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The nature of the bright subdwarf HD 49798 and its X-ray pulsating companion

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Abstract. An analysis of the observed properties of the subdwarf O6 close binary system HD 49798 and its 13.18 s ultrasoft X-ray pulsating companion (WGA J0648.0-4418) is presented. On evolutionary grounds we show that the subdwarf must have a degenerate CO core and is in the phase of shell helium burning, which explains its high luminosity. The subdwarf, which probably has a mass between $0.7 - 1.3M_{\odot}$, is the descendant of a massive asymptotic giant branch star that lost its hydrogen-rich outer layers in a common-envelope event. We show that all observations are consistent with the X-ray source being a weakly magnetized massive white dwarf which is accreting matter from the wind of its subdwarf companion. We exclude a neutron star companion on the ground of (1) the ultrasoft spectrum of the X-ray source; (2) the very close resemblance of the X-ray spectrum and luminosity with that of the soft intermediate polars; (3) the relative closeness of HD 49798, which implies a Galactic birthrate of such systems that is much larger than that of binary pulsars with a massive white dwarf companion, the natural descendants of systems like HD 49798 if the pulsar in this system were a neutron star.

Key words: stars: individual: (HD 49798) – binaries: close – stars: evolution – subdwarfs – white dwarfs – X-rays: stars

1. Introduction

HD 48798 is a single-lined spectroscopic binary with an orbital period of 1.55 d (Thackeray 1970, Stickland & Lloyd 1994). This hydrogen-deficient subdwarf of spectral type O6 is one of the brightest subdwarfs and has been studied extensively (Kudritzki & Simon 1978, Hamann et al. 1981). In the HR-diagram O subdwarfs generally are near the blue end of the horizontal branch. They are believed to be evolved objects on or just off the horizontal branch with cores nearly as massive as their total mass (Thejll et al. 1994, and references therein). Because of

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its close binarity HD 49798 has an unusual position among the subdwarfs and, as we will show, a different evolutionary history as well.

Recently, Israel et al. (1995) reported the detection of regular X-ray pulsations with a period of 13.18 s from this binary. The X-ray spectrum of the source is very soft, but has a high-energy excess. Clearly the X-ray pulsations must arise from a compact companion, either a neutron star or a white dwarf.

In this paper we discuss the possible nature of this companion and the evolutionary history of the system. The hydrogen-deficient nature of HD 49798 shows that this star is the stripped core of an initially much more massive star. The overabundance of N and underabundance of C shows that its present surface layers have been processed by the CNO-cycle, implying that they belonged to the (outer part of the) hydrogen burning core of a massive star, when this star was on the main-sequence. This, in combination with the short orbital period of the binary, implies that the star lost practically all of its hydrogen-rich envelope in a common-envelope phase which resulted in spiral-in.

In Sect. 2 we discuss the constraints on the masses of both components and the evolutionary history of the binary. The nature of the compact companion is discussed in Sect. 3.

2. The mass and evolutionary history of the sdO6 star HD 49798

2.1. The mass of the subdwarf

From spectroscopic and photometric observations, Kudritzki & Simon (1978; hereafter KS78), derived the atmosphere parameters, radius, distance and luminosity of the star, as listed in Table 1.

The upper limit to the radius and luminosity are derived from the upper limit to the distance, which has been estimated from the strength of interstellar lines. The lower limit to its radius follows from the assumption of corotation of the star with its orbit, which subsequently sets the lower limit to the distance and luminosity.

Table 1. The parameters of HD 49798 as derived from a fine-analysis of its spectrum.

$$\begin{aligned} T_e &= 47500 \pm 2000 \text{ K}^a \\ \log g &= 4.25 \pm 0.20^a \\ R_* &= 1.45 \pm 0.25 R_\odot^a \\ \log L/L_\odot &= 3.95 \pm 0.25^a \\ d &= 650 \pm 100 \text{ pc}^a \end{aligned}$$

$$(v \sin i)_{rot} = 45 \pm 5 \text{ km/s}^a$$

Surface abundances (mass fraction):

$$\begin{aligned} X_H &= 0.19; X_{He} = 0.78^a \\ X_N &= 0.025; X_{Si} = 0.001^b \\ X_C &< 0.05 X_{C,\odot}^c \end{aligned}$$

$$P_{orb} = 1.548 \text{ d}^d$$

$$e = 0^d$$

$$f(m) = 0.263 \pm 0.004 M_\odot^d$$

^a Kudritzki & Simon (1978)

^b Simon et al.(1980)

^c Gruschinske et al.(1980)

^d Stickland & Lloyd (1994)

The mass function, $f(m) = 0.263 M_\odot$, has lately been re-determined by Stickland & Lloyd (1994), after including IUE observations of the subdwarf. Once the mass of the compact star M_c and the orbital inclination i of the system are known, one can derive the mass of the subdwarf M_{sd} . The relation between the masses of the two stars for several inclinations is shown in Fig. 1. The mass function yields:

$$\left(\frac{M_{sd}}{M_c} + 1 \right) = \sqrt{\frac{M_c \sin^3 i}{f(m)}} \quad (1)$$

The absence of eclipses, together with $R \geq 1.2 R_\odot$ (see Table 1) and an orbital radius of between 6 and $8 R_\odot$ (for the masses involved) puts an upper limit on the inclination: $i < 82^\circ$ for $M_c = 1.4 M_\odot$ and $i < 79^\circ$ for $M_c = 0.8 M_\odot$, which in Fig. 1 is indicated with the solid line.

