X-ray pulsar HD 49798: a contracting white dwarf with a debris disk?

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ABSTRACT

HD 49798/RX J0648.0-4418 is a peculiar binary including a hot subdwarf of O spectral type and a compact companion in an orbit with an orbital period $P_{\text{orb}} = 1.55$ days (Thackeray 1970; Kudritzki & Simon 1978). When this source was discovered, it was the brightest hot subdwarf detected (Jaschek & Jaschek 1963), and is still one of the brightest hot subdwarfs so far (Mereghetti et al. 2011). Bisscheroux et al. (1997) suggested that an intermediate-mass star that entered into a common envelope while in the early AGB stage is the most likely progenitor of HD 49798.

Israel et al. (1995, 1997) detected a 13.2 s period X-ray pulse, which probably originated from the spin period ($P$) of a magnetic compact object accreting from the wind of a subdwarf, in which the wind loss rate is about $3 \times 10^{-9} M_{\odot}$ yr\textsuperscript{-1} (Hamann 2010). XMM-Newton data from 2002 to 2014 were used to derive a relatively low X-ray luminosity of $L_X \approx (1.3 \pm 0.3) \times 10^{32} (d/520 \text{ pc})^2$ erg s\textsuperscript{-1} ($d$ is the distance of the source, Mereghetti et al. 2016). Comparing the observed X-ray luminosity with the accretion luminosity estimated by the wind capture rate of the compact object, Israel et al. (1997) proposed that the X-ray pulsator is a neutron star (NS) rather than a white dwarf (WD). However, a very soft blackbody of temperature ($kT \sim 30$ eV), a hard power-law tail, and a large emitting area radius ($R_{\text{BB}} \sim 32 (d/520 \text{ pc}) \text{ km}$) derived from the blackbody spectral fit suggested a WD compact object (Mereghetti et al. 2009, 2011). Most recently, a relatively precise parallax obtained with Gaia EDR3 was used to measure the distance of this source to be $521 \pm 14$ pc (Gaia Collaboration 2020).

Based on data from the XMM-Newton satellite, Mereghetti et al. (2009) obtained an X-ray mass function and an orbital plane inclination angle ($79^\circ$–$84^\circ$) by detecting an eclipse in the X-ray light curve, and constrained the mass of the X-ray pulsator to be $1.28 \pm 0.05 M_{\odot}$, and the mass of the hot subdwarf to be $1.50 \pm 0.05 M_{\odot}$. Adopting the optically thick wind assumption, Wang & Han (2010) proposed that HD 49798/RX J0648.0-4418 could produce a type Ia supernova by accretion of a carbon oxygen (CO) WD in the future. Recently, Liu et al. (2015) argued that the X-ray pulsar companion of HD 49798 is a CO WD rather than an oxygen neon (ONE) WD according to a binary population synthesis simulation. If HD 49798 is accompanied by a NS, this source will appear as an ultraluminous X-ray source by the mass transfer triggered by Roche lobe overflow in the future, and will eventually evolve into a wide intermediate-mass binary pulsar (Brooks et al. 2017). Wu & Wang (2019) found that the WD would experience an off-center C burning and form a NS via iron core collapse supernova if the compact companion of HD 49798 is a CO WD. However, this source is unlikely to form a NS from an accretion-induced-collapse process if the compact object is a ONE WD (Liu et al. 2018).

Whether the X-ray pulsar companion of HD 49798 is a NS or a WD remains controversial. Mereghetti et al. (2016) performed a phase-connected timing analysis for XMM-Newton, Swift, and ROSAT data spanning more than 20 yr, and obtained a spin-period derivative of the X-ray pulsator of $P = (2.15 \pm 0.05) \times 10^{-15}$ s\textsuperscript{-1}. Recently, the compact companion was reported to be still spinning up at a steady rate of $P = (2.17 \pm 0.01) \times 10^{-15}$ s\textsuperscript{-1} according to the new XMM-Newton data.

