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X-rays from Hot Subdwarfs

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Abstract

Thanks to the high sensitivity of the instruments on board the *XMM-Newton* and *Chandra* satellites, it has become possible to explore the properties of the X-ray emission from hot subdwarfs. The small but growing sample of hot subdwarfs detected in X-rays includes binary systems, in which the X-rays result from wind accretion onto a compact companion (white dwarf or neutron star), as well as isolated sdO stars in which X-rays are probably due to shock instabilities in the wind. X-ray observations of these low mass stars provide information which can be useful also for our understanding of the winds of more luminous and massive early-type stars and can lead to the discovery of particularly interesting binary systems.

Keywords: X-rays: stars, binaries; Stars: subdwarfs, mass-loss; Stars: individual: HD 49798, BD +37°442, BD +37°1977, BD +28°4211, CD –30°11223, Feige 34

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1. Introduction

While soft X-ray emission from massive OB stars has been discovered more than thirty years ago (Seward et al., 1979; Harnden et al., 1979), only in recent years, thanks to the great sensitivity of the X-ray instrumentation carried by the *XMM-Newton* and *Chandra* satellites, it has become possible to reveal in the X-ray range also hot stars with much smaller masses and luminosities, such as the hot subdwarfs. These stars have high temperatures, corresponding to O and B spectral types, but luminosity values that place them below the main sequence in the HR diagram.

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The B type subdwarfs (sdBs) have masses of $\sim 0.5 M_{\odot}$, effective temperatures $20 < T_{\rm eff} < 40$ kK, and surface gravities $5 < \log g < 6$. They are interpreted as evolved low-mass stars that lost most of their hydrogen envelopes and are now in the He core burning phase. Subdwarfs of O spectral type (sdOs) constitute a less homogeneous group compared to the sdBs. They show a large range of temperatures ($40 < T_{\rm eff} < 100$ kK) and surface gravities $4 < \log g < 7$, and comprise both He-rich and He-poor stars.

X-ray emission associated with a hot subdwarf was seen for the first time in 1979 (see Sect. 3.1), but it took almost two decades to demonstrate that most of the observed X-rays actually originate from its compact companion star (Israel et al., 1997). Since then, little progress has been made in this field, until the developments of the last few years.

Extensive information on hot subdwarfs can be found in the excellent review by Heber (2009), which, however, does not cover their high-energy properties, having been written before most of the results described below were obtained. The aim of this paper is to review the X-ray properties of hot subdwarfs and discuss their relevance in the context of our understanding of mass-loss from hot stars. After a brief introduction on the X-ray emission from early type stars[1] and on the current knowledge of mass-loss in hot subdwarfs (Sect. 2), we describe all the available X-ray observations of hot subdwarfs in Sect. 3. The interpretation of these observations, in particular their implications on the stellar wind properties and on the subdwarfs with compact companions, are discussed in Sect. 4.

2. Relevance of X-ray observations of hot subdwarfs

There are two main processes that can lead to the production of X-rays in hot subdwarf stars: wind emission and accretion onto a compact companion. In both cases, X-ray observations can give information on the star properties, although, strictly speaking, the latter process does not involve emission from the hot subdwarf itself. The detection of accretion-powered emission gives the possibility to discover the hot subdwarfs with white dwarf or neutron star companions, which are predicted from evolutionary calculations, but not easily identified with optical observations.

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[1] An exhaustive coverage of this topic is provided by the other articles of this Special Issue.

It is well known that early-type stars can generate X-rays if their stellar winds contain plasma sufficiently hot to emit in this energy range. In the following, we will call this process "intrinsic" X-ray emission. Extrapolating to lower luminosities the empirical relation between X-ray and bolometric luminosity observed in normal OB stars, $L_X/L_{BOL} = 10^{-7\pm1}$ (Pallavicini et al., 1981; Nazé, 2009), one can estimate the expected X-ray emission for hot subdwarfs. This leads to expected X-ray luminosities of the order of 10^{27-32} erg s^{-1} and 10^{26-29} erg s^{-1} for O and B type subdwarfs, respectively. It must be remembered, however, that the above average relation has a large scatter.

The second possibility is that X-rays are produced by accretion onto a compact companion star, which can be either a white dwarf (WD) or a neutron star (NS).[2] As a first approximation, the accretion rate can be estimated using the Bondi-Hoyle formalism,[3] according to which the accretion radius onto an object of mass M is given by $R_A = 2GM/(V_W^2 + V_{ORB}^2)$, where V_W is the wind velocity and V_{ORB} is the orbital velocity. The mass accretion rate $\dot{M}_A$ is related to the relative velocity $V_R = (V_W^2 + V_{ORB}^2)^{1/2}$ and to the wind density by $\dot{M}_A = \pi R_A^2 \rho V_R$. The wind density ρ at the position of the compact object can be estimated as $\dot{M}_{\mathrm{W}} = 4\pi a^2 \rho V_W$, where $\dot{M}_{\mathrm{W}}$ is the wind mass-loss rate from the subdwarf and a is the orbital separation. From these relations one obtains the accretion-powered luminosity of a star with mass M and radius R

$$L_X = \frac{GM}{R}\dot{M}_A = \frac{GM}{R}\left(\frac{R_A}{2a}\right)^2 \frac{V_R}{V_W}\dot{M}_{\mathrm{W}} \sim \frac{GM}{R}\left(\frac{R_A}{2a}\right)^2 \dot{M}_{\mathrm{W}} \qquad (1)$$

Obviously, accretion onto a companion and intrinsic emission are not mutually exclusive, and both processes can occur in binary subdwarfs. In the lack of adequate X-ray data, it can be difficult to distinguish between the two possibilities, but, in both cases, the X-ray emission depends on the properties of the subdwarf's stellar wind. Therefore, X-ray observations provide a new diagnostic tool to investigate the poorly constrained mass-loss processes occurring in these stars.

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[2] Also binaries composed of a hot subdwarf and a black hole can exist, but their formation is less frequent (Nelemans, 2010).

[3] We assume that the subdwarf radius is smaller than its Roche-lobe; this condition is verified in all the hot subdwarf binaries discussed below.

