstrahlung with temperature \( kT \sim 30 \frac{M}{M_\odot} R_9^{-1} \) keV, where \( M \) is the white dwarf mass and \( R_9 \) its radius in units of \( 10^9 \) cm. Part of the hard X-ray emission may be intercepted and reprocessed by the white dwarf surface, giving rise to UV and soft X-ray thermal emission, with blackbody temperature of tens of eV. The relative importance of the soft and hard component depends on several factors, including geometrical effects, the white dwarf mass, magnetic field, accretion rate per unit surface, with the consequence that the observed values of the ratio \( L_{\text{soft}}/L_{\text{hard}} \) span a large range (Evans & Hellier 2007).

The value \( L_{\text{soft}}/L_{\text{hard}} \sim 10 \) observed for RX J0648.0–4418 is rather high, but not uncommon. For example, similar or larger values are found in EU UMa, DP Leo, and RX J1007–2016 (Ramsay & Cropper 2004). The blackbody temperature we derived for the soft component, as well as the dimensions of the emitting surface are well within the range of values measured for the polars. On the other hand, the best fit temperature of the bremsstrahlung component, \( kT_{BB} \sim 8 \) keV is rather small if one considers that, based on the relation mentioned above, massive white dwarfs should have the highest shock temperatures. This discrepancy might have to do with the unique properties of this white dwarf, which accretes from a low density stellar wind rather than through Roche-lobe overflow. The intensity and configuration of the magnetic field is also relevant for the properties of the X-ray emission, and might explain the differences between this system and classical cataclysmic variables. An upper limit on the dipolar field of RX J0648.0–4418 can be set by the requirement that its magnetospheric radius, \( R_M \), be smaller than the corotation radius \( R_{\text{COR}} = \left( \frac{GM_W}{P^2/4\pi^2} \right)^{1/3} = 9 \times 10^8 \)
cm. Since $R_M$ is defined by balancing the magnetic pressure and the ram pressure of the accreting matter, this translates in an upper limit on the white dwarf magnetic moment $\mu \sim 2 \times 10^{29}$ G cm$^3$. However, the above condition does not exclude the possibility that the source be in the sub-sonic propeller regime, in which $R_M < R_{COR}$, but the matter is too hot to accrete (Davies et al. 1979).

Using the equation that defines the transition between the accretion regime and the subsonic propeller regime (Bozzo et al. 2008), we obtain an upper limit $\mu < 3 \times 10^{28}$ G cm$^3$, corresponding to a field of the order of 1 kG at the white dwarf’s surface.

5. **HD 49798: THE FIRST X-RAY EMITTING HOT SUB-DWARF**

Early type stars emit X-rays with relatively soft thermal spectra ($kT \sim 0.5$ keV) and luminosity proportional to the bolometric luminosity. The average relation $L_X \sim 10^{-2} L_{bol}$ has been derived from the observations of main sequence, giant and supergiant stars of O spectral type. The X-ray emission is believed to originate from hot plasma heated by shocks and instabilities in the strong stellar winds of these stars (Pallavicini 1989). Despite their very high effective temperature, O type sub-dwarfs are much fainter than main sequence stars, and, up to now, X-ray observations provided only an upper limit of $\sim 10^{31}$ erg s$^{-1}$ for the sdO star BD $-$3°2179 (D’Antona et al. 1982).

The X-rays we detected during the eclipse are well described with a bremsstrahlung of temperature $0.5$ keV and luminosity $2 \times 10^{30}$ erg s$^{-1}$. Given the bolometric luminosity of HD 49798 $L_X \sim 10^{3.9} L_{bol}$, this corresponds to a ratio $L_X/L_{bol} = 7 \times 10^{-8}$. Thus, both from the spectral and luminosity point of view, the observed X-ray flux is consistent with emission from HD 49798. To our knowledge, this could be the first detection of X-ray emission from a sdO star. Further observations of this system, as well as searches for X-ray emission from other members of this class, can provide interesting information on the properties of X-ray production in stellar winds spanning a large range of parameters, from hot sub-dwarfs to supergiants.