From the assumption of corotation we can further limit the possible mass range. As then both the rotational period of the star and its maximum radius are known we also know its minimum rotational velocity. If we assume the axis of stellar rotation to coincide with that of the orbit, combination with the upper limit of $(v \sin i)_{rot}$ yields a lower limit to the inclination of 56° . In combination with the lower limit to the radius, together with $\log g \geq 4.05$, it results in a lower limit to the subdwarf mass of $0.58 M_\odot$. In the figure these limits are indicated by the dot-dashed line. We shall see below that the subdwarf is probably slightly more massive, at least $\sim 0.7 M_\odot$, as it must be able to produce the observed luminosity. This in turn gives a lower limit to the companion's mass of $0.88 M_\odot$.

To produce the observed rapid regular X-ray oscillations, an accreting magnetized compact object which is rotating rapidly

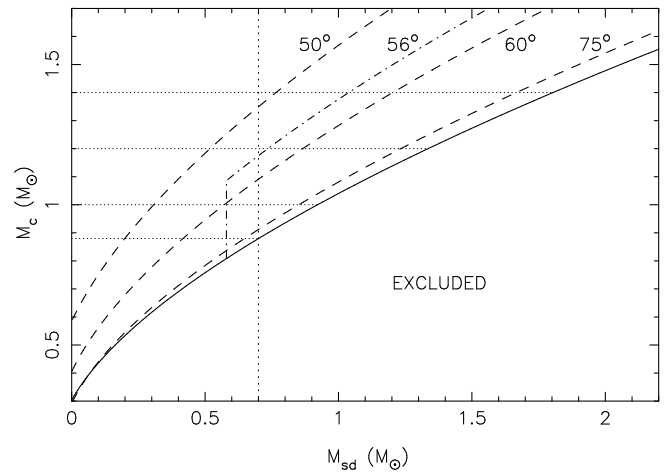


Fig. 1. Companion mass versus subdwarf mass, as found from the massfunction $f(m) = 0.263 M_\odot$ of HD 49798. The solid line indicates the maximum mass of the subdwarf for a given companion mass corresponding to the maximum inclination for which eclipses are absent ($\sim 80^\circ$). Dashed lines relate the masses for several inclinations (50° , 60° , 75°). The dot-dashed line denotes the minimum inclination (56°) and minimum subdwarf mass ($0.58 M_\odot$) under the assumption of corotation (see text). The heavy dotted line gives the minimum subdwarf mass which follows from its lower luminosity limit. Fine dotted lines give some possible companion star masses.

must be involved. For a neutron star companion of $1.3 - 1.4 M_\odot$ the mass of the subdwarf is in the range $0.85 - 1.8 M_\odot$ and for a white dwarf companion of mass $0.9 - 1.2 M_\odot$ the mass of the subdwarf is probably between 0.7 and $1.3 M_\odot$.

2.2. Evolutionary status of the subdwarf

Table 1 shows that the star, even though it is 'sub-luminous', has a very high bolometric luminosity: $L \approx 10^4 L_\odot$. It also has, for a subdwarf, an unusually low surface gravity, $\log g \approx 4.25$.

It has been suggested (KS78, see also Iben & Tutukov 1993, hereafter IT93) that HD 49798 is the helium-burning core of a star that has lost its envelope in a case B mass transfer event, i.e. before helium was ignited at the tip of the first giant branch (FGB). However, these authors have actually assumed the subdwarf to have a rather high mass of ($\sim 1.7 - 2 M_\odot$) for which there is now no good reason, as Fig. 1 shows. As we shall see in Sect. 2.3, with the implied smaller mass, a case B progenitor is highly unlikely to have produced the present orbit of the binary system. A comparison with stellar models – e.g. by De Greve & De Loore (1976), and unpublished models computed with a recent version of the Eggleton (1971) stellar evolution code – further reveals that it is unlikely that the subdwarf is in a core helium-burning phase. Models of core He-burning stars with approximately the observed surface hydrogen abundance of $X_H \approx 0.20$ and $M \lesssim 1.8 M_\odot$ are much more compact ($\log g \gtrsim 5.3$ and $R \lesssim 0.5 R_\odot$) and less luminous ($\log L/L_\odot \lesssim 3.6$) than is observed.

Table 2. Summary of the results of the calculations by Iben & Tutukov (1993) for stripped EAGB cores. Columns give: initial mass on the EAGB; assumed final Roche-lobe radius after spiral-in; remnant mass after spiral-in; time during which a H-rich envelope is present; mass-loss rate during the H-rich phase; and growth of the C-O core mass during the H-rich phase.

M_i (M_\odot)	R_L (R_\odot)	M_{rem} (M_\odot)	Δt (10^5yr)	$\log(\frac{\dot{M}}{M_\odot/\text{yr}})$	M_{CO} (M_\odot)
4.0	0.5	0.75	10	-8.2	0.45 – 0.55
	5.0	0.76	14	-7.9	0.45 – 0.73
5.0	0.5	0.97	4	-8.0	0.49 – 0.56
	5.0	0.99	8	-7.6	0.49 – 0.68
6.0	0.5	1.22	4	-7.5	0.51 – 0.62
	5.0	1.30	7	-7.0	0.51 – 0.74

Therefore, two possibilities remain to explain the evolutionary status of the subdwarf. First, the star may be in a *shell* helium-burning phase, which would explain both its low surface gravity and its high luminosity. Such stars follow an approximate core-mass luminosity relation (see IT93), and the luminosity of $\log(L/L_\odot) = 3.7 - 4.2$ is consistent with the presence of a CO core of $\sim 0.65 - 0.8 M_\odot$. The high luminosity is generated by a He-burning shell around a degenerate CO core, surrounded by a thick ($0.05 - 1.0 M_\odot$) He envelope.