2.1. X-ray emission in hot stars

Stars of O and B spectral type are sources of soft X-rays with luminosity up to a few 10^{33} erg s^{-1} and thermal spectra corresponding to plasma temperatures of a few million degrees. As well demonstrated, e.g., by the case of ζ Puppis (Hervé et al., 2013), high resolution X-ray spectra of the brightest OB stars can provide a wealth of information through the study of emission lines. However, for the majority of the early type stars detected in X-rays, only low resolution spectra are available, which can be adequately fit using simple models of thermal plasma emission. For example, the spectra of a large sample of massive OB stars detected with *XMM-Newton* were described with either a single Mekal model with kT$\sim$0.2–1 keV, or with the the sum of two or three Mekal models of different temperatures (Nazé, 2009). These data also showed evidence for additional[4] absorption, probably occurring in the stellar wind, in O stars but not in B stars.

Early-type stars are characterized by winds with typical mass-loss rates $\dot{M}_{\rm W}$ in the range 10^{-7}–10^{-5} $M_{\odot}$ yr^{-1} and terminal velocities of a few thousands km s^{-1}. It is believed that the observed X-rays are produced in these stellar winds, where the gas is shock-heated by instabilities (see, e.g., Owocki, 2013, for a review). The main properties of the winds in OB stars are explained in the context of the radiative line-driven wind theory (Castor et al., 1975; Kudritzki and Puls, 2000), according to which part of the radial momentum of the photons emitted from the star is transferred to the wind matter through line absorption and reemission. The theory predicts a dependence of $\dot{M}_{\rm W}$ on the star luminosity approximately given by $\dot{M}_{\rm W} \propto L^{\alpha}$, with α ~1.5–2. Since the photon absorption/emission process occurs mainly in the metals present in the wind, the mass-loss rate depends also on the metallicity Z, with $\dot{M}_{\rm W} \propto Z^{b}$ and $b \sim 0.6 - 0.7$ (Vink et al., 2001). These theoretical scaling laws are generally in good agreement with the observational data. However, some discrepancies have been found in stars with low-density winds, which show mass-loss rates one or two orders of magnitude below the predicted values (Martins et al., 2005; Marcolino et al., 2009). Such discrepancies might be, at least partially, explained by the fact that the UV line diagnostics used in these stars underestimate the actual mass-loss rates. The study of hot subdwarfs in the X-ray band, providing alternative handles on the properties of weak winds, can be of interest in this respect.

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[4] With respect to the value expected for the interstellar medium along the line of sight.

2.2. Stellar winds in hot subdwarfs

As mentioned above, the theory of radiatively-driven winds predicts that, for a given temperature and composition, the mass-loss rate scales with the star luminosity. This leads to the simple expectations that the winds of hot subdwarfs should be weaker than those of main sequence, giant and supergiant OB stars and that sdOs should have stronger winds than sdBs.

These predictions are indeed confirmed by the observations: evidence for stellar winds has been reported for some sdOs, but not yet conclusively for any sdB star. In fact, the mass-loss rates of a few sdOs have been derived from the P-Cygni profiles of the C_{IV} and N_V lines in the UV, yielding values of $\dot{M}_{\rm W} \sim 10^{-9}$–$10^{-8}$ $M_\odot$ yr^{-1} (Hamann et al., 1981; Jeffery and Hamann, 2010; Hamann, 2010). On the other hand, for what concerns sdB stars, the only evidence for mass-loss comes from the observation of a few objects with anomalous profiles of the H_α and HeI lines, interpreted as possible hints of a weak stellar wind (Heber et al., 2003).

Vink and Cassisi (2002) computed models of radiation-driven winds for low mass stars with 10 kK $< T_{\rm eff} <$ 35 kK, obtaining the following relation between the mass-loss rate and the star mass, M, luminosity, L, and metallicity Z:

$$\begin{gathered}\log\dot{M}_W = -11.70(\pm0.08) + 1.07(\pm0.32)\ \log(T_{\rm eff}/20\ {\rm kK}) \\ +2.13(\pm0.09)\ (\log(L/L_\odot) - 1.5) \\ -1.09(\pm0.05)\ \log(M/0.5M_\odot) + 0.97(\pm0.04)\ \log(Z/Z_\odot)\end{gathered}$$

The range of validity of this relation ($0.5 < M/M_\odot < 0.7$, $1.3 < \log(L/L_\odot) < 1.7$, and $0.1 < Z/Z_\odot < 10$) is appropriate for sdB stars. Fig. 1 shows the mass-loss rates as a function of $T_{\rm eff}$, computed with this relation for the case of $M = 0.6M_\odot$ and different values of L and Z. Unglaub (2008) computed mass-loss rates for sdBs obtaining values similar to those of Vink and Cassisi (2002) for stars of solar metallicity, but much lower values in the case of $Z < Z_\odot$ and high surface gravities.

The wind composition is an important parameter affecting the mass-loss rate, but unfortunately only limited information on the metallicity of hot subdwarfs is available. The above theoretical estimates for $\dot{M}_W$ are based on the assumption that the wind behaves as a single fluid, i.e. there is sufficient Coulomb coupling between the metals which are accelerated and the H and He atoms which constitute the bulk of the wind matter. Such a condition might not be valid in very low-density winds (Krtička and Kubát, 2010).