6. **DISCUSSION**

HD 49798/RX J0648.0–4418 is the only known X-ray binary containing a massive white dwarf accreting from a hot sub-dwarf. In principle, other systems of this kind, with a luminosity of $\sim 10^{32}$ erg s$^{-1}$, could be detected even at distances of several kpc by the current X-ray satellites. However, due to the very soft spectrum, the observed flux is very sensitive on the amount of interstellar absorption. For example, a column density of $3 \times 10^{21}$ cm$^{-2}$ would reduce by one order of magnitude the observed EPIC count rate of RX J0648.0–4418, making it difficult to identify other sources of this kind in the Galactic plane only through X-ray observations (RX J0648.0–4418 is at Galactic coordinates l=254°, b=−19°).

On the other hand, also from the point of view of the optical properties, this system seems quite uncommon. In fact, HD 49798 is rather atypical compared to other sdO stars (Heber 2009), which on average are less massive (M=0.5 $M_\odot$), less luminous, and have a higher surface gravity. This is probably a result of its evolution in a close binary in which a common envelope phase occurred, as clearly indicated by several arguments. The low H abundance ($X_H \sim 0.19$, Kudritzki & Simon 1978), suggests that HD 49798 is the stripped core of an initially much more massive and larger star. Also the high abundance of N and low abundance of C confirm that its present surface layers once belonged to the outer part of the hydrogen-burning core of a massive star. Slightly different evolutionary scenarios have been proposed to explain this system.

One possibility is that HD 49798 descend from a fairly massive progenitor that began to fill its Roche lobe before helium ignition (Case B evolution) and is currently in a core He-burning phase (Kudritzki & Simon 1978; Iben & Tutukov 1993). In this case, the mass of the He star is related to that of its progenitor by $M_{He}=0.043 M_\odot$ (Iben & Tutukov 1985), implying that HD 49798 was originally a star of $\sim 8 M_\odot$. Two other possibilities have been considered by Bisscheroux et al. (1997).

The first one is that HD 49798 consist of a degenerate CO core, surrounded by a helium envelope with a He-burning shell at its base. In this scenario, it would be the core of a progenitor of $\sim 5 M_\odot$ which lost mass during a common envelope event when it was on the early asymptotic giant branch (AGB). Alternatively, HD 49798 could be burning hydrogen in a shell, being the remnant of a star which shed its envelope while on the thermally pulsing AGB. However, this possibility is disfavored since it predicts a mass of only $\sim 0.6 M_\odot$ for the sub-dwarf.

At the observed mass transfer rate, with only a small ($< 10^{-3}$) fraction of the total mass lost in the sub-dwarf’s wind accreted, the white dwarf mass is increasing very slowly. At the end of the current He-burning phase, HD 49798 will expand and fill the Roche-lobe, giving rise to a much higher mass transfer rate. This will produce a higher X-ray luminosity and possibly bright outbursts like the one seen in the helium nova V445 Puppis (Woudt et al. 2009), which could be the descendent of a system similar to HD 49798/RX J0648.0–4418. The amount of accreted mass, $\sim 0.3–0.5 M_\odot$ (see figure 1 of Iben & Tutukov 1993), is sufficient to bring the, already quite heavy, white dwarf above the Chandrasekhar limit. However, the fraction of mass that is effectively retained depends on the rate and composition of the accreting matter, on the mass, composition and temperature of the white dwarf, and on the poorly known relevance of other factors, such as, e.g., rotation, magnetic fields, wind outflows. Thus the fate of RX J0648.0–4418 is uncertain.

Evolutionary computations for RX J0648.0–4418 have been recently performed (Wang & Han 2010) assuming the mass accumulation efficiency that takes into account the wind mass loss triggered by the He-shell flashes (Kato & Hachisu 2004). These indicate that RX J0648.0–4418 will reach a mass of 1.4 $M_\odot$ after only a few 10 years of Roche-lobe overflow, during which $\sim (5–6)\times 10^{-6}$ $M_\odot$ yr$^{-1}$ of He-rich matter are steadily converted to C and O, while the unburned matter is ejected by the system through an optically thick wind. Wang & Han (2010) assumed that RX J0648.0–4418 is a CO white dwarf that will explode as a type Ia supernova when the Chandrasekhar limit is reached. The fast rotation can increase the mass stability limit above the standard value for non-rotating stars, thus systems
like RX J0648.0–4418 could be the progenitor of over-
luminous type Ia supernovae. While an ONe composi-
tion seems more likely for RX J0648.0–4418 in view of
its large mass, also in this case there are some uncer-
tainties and other factors that might play a crucial role.
For example, it has been pointed out that massive white
dwarfs can have a CO composition as a result of rapid
rotation (Domínguez et al. 1993, 1996).