A shell He-burning subdwarf with a mass in the range between $0.7 M_\odot$ and $1.8 M_\odot$ fits very well with the core of a star which originally was on the early asymptotic giant branch (EAGB), where it had a mass between $\sim 4 M_\odot$ and $7 M_\odot$. After being stripped of its hydrogen-rich envelope in a common-envelope (CE) event, the remaining cores have luminosities, masses and radii in the range inferred above for HD 49798, as can be seen from the evolutionary tracks of such stripped EAGB star cores calculated by IT93. The relevant results of IT93 are summarized in Table 2. At present HD 49798 has a Roche radius of $2.5 - 3 R_\odot$, in between the values considered in the models of IT93. After stripping, these stars still have some hydrogen in their envelope, of order $0.01 M_\odot$, which in the calculations is subsequently lost by Roche-lobe overflow (RLOF) in a time between 4×10^5 and 1.4×10^6 yr. However, mass loss by stellar wind was not included in the calculations, and as IT93 point out, a radiation-driven wind could easily drive a somewhat larger mass-loss rate. This would prevent the remnant from filling its Roche lobe, as is the case with HD 49798. We shall return to the mass loss rate in Sect. 3.3, where we consider wind accretion onto the compact companion. After all hydrogen has been removed, these cores will continue to lose helium at a much higher rate by RLOF, until less than about $0.04 M_\odot$ of helium is left. Then they will shrink and cool into white dwarfs.

Alternatively, the subdwarf might be the core of a star which lost its H-rich envelope while on the thermally pulsing (TP) AGB. In this case the star should presently be shrinking and become a white dwarf, having only very recently shed its envelope in a CE phase. The luminosity is then provided (mainly) by shell-hydrogen burning, below a very thin hydrogen envelope.

Its present luminosity and mass should be nearly equal to the luminosity and core mass of its TP-AGB progenitor, which are related by the Paczyński (1970) core-mass luminosity relation. From the observed effective temperature and gravity, one can also determine the present luminosity-to-mass ratio: $\log(L/M) = 3.85 \pm 0.2$, in solar units. Combination of these two relations would limit the subdwarf mass to very low values, $0.6 - 0.65 M_\odot$.

There are two reasons why we favor the first possibility, i.e. a shell He-burning star. Firstly, the evolutionary timescale is up to 2 orders of magnitude longer (up to $\sim 10^6$ yr, as opposed to $\lesssim 10^4$ yr in the case of a shell H-burning proto-white dwarf). Secondly, because of the short time since CE ejection, one would expect the ejected envelope to be ionized by the hot subdwarf and to show up as a planetary nebula. Although some extended emission has been observed around HD 49798, this is believed to be unassociated with the star (Mendez et al. 1988).

We show in the following section that the present orbital period of the system implies that the progenitor must indeed have been on the asymptotic giant branch, most likely on the EAGB.

2.3. The progenitor system of HD 49798

With a present mass of $> 0.7 M_\odot$ the progenitor must have been either more massive than $4 - 5 M_\odot$, or have had a deep convective envelope, or both. Since the companion is a compact object of $\leq 1.4 M_\odot$, mass transfer would inevitably have led to the formation of a common envelope.

In order to trace back the evolution we therefore use the ‘Webbink-formalism’ for calculating the decrease in orbital radius during CE-evolution. Denoting the initial and final orbital radii as a_i and a_f , respectively, one has in this formalism (Webbink 1984, 1992):

$$\frac{a_f}{a_i} = \frac{M_c M_{1f}}{(M_{1f} + M_{1e})} \frac{1}{(M_c + 2M_{1e}/\eta\lambda r_i)} \quad (2)$$

where M_c is the mass of the compact companion, M_{1f} the mass of the core of the progenitor prior to spiral in, M_{1e} the mass of its envelope, η the ‘efficiency parameter’ for CE evolution, λ a parameter which depends on the density distribution in the envelope of the progenitor, and r_i the fractional Roche lobe radius of this progenitor prior to spiral in.

As discussed by Van den Heuvel (1994), η has a value that from an analysis of observed post-CE systems, in combination with results of numerical computations (Taam 1996), is expected to be in the range between 1 and 4 (implying an α parameter in the ‘Iben-Tutukov formalism’, e.g. see Iben & Livio (1993), of between 0.3 and 1.0). In fact, η -values > 1 imply that apart from the orbital binding energy, other sources of energy were available in the envelope of the giant for expelling this envelope, e.g. thermal energy, recombination energy, and pulsational energy. The thermal energy of the envelope is formally neglected in the ‘Webbink-formalism’, and its inclusion as an energy source reduces the envelope binding energy by a factor of about 0.5 (if atomic and molecular recombination energy is