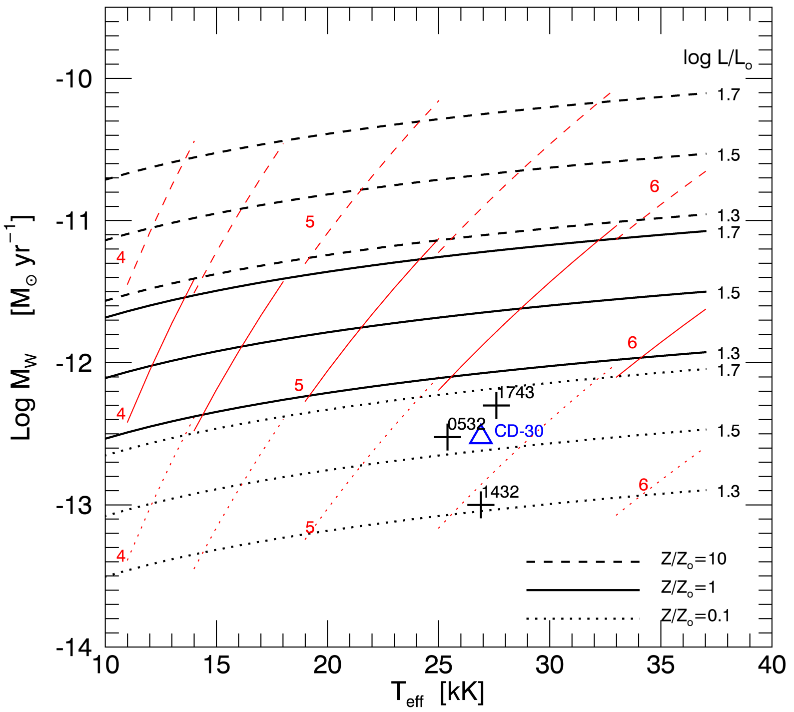

Figure 1: Mass-loss rate as a function of effective temperature, according to the relation of Vink and Cassisi (2002), for a star of 0.6 $M_\odot$. Each set of lines refers to a different metallicity value (Z=0.1 $Z_\odot$ dotted lines, Z=1 $Z_\odot$ solid lines, Z=10 $Z_\odot$ dashed lines) and three luminosity values (log ($L/L_\odot$) =1.3, 1.5, 1.7). The thin red lines show the corresponding values of log g. The triangle indicates the upper limit, derived from X-ray observations, on the mass-loss rate of the sdB star CD−30°11223, which has a WD companion. The crosses indicate the mass-loss rates upper limits derived for three other sdB stars (PG 1432+159, PG 1743+477, HE 0532−4503), with the hypothesis that they have neutron star companions (see Sect. 4.3).

Table 1: Hot subdwarfs detected in X-rays

	HD49798	BD+37°442	BD+37°1977	Feige34	BD+28°4211
Spectral type	sdO6	sdO9	sdO5	sdO	sdO
Luminosity ($L_\odot$)	1.4×10^4	2.5×10^4	2.5×10^4	400	90
$T_{\rm eff}$ (kK)	46.5	48	48	60	82
log g (cgs)	4.35	4	4	5.2	6.3
d (kpc)	0.6	2	2.7	0.3	0.1
Parallax (mas)	1.2±0.5	3.96±1.07	–0.5±1.84	3.09±1.93	10.89±1.46
V	8.3	10	10.2	11.2	10.5
$B-V$	–0.27	–0.28	–0.24	–0.3	–0.34
$F_X{}^{(a)}$ (erg cm^{-2} s^{-1})	6×10^{-14} $^{(b)}$	3×10^{-14}	4×10^{-14}	3×10^{-14}	10^{-14}
L_X (erg s^{-1})	2.5×10^{30} $^{(b)}$	10^{31}	3×10^{31}	3×10^{29}	10^{28}
P (s)	13.18	19.2 ?	–	–	–
P_{ORB} (d)	1.55	–	–	–	–
$F_X{}^{(a)}$ (erg cm^{-2} s^{-1})	7×10^{-13} $^{(c)}$	–	–	–	–
L_X (erg s^{-1})	3×10^{31} $^{(c)}$	–	–	–	–
Log $\dot{M}_{\rm W}$ ($M_\odot$ yr^{-1})	–9.2	–8.5	–8.5	–	–
V$_W$ (km s^{-1})	1200	2000	2000	–	–

Notes:

$^{(a)}$ Observed flux in the 0.2–10 keV range.

$^{(b)}$ During the eclipse of the compact companion

$^{(c)}$ Flux and luminosity of compact companion

3. X-ray observations of hot subdwarfs

The main properties of the five hot subdwarfs that have been detected in the X-ray band are given in Table 1. These stars are individually discussed in the following subsections. In Table 2 we list all the hot subdwarfs that have been observed with sensitive X-ray telescopes (*XMM-Newton*, *Chandra*, *Swift*), but without a significant detection.

3.1. HD 49798

HD 49798 is the X-ray brightest hot subdwarf and the only one for which most of the observed emission can be unambiguoulsy attributed to accretion onto a compact companion star. Early observations of this bright (V=8.3), single-lined spectroscopic binary revealed its orbital period of 1.5477 days and led to the measurement of the optical mass function f(M)= 0.27 $M_{\odot}$ (Thackeray, 1970; Stickland and Lloyd, 1994), but the nature of its unseen companion remained unknown for many years. Extensive optical/UV spectroscopic studies indicated that HD 49798 is a luminous ($\sim 5 \times 10^{37}$ erg s^{-1}) subdwarf of O6 spectral type, with peculiar abundances: it is rich in He and N, while C is underabundant (see Table 3). These abundances are consistent with evolutionary models according to which HD 49798 is the core of an intially much more massive star which lost its H envelope, most likely during a common-envelope phase.

X-rays from HD 49798 were first detected in 1979 with the *Einstein Observatory*, and later shown to be modulated with a period P=13.2 s thanks to a *ROSAT* observation carried out in 1992 (Israel et al., 1997). Such a short and regular periodicity can only be produced by the rotation of either a WD or a NS. As first suggested by Thackeray (1970), the fact that the companion star is a degenerate object explains why it is not visible in the optical/UV spectra, which are dominated by the emission of the much larger and brighter sdO star.

HD 49798 has been repeatedly observed with the *XMM-Newton* and *Swift* satellites. These data, spanning the years from 2002 to 2014, as well as the few previous observations with other satellites, indicate a remarkably stable X-ray emission. No significant variations were seen in the source flux, spectral shape, pulse profile, and spin period, with a limit on the period derivative of $|\dot{P}| < 6 \times 10^{-15}$ s s^{-1} (Mereghetti et al., 2013).

A dynamical measurement of the masses of HD 49798 and its compact companion has been obtained by the analysis of the orbitally-induced phase