Key words. white dwarfs – X-rays: binaries – stars: magnetic field – stars: evolution

1. Introduction

HD 49798/RX J0648.0-4418 is a peculiar binary, comprised of a hot subdwarf of O spectral type and a compact companion in an orbit with an orbital period $P_{\text{orb}} = 1.55$ days (Thackeray 1970; Kudritzki & Simon 1978). When this source was discovered, it was the brightest hot subdwarf detected (Jaschek & Jaschek 1963), and is still one of the brightest hot subdwarfs so far (Mereghetti et al. 2011). Israel et al. (1995, 1997) detected a 13.2 s period X-ray pulse, which probably originated from the spin period ($P$) of a magnetic compact object accreting from the wind of a subdwarf, in which the wind loss rate is about $3 \times 10^{-9} M_{\odot}$ yr\textsuperscript{-1} (Hamann 2010). XMM-Newton data from 2002 to 2014 were used to derive a relatively low X-ray luminosity of $L_X \approx (1.3 \pm 0.3) \times 10^{32} (d/520 \text{ pc})^2$ erg s\textsuperscript{-1} ($d$ is the distance of the source, Mereghetti et al. 2016). Comparing the observed X-ray luminosity with the accretion luminosity estimated by the wind capture rate of the compact object, Israel et al. (1997) proposed that the X-ray pulsator is a neutron star (NS) rather than a white dwarf (WD). However, a very soft blackbody of temperature ($kT \sim 30$ eV), a hard power-law tail, and a large emitting area radius ($R_{\text{BB}} \sim 32 (d/520 \text{ pc}) \text{ km}$) derived from the blackbody spectral fit suggested a WD compact object (Mereghetti et al. 2009, 2011). Most recently, a relatively precise parallax obtained with Gaia EDR3 was used to measure the distance of this source to be $521 \pm 14$ pc (Gaia Collaboration 2020).

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(Mereghetti et al. 2021). In principle, the accretion process of a compact object can result in a steady spin-up rate. The orbital separation of HD 49798 is about 8.0 $R_\odot$ (Mereghetti et al. 2009), and the effective Roche-lobe radius of the donor star can be estimated to be $\sim 3.1 R_\odot$ (Eggleton 1983). The radius of the subdwarf is 1.05 $\pm$ 0.06 $R_\odot$ (Krtička et al. 2019), and therefore it is impossible to transfer material by the Roche-lobe overflow. However, this source is a member of the few hot subdwarfs showing obvious evidence of stellar wind (Hamann et al. 1981; Hamann 2010). The observed spin-up rate favors a NS accretion showing obvious evidence of stellar wind (Hamann et al. 1981; Mereghetti et al. 2016); second, it is impossible to obtain such a large emitting area ($R_{\text{BB}} \sim 32$ km) fitted by the blackbody spectral; third, such a steady spin-up rate is difficult to interpret for a NS accretion from the stellar winds, in which variations of wind accretion rate and influence its spin period (Mereghetti et al. 2021).

If the compact companion of HD 49798 is a WD, it is very difficult to produce the observed spin-up rate by stellar wind accretion, unless disk accretion occurs (Mereghetti et al. 2016). Population synthesis simulations on hot subdwarf binaries also show that there are many more systems hosting WDs than systems hosting NSs (Yungelson & Tutukov 2005; Wu et al. 2018). Recently, Popov et al. (2018) provided a novel model, in which the contraction of a young WD with an age of $\sim 2$ Myr can successfully explain the observed spin-up rate. However, the wind accretion model predicted an X-ray luminosity of $L_X = 1.3 \times 10^{31}$ erg s$^{-1}$ (Krtička et al. 2019), which is one order of magnitude lower than the observed value $L_{X,\text{obs}} \approx (1.3 \pm 0.3) \times 10^{32}$ erg s$^{-1}$ (Mereghetti et al. 2016). Therefore, the nature of this peculiar X-ray source remains a puzzle. In this work, we propose an alternative model, invoking a debris disk to account for the observed X-ray luminosity.