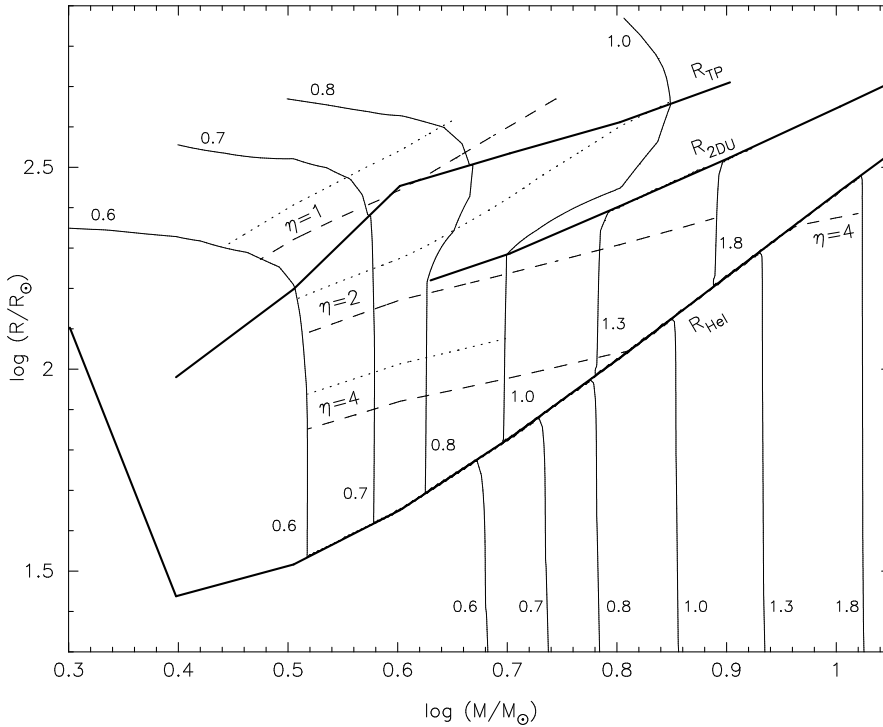


Fig. 2. Possible progenitor masses and radii of the subdwarf component of HD 49798. The dashed and dotted lines indicate, as a function of initial mass, the initial Roche-lobe radius that the progenitor should have had in order to obtain the present orbit, for the indicated values of the CE efficiency parameter $\eta = 1, 2$ and 4 . Dashed lines are for a companion mass $M_c = 1.4 M_\odot$; dotted lines are for $M_c = 1.0 M_\odot$. We have calculated these curves using Eq. (2) and assuming the remnant mass after CE evolution to be equal to the helium (H-exhausted) core mass. Thick solid curves are the stellar radii at helium ignition (R_{HeI}), at the start of the TP-AGB (R_{TP}), and at the start of the second dredge-up ($R_{2\text{DU}}$), as a function of initial mass. Thin solid curves are lines of constant He core mass (defined as the mass shell interior to which $X_{\text{H}} \leq 0.1$), for core masses between 0.6 and $1.8 M_\odot$, as indicated. These values for core masses and radii are taken from a set of evolution tracks computed by Pols et al. (1995).

not included in the thermal energy). Hence, in the absence of other energy sources, the maximum value of η is 2. On the FGB and on the EAGB, η can therefore not be much larger than 2, but on the TP-AGB it may well be > 2 . For the sake of argument, to trace back the original system of HD 49798, we will consider the ‘extremes’ $\eta = 1$ and $\eta = 4$.

We can now use Eq. (2) to compute the initial Roche-lobe radius $R_L = r_i a_i$ that the progenitor of HD 49798 should have had to produce the present orbital separation a_f (which is in the range $6 - 8 R_\odot$, see Sect. 2.1), as a function of progenitor mass $M_1 = M_{1e} + M_{1f}$, and for certain values of M_c and η . This requires knowledge of the helium core mass M_{1f} as a function of mass and stellar radius. We take the radii and core masses from a set of evolutionary calculations computed with the Eggleton (1971) code for single stars with $Z = 0.02$, $X = 0.7$, as described by Pols et al. (1995). The calculations by IT93 indicate that, after a CE event on the EAGB, the remnant mass is only slightly larger than the helium core mass. The remnant masses which we would infer from the core masses of the stellar models indeed correspond within a few per cent with those computed by IT93. Inspection of the stellar models also shows that the typical value of λ for a massive FGB star is $0.6 - 0.7$, while for an AGB star it is $0.7 - 0.9$, the larger value applying to more evolved stars. We use a value of $\lambda = 0.7$ throughout in computing the initial Roche radii. We compute r_i with the formula of Eggleton (1983).

The results are shown in Fig. 2, where we have plotted, as a function of progenitor mass, the progenitor’s Roche radius R_L as computed above, for values of η between 1 and 4 and for $M_c = 1.0$ and $1.4 M_\odot$. These can be compared with the stellar radii at core helium ignition, R_{HeI} , and at the start of the TP-

AGB, R_{TP} . Mass transfer starts on the EAGB if R_L is between these values, on the FGB if $R_L < R_{\text{HeI}}$, and on the TP-AGB if $R_L > R_{\text{TP}}$. Also shown are lines of equal core mass, indicating the range of possible progenitor masses. For instance, an EAGB progenitor could have had a mass between 3.8 and $7.5 M_\odot$ in the case of a $1.4 M_\odot$ neutron-star companion, but only between 3.8 and $5.0 M_\odot$ in the case of a $1.0 M_\odot$ white dwarf.

It is clear from Fig. 2 that, for any possible combination of progenitor mass and companion mass, and for any reasonable value of η , the progenitor of HD 49798 should have been on the AGB. In particular, we see that an FGB (i.e. case B) progenitor could almost certainly not have produced the present orbital radius of the system, since a value $\eta \gtrsim 4$ would have been required. These FGB stars have relatively smaller core masses, so that a curve of constant η lies at larger radius than for an EAGB progenitor. Even for the largest possible stellar radius on the FGB ($\sim 280 R_\odot$ for a $\sim 10 M_\odot$ progenitor, which would give a $1.8 M_\odot$ He-burning remnant), a value $\eta \sim 4$ would be required. An even larger η is necessary for a smaller progenitor mass (see, however, below).