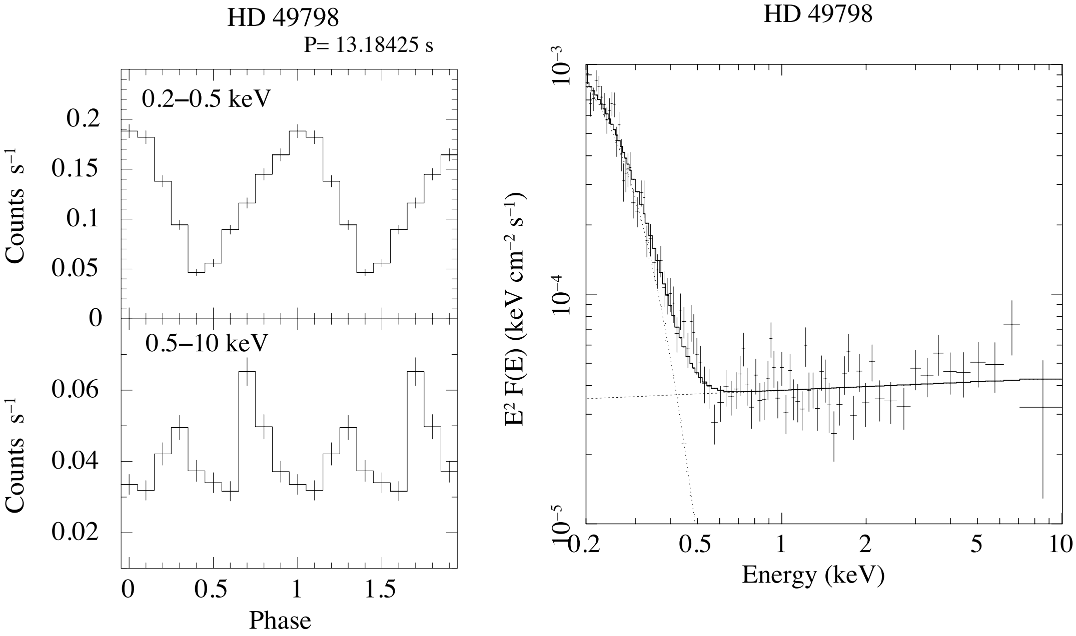

Figure 2: Results for HD 49798 obtained with the *EPIC* instrument on *XMM-Newton*. Left panel: X-ray light curve in two energy ranges folded at the spin period of 13.2 s. Right panel: X-ray spectrum fitted with a blackbody plus power law model (observation performed in October 2014).

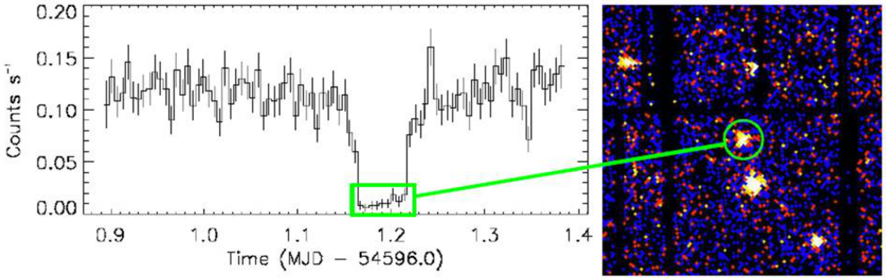

Figure 3: Left panel: X-ray light curve of HD 49798 obtained in May 2008 showing the eclipse with duration of 1.3 hours. Right panel: X-ray image (0.2–10 keV) accumulated during the eclipse in which emission from HD 49798 is clearly visible.

delays of the X-ray pulses, combined with the optical mass function and with the system inclination estimated from the duration of the X-ray eclipse (Mereghetti et al., 2009). The measured mass of HD 49798 is 1.50±0.05 $M_\odot$, among the highest seen in hot subdwarfs, while that of its compact companion is 1.28±0.05 $M_\odot$, consistent with either a NS or a massive WD.

Both the timing and spectral properties indicate that the X-ray emission from the compact companion of HD 49798 consists of two different components (Mereghetti et al., 2011b, 2013). The spectrum (Fig. 2, right panel) comprises a soft thermal component, well fit by a blackbody of temperature kT_{BB} ~30 eV and a hard component which dominates the emission above 0.5 keV. The latter is well fit by either a power law of photon index $\Gamma \sim 2$ or a thermal bremsstrahlung with temperature $kT_{BR} \sim 4$ keV. The folded pulse profile is single-peaked and strongly modulated below 0.5 keV, where the soft thermal component dominates, while it is double-peaked at higher energies (see Fig. 2, left panel). The striking difference in the pulse profile at low and hard energies suggests an interpretation in terms of two separate physical components, e.g. thermal emission from a hot spot on the star surface and non-thermal emission with a more complex beam pattern produced in the magnetosphere. The luminosity of $L_X = 3 \times 10^{31}$ erg s^{-1} (0.2-10 keV, d=0.6 kpc) indicates that the accreting companion of HD 49798 is most likely a WD[5], since accretion onto a NS would result in a luminosity larger by a factor $R_{WD}/R_{NS} \sim 300$ (see Eq.(1)).

As shown in Fig. 3, X-rays from the HD 49798 binary system are detected also when the compact object is eclipsed by the sdO star, which has a radius (1.45±0.25 $R_\odot$, Kudritzki and Simon (1978)) much larger than that of its companion (~3000 km for a massive WD or ~10 km for a NS). The X-ray emission during the eclipse is fainter, by a factor ~10, and harder than that seen in the orbital phases outside the eclipse. Its spectral properties and likely origin as intrinsic emission from HD 49798 are discussed in Sect. 4.1.

3.2. BD +37° 442

BD +37°442 is a luminous ($\sim 10^{38}$ erg s^{-1}), extremely helium-rich sdO star (Rebeirot, 1966; Husfeld, 1987). Its temperature, luminosity, and surface gravity, as well as its mass-loss properties (Jeffery and Hamann, 2010), are

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[5] This is also supported by the emission radius derived from the blackbody fit, ~40 km, larger than that of a NS and consistent with a hot spot on the surface of a WD.

similar to those of HD 49798 (see Table 1). However, contrary to HD 49798, no evidence for it being member of a binary system has been reported in the literature. A recent spectroscopic search for a binary signature did not detect any radial velocity variation on timescales from hours to months, down to a level of a few km s^{-1} (Heber et al., 2014).

Motivated by the X-ray detection of HD 49798 during eclipse, we searched for intrinsic X-ray emission from this allegedly single sdO star with an *XMM-Newton* observation carried out in August 2011. Soft X-ray emission from BD +37°442 was clearly detected, with a flux of 3×10^{-14} erg cm^{-2} s^{-1} (0.2-1 keV). Quite unexpectedly, a timing analysis of the X-ray data revealed (at $\sim 3\sigma$ statistical significance) a periodicitiy at 19.2 s (La Palombara et al., 2012). Fitting the X-ray spectrum of BD +37°442 with the sum of a soft blackbody and a power law component yields parameters similar to those of HD 49798, but with larger uncertainties: fixing the photon index to Γ=1 or 3, blackbody temperatures in the range ∼30–68 eV are obtained. The poorly constrained blackbody temperature and normalization do not permit a precise estimate of the total X-ray luminosity, which could be in the range from $\sim 10^{32}$ to 10^{35} erg s^{-1}. If confirmed, the periodicity at 19.2 s detected in BD +37°442 requires the presence of a compact companion, which, considering the large uncertainty on the X-ray luminosity, could be either a WD or a NS.