### 2. Debris disk accretion model

Some hot WDs have been discovered to be surrounded by a debris disk; for example SDSS 1228+1040 (Gänsicke et al. 2006; Manser et al. 2019), SDSS J1043+0855 (Gänsicke et al. 2007), SDSS J0845+2257 (Wilson et al. 2015), and SDSS J1344+0324 (Li et al. 2017). Recently, the WD G29-38 was reported to be currently accreting planetary material from a debris disk based on X-ray observations by Chandra X-ray Observatory (Cunningham et al. 2022). Although the compact companion of HD 49798 is in a binary system, we assume that it was surrounded by a debris disk similar to these latter, isolated WDs.

The magnetic accretion process of the WD from a debris disk is tightly related to the magnetospheric (Alfvén) radius $r_m$, at which the ram pressure of the infalling material is balanced with the magnetic pressure. The magnetospheric radius can be written as (Davidson & Ostriker 1973)

$$ r_m = \xi \left( \frac{\mu^2}{2GM^2} \right)^{1/7}, \tag{1} $$

1 It is worth emphasizing that the wind accretion rate strongly depends on the wind velocity at the vicinity of the accreting WD (Krtička et al. 2019). Moreover, the effect of ionization by the X-ray flux might decrease the wind velocity, thus increasing the accretion rate (Sander et al. 2018; Krtička et al. 2018).

where $G$ is the gravitational constant, $\xi$ a dimensionless parameter of the order unity, $M$ the WD mass, $\mu$ the mass inflow rate at $r_m$ in the debris disk, and $\mu = B_0 R^2 / 2$ ($B_0$ is the surface dipole magnetic field), which is the dipolar magnetic momentum of the WD.

Taking $\xi = 0.52$ for the disk accretion case (Ghosh & Lamb 1979), and inserting some typical parameters in Eq. (7):

$$ r_m = 1.2 \times 10^9 M_{14}^{-2/7} M_{1.28}^{-1/7} M_{3.1}^{4/7} \text{ cm}, \tag{2} $$

where $M_{14}$ is in units of $10^{14}$ g s$^{-1}$, $M_{1.28}$ is in units of 1.28 $M_\odot$, and $M_{3.1}$ is in units of $10^3$ G cm$^{-3}$.

The observed X-ray luminosity of HD 49798 is $L_X \approx (1.3 \pm 0.3) \times 10^{32}$ erg s$^{-1}$ (Mereghetti et al. 2016). Ignoring the X-ray luminosity produced by the stellar wind accretion, the accretion rate (i.e., the mass inflow rate at the inner edge of the debris disk) of the accreting WD in HD 49798 can be estimated to be

$$ \dot{M} = \frac{L_X}{GM} \approx (2.3 \pm 0.5) \times 10^{14} \text{ g s}^{-1}, \tag{3} $$

where $R$ is the WD radius. In this work, we take $R = 3000$ km.

Whether a debris disk around the WD could provide such an accretion rate is unclear. After a debris disk forms, the accretion rate should decrease self-similarly in accordance with $\dot{M} \propto t^{-\alpha}$ due to the influence of viscous processes (Cannizzo et al. 1990). In our debris disk model, an evolutionary law of the accretion rate similar to that of Chatterjee et al. (2000) is adopted as follows:

$$ \dot{M} = \begin{cases} M_0, & t < T \\ M_0(t/T)^{-\alpha}, & t \geq T, \end{cases} \tag{4} $$

where $T$ is of the order of the dynamical timescale in the inner regions of the debris disk, and $M_0$ is a constant accretion rate. The initial mass of the disk can be written as

$$ M_{d,i} = M_0 T \int_T^{\infty} M_0(t/T)^{-\alpha} dt. \tag{5} $$

Therefore, we have $\dot{M}_0 = (\alpha - 1) M_{d,i} / (\alpha T)$ if $\alpha > 1$ (Chatterjee et al. 2000). The dynamical timescale in the inner regions of the debris disk is given by

$$ \tau_{\text{dyn}} \sim \sqrt{\frac{r_m^3}{GM}} \approx 2 \left( \frac{r_m}{10^9 \text{ cm}} \right)^{3/2} \left( \frac{1.28 M_{3.1}}{M} \right)^{1/2} \text{ s}. \tag{6} $$

In the following calculations, we take $T = 1$ s and $\alpha = 19/16$, meaning that the opacity is dominated by electron scattering (Cannizzo et al. 1990).