If RX J0648.0–4418 is an ONe white dwarf, an accre-
tion induced collapse (AIC) might occur, instead than
a type Ia supernova explosion, leading to the formation
of a millisecond pulsar. There is strong evidence that
MSP are old neutron stars which underwent magnetic
field decay and spin-up due to accretion of mass and
angular momentum in low mass X-ray binary systems
(LMXRB) (Bhattacharya & van den Heuvel 1991). This
evolutionary scenario is supported by the observation of
short period X-ray pulsations in the persistent and/or
burst emission of several LMXRB, by the small eccen-
ctricity of MSP with white dwarf companions in the Galactic
disk (Archibald et al. 2009), and by the recent discovery of PSR J1023+0038
(Freire et al. 2011), the long sought missing-link be-
tween the LMXRB and MSP phase. On the other hand,
the formation of MSP by AIC of accreting white dwarfs
(e.g., Bailyn & Grindlay 1990) has been considered to
reconcile the apparent discrepancy in the birthrate of
LMXRB and MSP, and it cannot be excluded that a frac-
tion of the MSP population is formed through AIC.
The discovery of PSR J1903+0327, a Galactic plane
MSP with a high eccentricity orbit (e=0.44) around a
solar mass main sequence star (Champion et al. 2008;
Freire et al. 2011), gives further evidence for the possi-
bility of directly forming young MSP. The high spin rate
and low magnetic field of RX J0648.0–4418 make it an
ideal candidate for the direct formation of a MSP through
AIC.

7. CONCLUSIONS

HD 49798/RX J0648.0–4418 is a unique system, but its
X-ray properties are in several respects similar to those
seen in white dwarfs of the polar and intermediate po-
lar class. Its spectrum consists of a very soft, strongly
pulsed, thermal like emission plus a harder component
dominated above ~1 keV. The two components have
different pulse profiles and show small uncorrelated vari-
ations on long time scales. These similarities suggest
that the X-ray emission properties depend mainly on the
physical conditions near the white dwarf, with little influ-
ence of the large scale accretion scenario (wind accretion
in RX J0648.0–4418 wrt Roche lobe overflow in cata-
clysmic variables).

With a dynamically measured mass of 1.28±0.05 $M_{\odot}$,
RX J0648.0–4418 is one of the most massive white dwarf
currently known and the one with the shortest spin pe-
riod, only a factor ~5 larger than the break-up limit. It
is also the only known white dwarf accreting from the
wind of a hot sub-dwarf star. This system is the out-
come of a common envelope evolution, most likely of an
original pair of stars with mass of ~8–10 $M_{\odot}$. Its future
evolution might lead to the formation of a neutron star
through accretion induced collapse or to the explosion of
a type Ia supernova.

Both possibilities have interesting implications. Accre-
tion induced collapse of a fast-spinning and low magnetic
field white dwarf could be a promising scenario for the
direct formation of non-recycled millisecond pulsars. In
the second case, being the result of the evolution of rel-
atively massive stars (~8–9 $M_{\odot}$), this would be a type
Ia supernova formation channel with a short delay time.
Future X-ray and optical observations can lead to more
accurate determination of the system parameters, pro-
viding crucial information to investigate in more detail
the past and future evolution of this system. For exam-
ple, further observations of the orbital phases including
the eclipse can give a more precise measurement of its
duration, a better characterization of the X-ray emission
from HD 49798, as well as some information on the struc-
ture of its wind by measuring possible variations of $N_H$.
High-resolution spectroscopy of the soft X-ray spectral
component and deeper observations above a few keV are
needed to better compare the properties of this peculiar
X-ray binary with those of other accreting white dwarfs,
and, in particular, to better constrain the magnetic field
geometry and intensity.

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4 This is due to tidal circularization during the long LMXRB
phase; eccentric MSP binaries can be formed if the companion
is another neutron star that received a kick in the supernova explo-
sion in which it was born, or for systems formed in dense envi-
ronments where stellar dynamic interactions are important, like
globular clusters.
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