If BD +37°442 is indeed in a binary system, the lack of radial velocity variations in its spectrum is puzzling. Three explanations are possible: a) a very small orbital inclination; b) a very long orbital period (> several months); c) the reported pulsations are not real. Case a) seems unlikely because the large projected rotational velocity (60 km s^{-1}, Heber et al. (2014)) would imply a significant misalignment between the orbital and the star rotation axis. Also case b) presents some difficulties because a large orbital separation would probably result in a low mass accretion rate, unless the orbit is highly eccentric, causing X-ray emission mainly close to periastron passage (in this case time variability of the X-ray emission is expected). More observations are needed to confirm the presence of pulsations and investigate more deeply the different possibilities. As discussed in Sect. 4.1, the X-ray spectrum of BD +37°442 can also be fit by a sum of thermal plasma models (see Table 3 and Fig. 4, middle panel), consistent with intrinsic emission from an isolated sdO.

Table 2: Upper limits on the X-ray emission from hot subdwarfs

Name	Type	d (kpc)	$P_{\rm ORB}$ (days)	$L_X$$^{(a)}$ (erg s^{-1})	Ref.$^{(b)}$
CD –30°11223	sdB+WD	0.36	0.049	$<1.5\times10^{29}$	2
PG 1043+760	sdB+WD?	0.12	0.66	$<6.8\times10^{30}$	1
PG 1432+159	sdB+NS/BH?	0.22	0.8	$<9.9\times10^{30}$	1
PG 2345+318	sdB+WD?	0.24	0.9	$<1.3\times10^{31}$	1
HE 0532-4503	sdB+NS/BH?	0.27	2.8	$<7.4\times10^{31}$	1
CPD –64 481	sdB+WD?	0.28	0.21	$<6.8\times10^{29}$	1
PG 1101+249	sdB+WD/NS/BH?	0.35	0.39	$<1.7\times10^{30}$	1
PG 1232–136	sdB+BH?	0.363	0.57	$<5.0\times10^{29}$	2
GD 687	sdB+WD?	0.38	1.1	$<1.0\times10^{31}$	1
HE 0929–0424	sdB+WD/NS/BH?	0.44	1.9	$<2.9\times10^{31}$	1
PG 1743+477	sdB+NS/BH?	0.52	1	$<1.8\times10^{31}$	1
PG 0101+039	sdB+WD?	0.57	0.33	$<1.0\times10^{30}$	1
TON S 183	sdB+WD?	0.83	0.54	$<2.5\times10^{30}$	1
BD+75°325	sdO	0.136	-	$<5.8\times10^{28}$	3
BD+25°4655	sdO	0.11	-	$<5.1\times10^{28}$	3
BD–22°3804	sdO	0.185	-	$<9.7\times10^{28}$	3
BD+39°3226	sdO	0.235	-	$<1.5\times10^{29}$	3
BD–03°2179	sdO	0.631	-	$<2.4\times10^{30}$	3
CD–31°4800	sdO	0.132	-	$<5.1\times10^{28}$	3
BD+48°1777	sdO	0.163	-	$<1.2\times10^{29}$	3
LS V +22° 38	sdO	0.18	-	$<1.5\times10^{29}$	3
LS IV –12° 1	sdO	0.4	-	$<4.4\times10^{29}$	3
LSE 153	sdO	0.25	-	$<3.6\times10^{29}$	3
LSS 1275	sdO	<1	-	$<2.1\times10^{31}$	3
LSE 263	sdO	0.25	-	$<4.6\times10^{29}$	3
BD+18°2647	sdO	0.275	-	$<3.3\times10^{29}$	3
LSE 21	sdO	0.05	-	$<7.1\times10^{27}$	3
LS IV +10° 9	sdO	0.23	-	$<1.5\times10^{29}$	3
LS I +63° 198	sdO	0.2	-	$<1.4\times10^{29}$	3

Notes:

$^{(a)}$ Luminosity in the 0.2–10 keV range, assuming a thermal spectrum similar to that of BD +37°442.

$^{(b)}$ (1) Mereghetti et al. (2011a); (2) Mereghetti et al. (2014); (3) La Palombara et al. (2014);

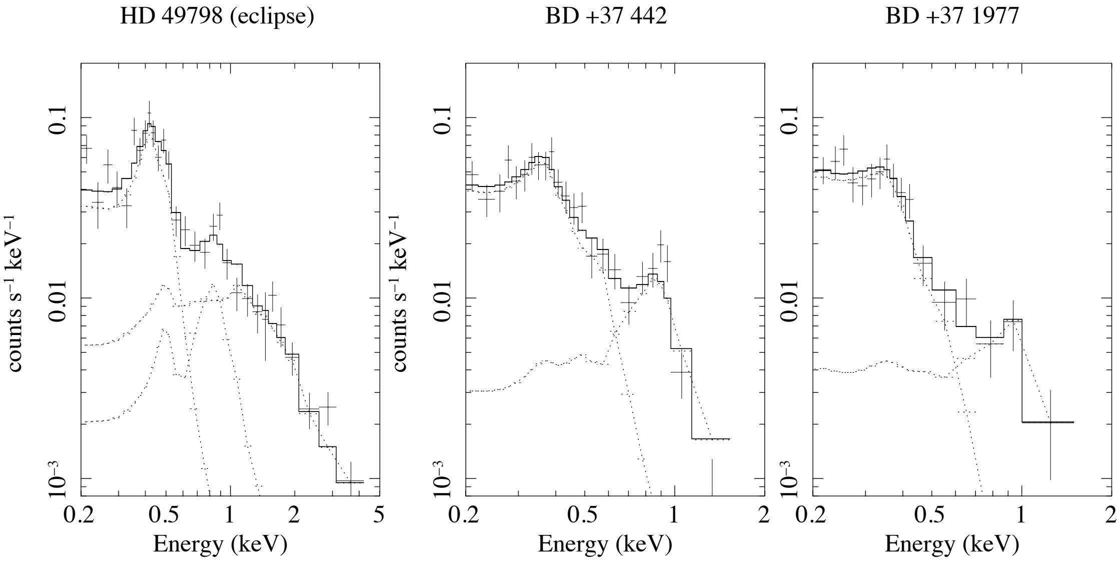

Figure 4: Left panel: *XMM-Newton* EPIC (MOS+pn) spectrum of HD 49798 during the eclipse. The solid line shows the best fit with three thermal plasma models (Mekal) with temperatures kT_1=0.11 keV, kT_2=0.57 keV, and kT_3=4 keV (fixed). The spectrum has been obtained by summing observations performed in 2008, 2011 and 2013, giving a total exposure time of 25 ks. Middle panel: *XMM-Newton* EPIC (MOS+pn) spectrum of BD +37°442 fitted with two Mekal models with temperatures kT_1=0.11 keV and kT_2=0.65 keV. Right panel: *XMM-Newton* pn spectrum of BD +37°1977 fitted with two Mekal models with temperatures kT_1=0.13 keV and kT_2=0.79 keV. In all the spectra the interstellar absorption and the abundances have been fixed at the values given in Table 3. The dashed lines show the individual Mekal components.