Fig. 2 also shows that if the progenitor of HD 49798 was on the TP-AGB, the progenitor mass should have been $\lesssim 3.5 M_\odot$ since, as we saw in Sect. 2.2, in that case the subdwarf mass is $\lesssim 0.65 M_\odot$. Furthermore, the CE efficiency should have been small, $\eta \lesssim 1$, in order to produce the present orbit. However, especially a TP-AGB star might be expected to have $\eta > 1$, i.e. to have extra energy sources available for envelope ejection, since such a star is eventually capable of doing so without the help of a companion.

Also plotted in Fig. 2 is the radius $R_{2\text{DU}}$ at the start of the second dredge-up on the EAGB, when the convective envelope

starts to eat into the helium core for stellar masses $\gtrsim 4.5 M_{\odot}$. If $R_L > R_{2DU}$, the remnant of CE evolution may have only a short-lived phase during which a H-rich envelope is present, since the helium core of such a progenitor is already rapidly expanding (which is the very reason for the penetration of the convective envelope). Therefore one may expect the CE remnant to enter quickly into a stage of Roche-lobe overflow at rather high mass-loss rate, during which helium rather than hydrogen is transferred, such as occurs in the later phases of the calculations of IT93. Although no calculations have been done for this case, it seems likely that the progenitor of HD 49798 had a Roche radius $< R_{2DU}$ (if its mass was $\gtrsim 4.5 M_{\odot}$), since HD 49798 has a H-rich atmosphere and is not filling its Roche lobe.

Finally, it appears from Fig. 2 that the progenitor of HD 49798 must already have evolved some way up the EAGB before the CE phase, since even the $\eta = 4$ curve is well above the R_{HeI} line. This is consistent with its present luminosity and inferred CO-core mass (see Sect. 2.2), which are somewhat higher than those of the IT93 models (see Table 2). These models were calculated for progenitors that had just reached the base of the EAGB.

Two potentially important effects are not included in the calculations and in the discussion above: (1) convective-core overshooting during the main sequence, and (2) stellar-wind mass loss prior to Roche-lobe filling. Both effects (if present) will reduce the envelope mass relative to the core mass, and therefore facilitate CE ejection. In other words, a smaller value of η would be required to produce the present orbit. Convective overshooting may increase the core mass by as much as 25% (Maeder & Meynet 1989), and also somewhat increases the stellar radii at He-ignition and at the start of the TP-AGB. On the EAGB, and especially on the TP-AGB, stellar winds during preceding phases (e.g. core helium burning on the giant branch) may have further reduced the envelope mass. However, stellar winds cannot reduce the envelope mass substantially before He ignition, since the FGB phase is rather short-lived in these intermediate-mass stars. Consequently, an FGB progenitor of even the largest mass would still require $\eta \gg 2$, even if one makes reasonable allowance for both effects (overshooting and mass loss). As we have argued above, η is probably $\lesssim 2$ on the FGB, so that we remain confident that a case B progenitor is extremely unlikely to have produced the present orbit of HD 49798.

We conclude that, regardless of whether the compact star is a neutron star or a white dwarf, and for any reasonable value of η , the progenitor of the subdwarf component of HD 49798 was on the AGB, in all likelihood the EAGB. This implies that at present this star has a degenerate CO-core and is in the phase of shell helium burning, which is consistent with the high luminosity of HD 49798.

3. Is the companion a neutron star or a white dwarf ?

3.1. The ROSAT observation

In November 1992 the companion of HD 49798, listed in the WGA Catalogue as J0648.0-4418 (White et al. 1994), has been observed with the ROSAT PSPC (0.1-2.4 keV). Israel et al. (1995) found the signal to be modulated with a period of 13.18 s and an energy independent pulsed fraction of about 60 %.

In order to obtain information on the possible spectral parameters, we analyzed the PSPC data, extracted from the ROSAT archive. The total net exposure time is 5453 seconds. In the extraction of the source photons, care was taken to exclude possible contamination from a nearby (1'2) unrelated weak source. The background was estimated from a source-free nearby region. The source spectrum is soft, but a weak hard component, which cannot be attributed to contamination from the weaker source, is clearly visible. We fitted the spectrum to a combination of a blackbody (for the soft component) and thermal Bremsstrahlung (for the hard component). Given the weakness and limited spectral coverage of the hard component, we fixed the temperature of the Bremsstrahlung component to 10 keV, which is an average temperature, and used in similar cases (Haberl & Motch 1995). From the fact that the two components dominate in different regions of the spectrum, it is certain that the results on the blackbody component are not heavily affected by the specific choice of the model for the hard component.