To account for the observed spin-up rate, Popov et al. (2018) proposed that the compact companion of HD 49798 is a contracting WD with a cooling age of $\sim 2$ Myr. Similar to G29-38, we also assume that RX J0648.0-4418 experienced accretion for 10% of the cooling age (Jura 2003b), that is, the age of the debris disk is $t_0 = 2 \times 10^5$ yr. To explain the observed X-ray luminosity, the accretion rate from the debris disk should be $\dot{M} = 2.3 \times 10^{14}$ g s$^{-1}$ when $t = t_0 = 2 \times 10^5$ yr, hence the evolution of the accretion rate when $t \geq T$ satisfies

$$ \dot{M} = 2.3 \times 10^{14} \left( \frac{t}{2 \times 10^5 \text{ yr}} \right)^{-19/16} \text{ g s}^{-1}. \tag{7} $$

This yields $\dot{M}_0 = 3.6 \times 10^{30}$ g s$^{-1}$ from Eqs. (4) and (7), and the initial mass of the debris disk is estimated to be $M_{d,i} \approx 0.001 M_\odot$. 

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according to Eq. (5). The current mass of the debris disk is derived to be
\[
M_{\text{d,c}} = \int_{t_0}^{\infty} M_0 (t/T)^{-19/16} \, dt \approx 3.9 \times 10^{-6} M_\odot.
\]  
(8)

If the gas-to-dust ratio is 100 (Jura 2003a), the current dust mass of the debris disk is \(M_{\text{dust}} \approx 3.9 \times 10^{-8} M_\odot\).

For reference, we also calculate the debris-disk mass of G29-38 using this model. The current accretion rate of G29-38 is about \(1.63 \times 10^9\) g s\(^{-1}\) (Cunningham et al. 2022), and it has been actively accreting for \(4 \times 10^7\) yr, that is, \(t_0 \approx 40\) Myr (Jura 2003b). Therefore, the accretion rate from the debris disk is \(\dot{M} = 1.63 \times 10^8 (t/40\text{Myr})^{-19/16}\) g s\(^{-1}\). Similar to Eq. (8), the current debris-disk mass can be estimated to be \(5.5 \times 10^{-9} M_\odot\), which is not in contradiction with the minimum disk mass of \(\approx 10^{-10} M_\odot\) estimated by Jura (2003b). Based on three-dimensional radiation-hydrodynamics stellar-atmosphere models, Cunningham et al. (2021) roughly estimated the debris-disk lifetimes around WDs to be \(\log(t/\text{yr}) = 6.1 \pm 1.4\). Therefore, the debris-disk age of G29-38 is probably overestimated. If so, the current disk mass predicted by our model will correspondingly decline.

Taking \(M = 1.28 M_\odot\) and \(R = 3000\) km, the X-ray luminosity of the WD accreting from the debris disk can be derived from \(L_X = G M M / R\) and Eq. (7). Figure 1 plots the evolution of X-ray luminosity (we ignore the radius change of the WD in the contraction stage). It is clear that a WD accreting from a nascent debris disk can appear as a luminous X-ray source (\(\sim 10^{38}\) erg s\(^{-1}\)) with a lifetime of up to 2 yr, which is similar to a black hole accreting from the fallback disk in ultraluminous X-ray sources (Li 2003). However, its maximum X-ray luminosity is difficult to exceed \(\sim 10^{38}\) erg s\(^{-1}\) due to the Eddington luminosity \(L_{\text{Edd}} = 1.9 \times 10^{38}\) ergs s\(^{-1}\) (if the accreting material is hydrogen, King & Lasota 2019). With the decline in the mass infall rate, the magnetospheric radius will firstly exceed the corotation radius, and the accreting WD transitions to a lower X-ray state that lacks X-ray pulsation (Campana et al. 2016). Subsequently, the magnetospheric radius will exceed the light cylinder radius \(R_c = c P/2\pi\), and produce radio emission (Illarionov & Sunyaev 1975; Campana et al. 1998). According to the critical luminosity of WDs transitioning from accretion to the propeller regime, as determined by Campana et al. (2018), the accreting WD of HD 49798 will transition to the propeller phase if the accretion luminosity declines to the limiting luminosity \(L_{\lim} = 0.7 \times 1.4 \times 10^{32}\) erg s\(^{-1}\), which depends on the dipolar magnetic momentum of the accreting WD\(^2\).

