The discovery of a massive white dwarf in the peculiar binary system HD 49798/RX J0648.0–4418

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Abstract.

An XMM-Newton observation performed in May 2008 has confirmed that the 13 seconds pulsations in the X-ray binary HD 49798/RX J0648.0–4418 are due to a rapidly rotating white dwarf. From the pulse time delays induced by the 1.55 days orbital motion, and the system’s inclination, constrained by the duration of the X-ray eclipse discovered in this observation, we could derive a mass of 1.28 ± 0.05 M⊙ for the white dwarf. The future evolution of this post common envelope binary system will likely involve a new phase of mass accretion through Roche-lobe overflow that could drive the already massive white dwarf above the Chandrasekhar limit and produce a Type Ia supernova.

Keywords: White dwarfs, Type Ia SNe, Hot subdwarfs, Common envelope evolution

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INTRODUCTION

White dwarfs have masses in a narrow range centered at about 0.6 M⊙ (see, e.g., [1]), but a few examples of massive white dwarfs (>1.2 M⊙) have been reported [2, 3]. Massive white dwarfs in binary systems, where mass transfer can occur, are particularly interesting since they are good candidates for the formation of Type Ia supernovae.

Using data obtained with the XMM-Newton satellite, we have recently found compelling evidence [4] for the presence of a white dwarf with mass >1.2 M⊙ in the X–ray binary system HD 49798/RX J0648.0–4418. In the next section we describe the properties of this peculiar binary, composed of a 13 s X–ray pulsar orbiting a hot subdwarf star. We then briefly review the new XMM-Newton results and discuss some of their implications.

THE PECULIAR BINARY HD 49798/RX J0648.0–4418

HD 49798/RX J0648.0–4418 is the only known binary system composed of an early type subdwarf star and a pulsating X-ray source. The optical/UV emission from this system is dominated by the bright star HD 49798: with a V band magnitude of 8.3, this is the brightest known hot subdwarf. Extensive observations carried out since the time of its discovery led to classify it as a star of sdO5.5 type, and showed that HD 49798
FIGURE 1. Black solid line (left axis): Light curve of RX J0648.0–4418 in the 0.15–0.4 keV range showing an eclipse lasting 4700 s. The dashed line indicates the background level. Blue points (right axis): time delays of the pulsations measured at different orbital phases with the best fit sinusoid (red line). Inset: spin-period pulse profile in the 0.15–0.4 keV (P=13.18425±0.00004 s).

is a single-lined spectroscopic binary with orbital period $P_{\text{orb}} = 1.55$ days [5, 6]. The optical mass function could be measured with great precision, $f_{\text{opt}} = 0.263 \pm 0.004 M_{\odot}$ [7], but the nature of the companion star (unseen in the optical) remained obscure for decades.

The situation changed when the ROSAT satellite detected a strong flux of soft X-rays from this system and periodic X-ray pulsations at $P=13.2$ s were discovered [8]. This finding showed that the companion star is either a neutron star or a white dwarf. However, as discussed in [9] and confirmed by our new data [4], the X-ray luminosity is much smaller than that expected from a neutron star accreting in the stellar wind of HD 49798 [10], leading to the conclusion that RX J0648.0–4418 is a white dwarf.

**XMM-NEWTON RESULTS**

The presence of fast X-ray pulsations makes this system equivalent to a double spectroscopic binary, with the possibility to derive all the orbital parameters and, in particular, the masses of the two components. With this objective, we observed HD 49798/RX J0648.0–4418 for 44 ks on May 10-11, 2008 with XMM-Newton. Although four XMM-Newton observations were already performed in 2002, they are not particularly useful due to their very short duration [11]. Based on the well known optical ephemeris [7], the new observation was scheduled in such a way to include the
orbital phase at which an X-ray eclipse could be expected ($\Phi=0.75$), which previous X-ray observations did not cover. The 0.15–0.4 keV light curve (Fig.1), obtained with the EPIC instrument, clearly shows the presence of an eclipse lasting $\sim$1.3 hours. Since the radius of HD 49798 is known from optical observations ($R_C=1.45\pm0.25\ R_\odot$ [6]), the system inclination can be constrained from the duration of the eclipse using the relation $(R_C/a)^2 = \cos^2i + \sin^2i \sin^2\Theta$, where $a$ is the orbital separation and $\Theta$ is the eclipse half angle. This gives an inclination in the range 79–84$^\circ$.