As is always the case with soft PSPC spectra with unknown column absorption, the two spectral parameters blackbody temperature kT_{bb} and absorption column density N_{H} are not well determined, since they are strongly correlated with each other. In Fig. 3 the 90% χ^2 contour level for kT_{bb} and N_{H} is shown. The accepted region is open on the low-temperature side, so the only firm constraint on the basis of the goodness of fit comes from the high-temperature side. From this constraint ($kT_{\text{bb}} = 52$ eV, $N_{\text{H}} = 8 \times 10^{19} \text{ cm}^{-2}$) we derive $L_{\text{bb}}^{\text{bol}} > 8 \times 10^{31} \text{ erg/s}$ and a blackbody radius $R_{\text{bb}} > 8 \text{ km}$. On the low-temperature side the luminosity can only be constrained by the value of the Eddington limit of 10^{38} erg/s , above which accretion is not possible. To obtain such a high luminosity at low temperature, the emitting area must be large: $R_{\text{bb}} > 10^4 \text{ km}$. Also plotted are the luminosity levels (dotted lines) and the different radii for the blackbody emission (assuming a distance of 0.65 kpc). The luminosity of the hard component, under the assumption of a Bremsstrahlung temperature of 10 keV is in the range $3 - 5 \times 10^{30} \text{ erg/s}$.

The observation of pulsations in this X-ray source puts limits on the size of the emitting area, as it must be self-occulted by the compact object. If the soft component in the spectrum is well represented by a blackbody, we can constrain the luminosity at high values. For a neutron star it turns out that it would be located at the right end of Fig. 1, with $L_{\text{bb}} \lesssim 10^{32} \text{ erg/s}$ and $T_{\text{bb}} \sim 50 \text{ eV}$, implying an extremely low accretion rate (see Chapt 3.3).

In case of a white dwarf the radius would be $\sim 6000 \text{ km}$ and thus the luminosity should be below 10^{35} erg/s , corresponding to a blackbody temperature above $\sim 15 \text{ eV}$. A white-dwarf spectrum however, might not be represented satisfactorily by a

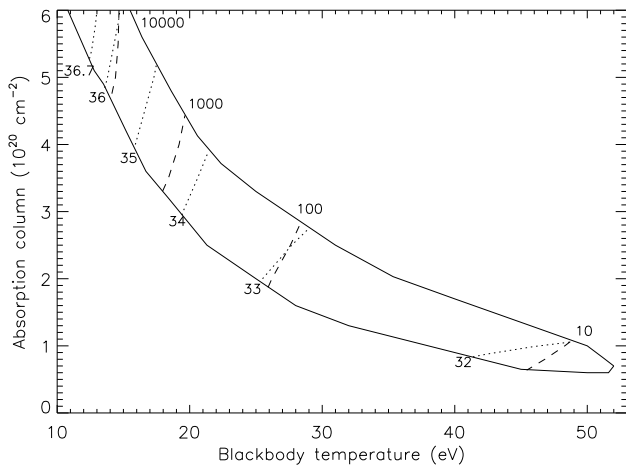


Fig. 3. The 90% confidence contour (solid line) for a grid of absorption column N_H against blackbody temperature kT_{bb} , calculated for a model which combines a blackbody with a fixed thermal Bremsstrahlung component of $kT_{Brems} = 10$ keV, for a distance of 0.65 kpc. The 60% and 95% confidence levels are very close, and have been left out to keep the figure clear. The dotted lines are of constant bolometric blackbody luminosity (in logarithmic units). The dashed lines are radii of the emitting surface in km, corresponding to the blackbody luminosity L_{bb} of the soft component.

blackbody, as Heise et al. (1994) showed in their calculations of spectra from model atmospheres. They found about one order of magnitude lower X-ray luminosity at the same temperature. As we shall see later this result is very important if the compact object is a white dwarf. Then such a model atmosphere would fit well with an “accretion spot” at the magnetic pole of the white dwarf.

3.2. Soft intermediate polars

The fast pulse period, reflecting the spin period of the compact object, suggests that it is a neutron star, but if we compare the X-ray spectrum with that of other X-ray pulsars, we note that not one neutron star is known with such a huge soft component and weak hard spectral tail.

The X-ray spectrum is, however, remarkably similar to the spectra of soft intermediate polars (Haberl & Motch 1995). They show a soft component with $kT_{bb} \sim 40 - 60$ eV and a weak hard tail (which they fix at $kT_{Brems} = 10$ keV). The distances and thereby the luminosities of the sources reported by Haberl & Motch are not well known. The general idea about intermediate polars is that they are magnetized white dwarfs which have their magnetic axes misaligned with their rotational axes. The accreted matter will be funnelled onto the polar caps by the magnetic field, thus giving rise to a rotating “hot spot” which may be occulted by the white dwarf itself. They have luminosities in the range $10^{30} - 10^{33}$ erg/s.

In a subgroup of the intermediate polars, the DQ Herculis systems, one finds very rapidly spinning white dwarfs. It appears that the shortest period systems tend to have the softest X-ray

spectra (Patterson 1994). Their magnetic fields are, in general, not very strong, $\sim 10^4 - 10^5$ Gauss, as the radius of the magnetopause should be smaller than about the radius of a Keplerian orbit with $P = P_{spin}$. The shortest spin period so far found in these systems is that of AE Aquarii, which has $P = 33$ s (Patterson 1979). The observed ROSAT spectrum of this source, consisting of a large soft component and a weak hard tail (Clayton & Osborne 1996), is similar to that of HD 49798 / WGA J0648.0-4418. The timing analysis of the latter is presently being done by Israel et al. (in prep) and might reveal more similarities. It thus appears that the X-ray spectrum and luminosity of this source are fully consistent with that of a rapidly rotating weakly magnetized white dwarf. This would make this the fastest spinning white dwarf observed so far.

3.3. Accretion from wind of the subdwarf

If the upper limit of the distance to HD 49798 is correct, the radius of the subdwarf is less than $1.7 R_{\odot}$ (KS78) and hence smaller than the smallest possible Roche lobe for its mass range. As in this case the X-ray luminosity cannot be caused by accretion due to Roche-lobe overflow, we will consider accretion from a stellar wind.