Similar to NSs, the spin evolution of WDs depends on the interaction between magnetic field lines and disk plasma, which can give rise to a continuous exchange of angular momentum between the WD and the disk. If the magnetospheric radius is smaller than the corotation radius (at which the Keplerian angular velocity is equal to the spin angular velocity of the WD), \(r_{\text{co}} = \sqrt[3]{\frac{G M P^2}{4 \pi^2}} = 9.1 \times 10^5 M_{1.28}^{1/3}\) cm, \(r_{\text{co}}\)

the WD accretes the specific angular momentum of material at \(r_{\text{co}}\).

The maximum accretion torque receiving by the WD is \(T_{\text{acc}} = G M v_G M / r_{\text{co}}\). Therefore, the maximum spin-up rate of the WD due to accretion from a debris disk can be expressed as
\[
\dot{I} = \frac{P^2 M v_G M}{2 \pi I} \approx -1.1 \times 10^{-17} \frac{P_{13.2}^2 M_{14} M_{28}^{2/3}}{I_{30}^{1/3}} \text{ s}^{-1},
\]  
(10)

where \(I_{30}\) is the moment of inertia of the WD in units of \(10^{30}\) g cm\(^2\), \(P_{13.2} = P/13.2\) s. For some typical parameters, the maximum spin-up rate produced by accretion from the debris disk is between one and two orders of magnitude lower than the observed value. Therefore, accretion from a debris disk can indeed account for the observed X-ray luminosity, while it cannot produce the detected spin-up rate of HD 49798/RX J0648.0–4418.

Figure 2 shows the evolution of the spin-period derivative produced by the accretion from the debris disk. According to our assumption, the debris disk should exist when the WD age is in the range of 1.8 Myr–2.0 Myr. Comparing with Fig. 2 in Popov et al. (2018), \(P\) produced by the debris disk is smaller than that resulting from the WD contraction for the debris-disk age \(t = 5000\)–\(2 \times 10^3\) yr. However, a young (with an age of less than 5000 yr) debris disk plays an important role in influencing the spin evolution of the WD.

To support a steady accretion, the inner radius of the debris disk (i.e., the magnetospheric radius \(r_m\)) should satisfy the following relation:
\[
R < r_m \leq r_{\text{co}}.
\]  
(11)

Taking \(M_{1.28} = 1\) and \(M_{14} = 2.3\), the dipolar magnetic moment of the WD can be constrained to
\[
0.1 < \mu_{30} < 0.9.
\]  
(12)

Therefore, the surface dipolar magnetic field of the WD is in the range of \((0.7–7) \times 10^4\) G.

For a magnetic WD, the accretion flow along the magnetic field lines would form an accretion column inside the polar cap (Shapiro & Teukolsky 1983). The polar cap opening angle of the last open field line is (Ruderman & Sutherland 1975)
\[
\theta_{\text{open}} = \sqrt{\frac{R}{R_{1,\text{LC}}}},
\]  
(13)
where $R_{LC} = cP/2\pi$ is the radius of the light cylinder. Therefore, we can estimate the polar cap radius of the WD in HD 49798 to be

$$R_{dp} \approx R \sqrt{\frac{\frac{1}{2}}{R_{LC}}} = 200P_{13.2}^{-1/2} \text{ km.}$$

This radius is six times as large as the observed radius of the emitting area $R_{EB} \approx 32(d/520\text{pc})$ km at a distance of 520 pc (Mereghetti et al. 2016; Gaia Collaboration 2020).