Table 3: Spectral parameters of three sdO stars fitted with the sum of two or three thermal spectra.

	HD 49798	BD+37°442	BD+37°1977
N_H (cm^{-2})	5×10^{20}	5×10^{20}	10^{20}
kT_1 (keV)	0.11	0.11	0.13
kT_2 (keV)	0.57	0.65	0.79
kT_3 (keV)	4.	–	–
Abundances$^{(a)}$			
$X_{\rm H}$	0.19	0.0013	0.0013
$X_{\rm He}$	0.78	0.96	0.96
$X_{\rm C}$	0.0001	0.025	0.025
$X_{\rm N}$	0.025	0.003	0.003
$X_{\rm O}$	0.0028	0.005	0.005
$X_{\rm Si}$	0.001	0.0008	0.0008
$X_{\rm Fe}$	0.0011	0.0006	0.0006

$^{(a)}$ mass fraction.

3.3. BD +37° 1977

This luminous and He-rich sdO has been dubbed the spectroscopic twin of BD +37°442, because the optical/UV spectral properties of these two stars are very similar. The X-ray emission from BD +37°1977 was discovered thanks to a *Chandra* survey of a flux-limited sample of sdOs (La Palombara et al., 2014) and recently studied in more detail with a dedicated *XMM-Newton* observation in which it was detected in the 0.15-1.5 keV range (La Palombara et al., 2015). Its very soft X-ray spectrum is well fit by the sum of two thermal plasma models with temperatures of about 0.13 keV and 0.8 keV, provided that adequate elemental abundances are used (see details in Table 3). The X-ray luminosity is 3.3×10^{31} erg s^{-1} (for d=2.7 kpc). A search for periodicities gave negative results, but, given the faint X-ray flux, the upper limits on the pulsed fraction are not particularly constraining. BD +37°1977 is a bright and relatively well studied star in the optical/UV bands and no radial velocity variations have been reported in the literature. It is thus natural to interpret these results in terms of intrinsic X-ray emission from the sdO star.

3.4. BD +28°4211 and Feige 34

BD +28°4211 and Feige 34 are the only other sdOs detected in the *Chandra* survey carried out by La Palombara et al. (2014). Being very faint sources (X-ray fluxes of a few 10^{-14} erg s^{-1}), they yielded only a few counts in these short observations: enough for a significant detection in the low-background *Chandra* HRC-I instrument, but insufficient for a timing analysis.

The parallax of BD +28°4211 obtained with *Hipparcos* implies a very small distance. Therefore, this star, with an X-ray luminosity of only $\sim 10^{28}$ erg s^{-1}, is the closest hot subdwarf detected in the X-ray band. Note that the angular resolution of the *Chandra* data is sufficiently good to unambiguosly associate the observed X-ray emission to BD +28°4211 and not to a faint companion star lying at an angular distance of only 2.8 arcsec (Massey and Gronwall, 1990). A detailed analysis of the UV and optical spectra of BD +28°4211 with NLTE models indicates a surface gravity in the range $6.1 < \log g < 6.5$ (Latour et al., 2013, 2015). Thus, contrary to the three objects discussed in the previous subsections, this star belongs to the class of low-luminosity, compact sdOs.

The same might be true for Feige 34, for which Thejll et al. (1995) derived $\log g = 6.8$ (this is, however, at variance with the value $\log g = 5.2$ reported by Werner et al. (1998)). Feige 34 has an infrared excess which might result either from free-free emission in a wind or from a late type companion star. The latter possibility is favored by the analysis of Thejll et al. (1995), who estimate that the putative companion should be of M2 spectral type. Since also late-type stars are known X-ray emitters, it cannot be excluded that (part of) the observed X-ray emission is due to the putative companion.

3.5. sdBs with (candidate) compact companions

Up to now, no sdB star has been detected at X-ray energies. The recent observations carried out with sensitive satellites focussed on sdBs in binaries with either confirmed or candidate compact companions. Although none of the observed targets were detected, these observations are relevant because they provide upper limits that are orders of magnitude smaller than those previously available from the *ROSAT* All Sky Survey.

CD –30°11223 is the most interesting sdB for which a deep upper limit on the X-ray luminosity has been obtained. Contrary to the case of the other sdB binaries discussed below, the presence of a compact companion is certain: it is a WD with a dynamically-measured mass of 0.7 $M_{\odot}$, orbiting the subdwarf star with a period of only 1.2 hr, the shortest known among sdB binaries (Vennes et al., 2012; Geier et al., 2013). A 50 ks long observation with *XMM-Newton* yielded a luminosity upper limit of $L_X \sim 1.5 \times 10^{29}$ erg s^{-1} (for d=364 pc), which, as discussed in Sect. 4.3, provides interesting constraints on the mass-loss rate from this sdB (Mereghetti et al., 2014).

The presence of a compact companion has been suggested for several other sdB stars. These systems with "candidate" compact companions have been selected by means of radial and rotational velocity measurements of single-lined spectroscopic binaries (Geier et al., 2010). The assumption of synchronous rotation in these systems allows one to estimate the orbit inclination and thus to set a lower limit to the mass of the companion. If this limit exceeds the value expected for a late-type main-sequence star, it is likely that the companion is a WD or a NS. A search for X-ray emission from a sample of twelve such systems, chosen among those with the lowest interstellar absorption and shortest orbital periods, was carried out with the *Swift* satellite (Mereghetti et al., 2011a). Upper limits in the range $\sim 10^{30} - 10^{31}$ erg s^{-1} were obtained for their X-ray luminosities (Table 2). The implications for the wind mass-loss rates of these sdBs are discussed in Sect. 4.3.

4. Discussion

4.1. Intrinsic X-ray emission from hot subdwarfs

In Fig. 5 we compare the X-ray and bolometric luminosities of the sdO stars to those of the normal O-type stars seen in the *ROSAT* All Sky Survey (Berghoefer et al., 1996). For the case of HD 49798 we consider here only the X-rays observed during the eclipse of its compact companion, which are most likely due to intrinsic emission from the sdO star[6]. It is clear that the luminosities of the five sdOs detected in X-rays, as well as the upper limits of the undetected ones, are consistent with an extrapolation of the average relation $L_X/L_{BOL} = 10^{-7\pm1}$ followed by the more luminous O-type stars (Pallavicini et al., 1981; Nazé, 2009).