Modelling of the wind parameters of this subdwarf presents a number of problems. The velocity of the wind has been estimated by Hamann et al. (1981) and Bruhweiler et al. (1981). Hamann et al. found from the P-Cygni profile of N V a value of 1350 km/s, although they had to locate this maximum velocity, which is normally reached at infinity, at a distance of $1.7 R_{*}$ from the star. This could mean that the ionisation fraction of N V drops to zero at that distance, with the wind still being accelerated further out. Bruhweiler et al. found, apart from the wind indicated by the N V profile (they report 1500 km/s), a low velocity wind, < 500 km/s, from the N IV profile as well.

Springmann & Pauldrach (1992) show from calculations that in hot thin winds radiative decoupling of H and He from the heavier elements is likely to occur. They suggest that this effect is important for this subdwarf as well, like in τ Sco for which they calculate a reduction of 40% in H- and He-wind velocity. This would mean that the velocity of the bulk of the wind matter may be as low as 800 km/s.

The amount of mass lost in wind has also been estimated by Hamann et al. (1981). Their lower limit of $10^{-9.3} M_{\odot}/\text{yr}$ is estimated with the aid of a wind model, but since wind theory has changed substantially since 1981, the limit might change if newer models were used. Their upper limit of $10^{-8} M_{\odot}/\text{yr}$ is based on the assumption that the stellar atmosphere is approximately in hydrostatic equilibrium. This last estimate only indicates an order of magnitude for the mass-loss rate and does not exclude an upper limit which is three times as high (W.R. Hamann 1996, private communication).

On the other hand, from the evolutionary calculations by IT93 we see that a shell-burning star, in the allowed mass range, must lose matter at a rate $\sim 10^{-8} - 10^{-7} M_{\odot}/\text{yr}$ to stay within its Roche lobe (see Table 2). As HD 49798 is definitely inside its Roche lobe we conclude that the mass-loss rate must be about

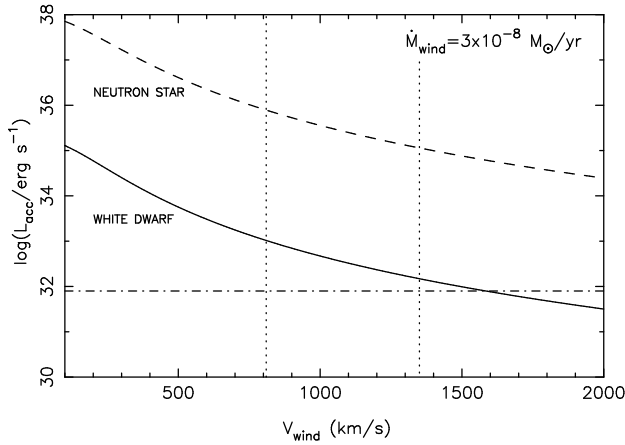


Fig. 4. Expected luminosity from wind accretion as function of wind velocity near the compact star, as follows from the Bondi-Hoyle formalism with $\dot{M}_{\text{wind}} = 3 \times 10^{-8} M_{\odot}/\text{yr}$. The dashed line is for a $1.4 M_{\odot}$ neutron star with $R = 10 \text{ km}$ and $a = 8 R_{\odot}$, the solid line for a $1 M_{\odot}$ white dwarf with $R = 6000 \text{ km}$ and $a = 7 R_{\odot}$. The lower limit of the luminosity ($8 \times 10^{31} \text{ erg/s}$) of the X-ray source is indicated with the dot-dashed line. Dotted lines indicate wind velocities discussed in the text.

$10^{-8} M_{\odot}/\text{yr}$ for the low mass models and up to $10^{-7} M_{\odot}/\text{yr}$ for the most massive ones. We will adopt a rate $\dot{M}_{\text{wind}} = 3 \times 10^{-8} M_{\odot}/\text{yr}$, which is consistent both with the spectroscopic analysis and the evolutionary models.

We can make an estimate of the amount of mass \dot{M}_{acc} captured from the wind by the gravitational field of the compact star, and of the luminosity L_{acc} , due to the release of potential energy in the process of accretion, by using the Bondi-Hoyle formalism as described by Davidson & Ostriker (1973):

$$L_{\text{acc}} = \frac{GM_c}{R_c} \dot{M}_{\text{acc}} \quad ; \quad \dot{M}_{\text{acc}} = \frac{G^2 M_c^2 \dot{M}_{\text{wind}}}{a^2 v_{\text{rel}}^4} \quad (3)$$

Here G is the constant of gravitation, M_c and R_c the mass and radius of the compact object, a the orbital separation, \dot{M}_{wind} the mass lost in the wind of the subdwarf and v_{rel} the relative velocity of the compact star and the wind.

The accretion rate \dot{M}_{acc} , and therefore also the luminosity, strongly depends on the relative wind velocity ($L_{\text{acc}} \propto v_{\text{rel}}^{-4}$). A reduction of 40%, from 1350 km/s to 810 km/s, as mentioned in Springmann & Pauldrach (1992) for a similar stellar wind, would already increase the luminosity with more than a factor 7. The relation between L_{acc} and v_{wind} is shown in Fig. 4, for both a neutron star and a white dwarf companion.