Although the estimated polar cap radius is larger than the radius of the emitting zone derived from the black body spectral fit, it is already noted that the radius $R_{dp}$ of the conventional polar cap is ten times larger than that of the radiation area in the neutron star field (Hermsen et al. 2013; Szary et al. 2017; Geppert 2017). Strong and small-scale local magnetic field structures in the polar cap surface were thought to be responsible for the small radius $R_{pc}$ of the polar cap (Szary et al. 2015; Sznajder & Geppert 2020). According to the magnetic flux conservation law, if the magnetic field at the polar cap of the WD $B_{p} = 36B_{s} = (2.5–25) \times 10^{3}$ G, the small radius of the emitting zone can be easily understood.

### 3. Summary and Discussion

Stellar wind accretion from the hot subdwarf is insufficient to produce the observed X-ray luminosity of HD 49798 (Křížek et al. 2019). In this work, we propose an alternative model to account for the observed X-ray luminosity of HD 49798. If the compact companion of HD 49798 is a WD surrounded by a debris disk, by the interaction between the magnetic field and the debris disk, the accretion flow along the magnetic field lines could produce an accretion column on the polar cap of the WD, thereby naturally resulting in the observed X-ray pulses. Based on the model of time-varying accretion from a debris disk given by Chatterjee et al. (2000) and the observed X-ray luminosity, the initial mass and the current mass of the debris disk are constrained to be $–0.001M_{\odot}$ and $3.9 \times 10^{-6}M_{\odot}$, respectively. Based on the accretion theory, the surface magnetic field of the WD is constrained to be $B_{s} = (0.7–7) \times 10^{3}$ G, while the small polar cap zone requires a relatively strong local magnetic field ($B_{p} = (2.5–25) \times 10^{3}$ G) to account for a small emitting area. The accretion torque exerted by the proposed debris disk can only influence the spin evolution of the WD when the debris-disk age is less than 5000 yr, and its effect is obviously smaller than that caused by the contraction of the WD in the current stage. Therefore, the debris disk cannot spin the accreting WD up to the observed rate in the current stage, which should arise from a change of the moment of inertia of the WD at the contraction stage (Popov et al. 2018).

The black body spectral fit for HD 49798 infers a radius of the emitting area of $R_{BB} \approx 32(d/520\text{pc})$ km (Mereghetti et al. 2016). This emitting area should be the real polar cap zone resulting from the accretion column on the surface of the WD. However, our calculated polar cap radius is 200 km. The difference between the real polar cap zone and the theoretical value probably originates from strong and small-scale local magnetic field structures in the polar cap surface (Szary et al. 2015; Sznajder & Geppert 2020).

The debris disks around some isolated WDs probably originate from the tidal disruption of either comets (Debes & Sigurdsson 2002) or asteroids (Jura 2003b). Our scenario predicts a heavy debris disk with a mass of $~10^{-6}M_{\odot}$, which is four orders of magnitude higher than that in the WD G29-38 (Jura 2003b). This mass discrepancy should arise from different origins of the debris disks. As HD 49798 may experience a common envelope evolutionary phase (Bisscheroux et al. 1997), the debris disk around the WD may originate from the engulfment of the progenitor envelope of the hot subdwarf. For example, the engulfment of a low-mass companion star of HD 233517 when it evolved into a red giant resulted in a heavy debris disk of $~0.01M_{\odot}$ (Jura 2003a). However, it is challenging to confirm the debris disk by detecting the infrared excess from RX J0648.0–4418 as in G29-38. First, the distance of RX J0648.0–4418 is greater than that of G29-38 by a factor of 40; second, the detected radiation flux from the debris disk should be low due to a large orbital plane inclination angle$^{3}$ (79°–84°, Mereghetti et al. 2009). On the other hand, a low X-ray state of RX J0648.0–4418 or a spin-down rate, if detected in the future, could be used to confirm the existence of a debris disk. We expect that further multiband observations of this source could help us to confirm or rule out the existence of a debris disk.

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$^{3}$ The debris disk should be in the same plane as the orbital plane if it comes from the engulfment of the progenitor envelope of the hot subdwarf in the common envelope stage.
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