From the X-ray spectral point of view, the sdOs are similar to the normal O-type stars. As shown in Fig. 4, good fits to the X-ray spectra of HD 49798 (during the eclipse), BD +37°442 and BD +37°1977 can be obtained with

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[6] Actually it cannot be completely excluded that (some of) the X-rays detected during eclipse are due to emission from the compact object reprocessed in the wind of the hot subdwarf (see discussion in Mereghetti et al. (2013)); this might explain its harder spectrum compared to the other sdO stars.

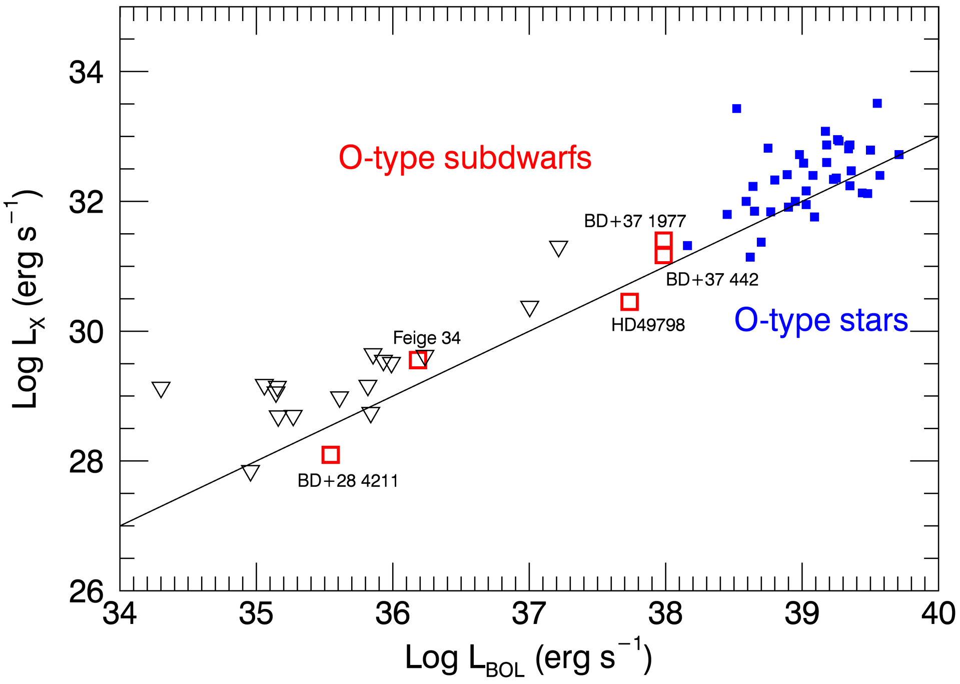

Figure 5: X-ray versus bolometric luminosity for hot subdwarfs. The five red squares indicate the sdO detected in X-rays, while the upper limits for the non-detected sdOs are shown by the black triangles. The blue squares show for comparison the O stars detected in the ROSAT All Sky Survey (Berghoefer et al., 1996). The line indicates the relation $L_X/L_{BOL} = 10^{-7}$.

the sum of two or three plasma emission models with different temperatures, provided that the proper element abundances are adopted. It is interesting to note that these three X-ray emitting sdOs are among the few hot subdwarfs for which evidence of mass-loss has been reported. No spectral information is available for the two remaining faint sdOs, which were only observed with the *Chandra* HRC instrument.

These findings suggest that the process of X-ray emission due to wind instabilities and shock heating is not restricted to the dense winds of the luminous and massive hot stars, but it can also operate in the weak winds of sdO stars. The five sdOs detected in X-rays have rather different atmospheric compositions: BD +37°442 and BD +37°1977 have almost pure He atmospheres and are C-rich (Bauer and Husfeld, 1995; Jeffery and Hamann, 2010); HD 49798 has one atom of He for each of H and is N-rich (Kudritzki and Simon, 1978); the compact sdO BD +28°4211 has solar He and subsolar to solar abundances of several metals (Latour et al., 2013, 2015); finally, He is slightly deficient for Feige 34, while Fe and Ni are enhanced by factors of 10 and 70 (Werner et al., 1998). These characteristics can in principle cause differences in their winds which might be explored with future, more sensitive X-ray observations.

4.2. X-ray emission from compact companions: the case of HD 49798

While the possible presence of a compact companion in BD +37°442 needs a confirmation of the reported 19 s periodicity, there is no doubt that the spectroscopic binary HD 49798 hosts either a WD or a NS spinning with a period of 13.2 s. As discussed below, accretion onto this compact object is the most natural explanation for the observed pulsed X-rays. The presence of a power-law spectral component rules out a purely thermal emission powered by the internal heat of a cooling NS, while the possibility of rotation-powered emission seems unlikely. The X-ray luminosity of a rotation-powered NS or WD with spin period P=$2\pi/\Omega$ is $L_X = \eta_X \mathrm{I}\Omega\dot{\Omega}$, where η_X is the efficiency of conversion of rotational energy into radiation and I is the moment of inertia. If the HD 49798 companion is a NS ($I_{\rm NS} \sim 10^{45}$ g cm^2), the minimum spin-down rate required to power the observed luminosity is $\dot{P}_{\rm min} = 6 \times 10^{-15} (L_X/10^{32} \mathrm{erg/s})(0.001/\eta)$ s s^{-1}, barely compatible with the current upper limit $|\dot{P}| < 6 \times 10^{-15}$ s s^{-1} (Mereghetti et al., 2013). Thus rotation-powered emission from a NS can be ruled out, unless an implausibly high efficiency is invoked. In the case of a WD companion ($I_{\rm WD} \sim 10^{50}$

g cm^2), the required $\dot{P}_{\rm min}$, being a factor $\sim 10^5$ smaller, would be compatible with the observations. A strongly magnetized WD could accelerate relativistic particles, likewise a radio pulsar, thus producing non-thermal magnetospheric X-ray emission. Although the existence of rotation-powered "WD-pulsars" has been proposed (e.g. Usov, 1988), none have been found so far. Also considering that the energetically-dominant thermal component in the HD 49798 X-ray spectrum would be difficult to explain in this scenario, we conclude that the possibility of rotation-powered emission is quite unlikely and concentrate in the following on the accretion scenario.