From a timing analysis of the 13.2 s pulsations in the EPIC data it was also possible to measure the delays in the times of arrival of the pulses induced by the orbital motion (Fig. 1) and thus obtain the projected semi-major axis $A_X \sin i = 9.78\pm0.06$ light-s. This corresponds to an X-ray mass function $f_X = 0.419\pm0.008\ M_\odot$ that, combined with the optical mass function [7] and with the inclination derived above, yields the masses of the two stars: $M_X=1.28\pm0.05\ M_\odot$ for the white dwarf and $M_C = 1.50 \pm 0.05\ M_\odot$ for HD 49798. Independently of the radius of HD 49798, a firm lower limit of 1.2 $M_\odot$ (2$\sigma$ c.l.) on the white dwarf mass is obtained for $i=90^\circ$.

The X-ray emission from RX J0648.0–4418 is very soft. As shown in Fig.2 its spectrum can be fitted with the sum of a blackbody with temperature $kT = 39$ eV, contributing most of the observed flux, and a power law with photon index $\sim2$. For the distance of 650 pc, derived from optical observations [6], the X-ray luminosity in the 0.2-10 keV energy range is $\sim2\times10^{31}$ erg s$^{-1}$.

**DISCUSSION**

The above findings indicate that RXJ0648.0–4418 is one of the most massive white dwarfs currently known and the one with the shortest spin period. We note that most white dwarf masses are derived with indirect methods, such as surface gravity estimates obtained by spectral modelling, or the measurement of gravitational redshift. These methods, beside depending on models and assumptions, provide combined in-

**FIGURE 2.** X–ray spectrum of RX J0648.0–4418 as measured with the EPIC pn camera on XMM-Newton. Top panel: data points and best fitting model. Bottom panel: residuals from the model in units of standard deviations.
formation on mass and radius, hence the resulting masses cannot be used to determine independently the mass-radius relation. Our mass determination for RX J0648.0–4418 is directly based on a dynamical measurement, thus making this star an ideal target to better constrain the white dwarfs equation of state. The mass lower limit, coupled with the 13 s spin period, allows us to set an upper limit of 6000 km on the white dwarf’s radius, based only on simple rotational stability considerations [12].

The high mass and fast spin of RX J0648.0–4418 likely result from a previous evolutionary phase in which the accretion of mass and angular momentum took place at a much larger rate than currently observed. The accretion of mass down to the white dwarf surface implies that the magnetic dipole is \( \lesssim 10^{29} \left( \frac{M}{10^{-8} M_\odot} \right)^{15/16} \left( \frac{1350 \text{ km s}^{-1}}{V_{\text{WIND}}} \right)^{15/4} \) Gauss cm\(^3\), where we have normalized the wind mass loss \( \dot{M} \) and terminal velocity \( V_{\text{WIND}} \) to the values measured for HD 49798 [10]. A stronger magnetic field would prevent accretion through the onset of the propeller effect. Thus, HD 49798/RX J0648.0–4418 can be seen as a white dwarf analogous of low mass X-ray binaries in which weakly magnetic neutron stars are spun-up to short spin periods and shine as recycled millisecond radio pulsars when accretion onto them stops [13].

The future evolution of HD 49798 will probably lead to a new phase of unstable mass transfer through Roche-lobe overflow [14], during which the accretion of helium-rich material might push the already massive white dwarf above the Chandrasekhar limit and trigger a Type Ia supernova explosion.

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