We can see from Fig. 4 that, with $\dot{M}_{\text{wind}} = 3 \times 10^{-8} M_{\odot}/\text{yr}$ and $v_{\text{wind}} = 800 - 1350 \text{ km/s}$, a neutron star is expected to produce an accretion luminosity of $\sim 10^{35} - 10^{36} \text{ erg/s}$, corresponding to an accretion rate $\dot{M}_{\text{acc}} \sim 10^{-10} - 10^{-11} M_{\odot}/\text{yr}$. In order to be consistent with the low luminosity of $10^{32} - 10^{33} \text{ erg/s}$ at the small blackbody radii inferred from Fig. 3, there should be a much higher wind velocity or much lower mass-loss rate to reduce the accretion rate by more than a factor 100. Then

also the low-velocity wind component must be absent, which is exactly the opposite to what Springmann & Pauldrach (1992) suggest for the subdwarf’s wind.

From the curve indicating the $1 M_{\odot}$ white dwarf, we see that with $\dot{M}_{\text{wind}} = 3 \times 10^{-8} M_{\odot}/\text{yr}$, a wind velocity between 1350 and 800 km/s will result in an accretion luminosity between $10^{32} - 10^{33} \text{ erg/s}$. So, even when the low-velocity wind component is absent or when the wind mass-loss rate is lower, the accretion luminosity is still consistent with the observed X-ray luminosity.

We thus conclude that, taking the constraints set by \dot{M}_{wind} , v_{wind} , T_{bb} , soft X-ray luminosity and radius of the emitting region into account, a white dwarf model with accretion onto a limited “spot” near the magnetic pole(s) can consistently explain all the observations, whereas a neutron star cannot. What the latter cannot explain is in particular the extreme softness of the spectrum in combination with a low X-ray luminosity.

3.4. The birthrate problem implied by a neutron-star companion

If the pulsating X-ray source in the system were a neutron star, the final evolutionary state of this system would be: a binary radio pulsar with a circular orbit, consisting of a massive white dwarf and a recycled pulsar, as argued by Van den Heuvel (1994). The latter type of pulsars tend to have much weaker magnetic fields and faster spin than ordinary non-recycled pulsars (see, for example, the reviews by Bhattacharya and van den Heuvel 1991, and Bhattacharya 1995). At present four such binary pulsars consisting of a massive white dwarf and a recycled pulsar in a circular orbit (hereafter intermediate-mass binary pulsars or IMBPs) are known: PSR 0655+64, PSR J2145-0750, PSR J1022+1001 and PSR J0621+1002 (Bailes et al. 1994, Camilo et al. 1996). In all these systems the spin-down age of the pulsar is extremely long, $> 4 \times 10^9 \text{ yrs}$, implying an extremely old age and long lifetime of these systems.

By contrast, the duration of the present evolutionary state of HD 49798, until the subdwarf has transferred its hydrogen and helium envelopes, is only of order 10^6 years or less (IT93). As the system is quite close to us (0.65 kpc), systems of this type should be quite common in the Galaxy. If HD 49798 contains a neutron star and is the progenitor of an IMBP, the birthrate of systems like HD 49798 should be equal to (or less than) that of IMBPs. Because of the very different lifetimes, this implies that in a steady state the total Galactic number of IMBPs should be at least 4000 times larger than that of HD 49798-like systems. The four known IMBPs are all within 2 kpc distance, and comprise about 20% of the presently known population of low-mass binary pulsars (LMBPs) within that distance. Lorimer (1995) estimates that the local Galactic surface density of LMBPs is $\sim 20 \text{ kpc}^{-2}$, but that the true number could be up to an order of magnitude larger due to an unseen low-luminosity population and beaming effects. We therefore estimate that the local surface density of IMBPs is $\lesssim 40 \text{ kpc}^{-2}$, which implies a local density of HD 49798-like systems of $< 0.01 \text{ kpc}^{-2}$ if the birthrates are equal. Assuming that we have no preferential position within the space distribution of either IMBPs or HD 49798-like systems

in the Galaxy, the probability to find (at least) one HD 49798 within 0.65 kpc is less than 1.3 %. We therefore conclude that, on the basis of the relative closeness of HD 49798 and the implied birthrate of such systems if the companion were a neutron star, a neutron-star companion can be excluded at the 98.7 % confidence level.

4. Conclusion

The observation of the binary HD 49798 / WGA J0648.0-4418 in X-rays has supplied the first direct information on the secondary star, which allowed us to characterize this binary much more accurately than before. The detection of X-ray pulsations, revealing the compact nature of the secondary star, enabled us to constrain the possible mass range of both the secondary and the subdwarf. The mass of the subdwarf must be less than $1.8 M_{\odot}$, and is in the range $0.7 - 1.3 M_{\odot}$ for a white dwarf companion of $0.9 - 1.2 M_{\odot}$.

We reconstructed the evolutionary history of the system and conclude that at present the subdwarf is in a phase of shell helium burning and has a degenerate CO core of $\sim 0.65 - 0.8 M_{\odot}$. It is the core of a progenitor with a mass probably between 4 and $6 M_{\odot}$ which shed its envelope in a common envelope event when it was on the early AGB.

The X-ray spectrum with the large pulsed soft component, its very good resemblance with the spectra of the intermediate polars, and the birthrate considerations, they all point in the direction of a white dwarf companion, and make it very unlikely that it is a neutron star. The X-ray luminosity and pulsations are explained by a magnetized white dwarf, accreting matter from the wind of the subdwarf. This model may be tested by a better determination of the wind parameters of the subdwarf and by further X-ray observations.

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