Independent on the WD or NS nature of the companion star, HD 49798 does not fill its Roche-lobe. Therefore, accretion in this binary occurs by capture of the sdO stellar wind and the expected X-ray luminosity can be estimated with Eq. (1). Mereghetti et al. (2009), based on the wind parameters of HD 49798 available at that time (Hamann et al., 1981), concluded that the compact object is a WD, since an accreting NS would have been more luminous than observed. An updated estimate of the mass-loss rate (Log $\dot{M}_{\rm W}$ = –9.2 yr^{-1}) and wind terminal velocity (V_W=1200 km s^{-1}) has been recently obtained (W. Hamann, private communication, for d=0.6 kpc). With these values and a radius of 3000 km, appropriate for a massive WD, eq. (1) gives a luminosity of $L_X \sim 10^{31}$ erg s^{-1}, which is in reasonable agreement with the observed value of $L_{0.2-10{\rm keV}} = 3\times10^{31}\left(\frac{d}{0.6kpc}\right)^2$ erg s^{-1}. For the alternative possibility of an accreting NS (R=10 km), eq. (1) would give $L_X \sim 3\times10^{33}$ erg s^{-1}. Even taking into account that the total luminosity, including the unobserved contribution of the blackbody component below 0.2 keV, could be a factor ∼4 higher than the above value, it seems difficult to reconcile the expected NS luminosity with the observations, unless the source distance is greatly underestimated.

Iben and Tutukov (1994) discussed an evolutionary path leading to a system like HD 49798. This involves an initial binary with masses of ∼8–9 $M_\odot$ in which the WD, formed from the originally more massive star, is engulfed in the envelope of the secondary, when the latter expanded to become a red-giant with a non degenerate He core. This leads to the expulsion of the common envelope and to the emergence of a much more compact binary, composed of a CO or ONe WD and a He-star, as currently observed. HD 49798 is now within its Roche-lobe, but it will expand again in the future, transferring He-rich matter onto its companion at a higher rate. If the companion is indeed a massive WD, this could lead to a type Ia supernova explosion or to the formation of a rapidly spinning NS through accretion-induced collapse (Wang and Han, 2012; Hurley et al., 2010; Tauris et al., 2013). Being the descendent of intermediate mass stars ($\sim$8–9 $M_\odot$), the HD 49798 binary would be the progenitor of a type Ia supernova with a short delay time, unless, as suggested by Di Stefano et al. (2011), the explosion is delayed due to the fast rotation of the WD. In the alternative case of accretion-induced collapse, the resulting NS would probably have a high rotational velocity. This would be an evolutionary path to create millisecond pulsars without going through recycling in a low mass X-ray binary (Bhattacharya and van den Heuvel, 1991). Recently, Liu et al. (2015) performed population synthesis computations of different evolutionary channels leading to the formation of ONe WD + He-star binaries. They found that systems with long orbital period and high He-star mass, as observed in HD 49798, are rarely formed and conclude that the companion of HD 49798 is more likely to be a CO WD, which can reach Chandrasekhar mass limit and produce a type Ia SN after a few 10^4 years of mass transfer, as computed by Wang and Han (2010).

4.3. Limits on the mass-loss rate from hot subdwarfs

The non-detection of accretion-powered X-ray emission in binaries containing compact objects (Sect. 3.5) can be used to constrain the properties of stellar winds from the hot subdwarfs in these systems. Thanks to their higher X-ray efficiency, binaries containing NSs can provide more stringent limits than those containing WDs. Although no confirmed NS+sd system has been found yet, a few candidates which deserve further study have been proposed (Geier et al., 2010). We note that the constraints on the stellar mass-loss derived in this way are affected by a few uncertainties, such as the source distances, the X-ray spectrum assumed to convert count rates to fluxes, the accretion model and geometry used to relate the X-ray luminosity to the mass accretion rate. With these caveats in mind, we can discuss the results obtained for the WD+sdB binary CD –30°11223 (Mereghetti et al., 2014) and for a dozen of other sdB binaries which are suspected to host compact objects (Mereghetti et al., 2011a).

Under the assumption of Bondi-Hoyle accretion (eq. (1)), and assuming a power law spectrum with photon index Γ=2, a 3σ upper limit of $\dot{M}_{\rm W} \sim 3\times10^{-13}$ $M_\odot$ yr^{-1} was derived for the mass-loss rate of CD –30°11223. The distance of this source is well known (364 pc, Geier et al. (2013)), thus the main uncertainty is related to the assumed X-ray spectrum. As discussed in Mereghetti et al. (2014), any thermal spectrum with temperature in the

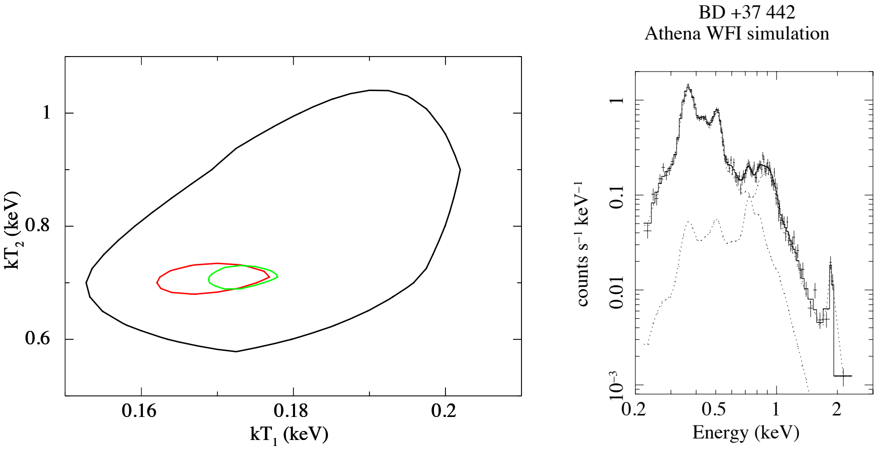

Figure 6: Left panel: Contour plots showing the uncertainty on the temperatures of the two thermal components in the X-ray spectrum of BD +37°442. The black line indicates the current error region (2σ confidence level) obtained with *XMM-Newton* data. The red and green lines indicate the error regions derived from a simulated observation (50 ks exposure time) with the Athena WFI and X-IFU instruments, respectively. Right panel: Simulated spectrum of BD +37°442 for a 50-ks long observation with the Athena/WFI instrument.

range 0.1-10 keV, would give a limit on $\dot{M}_{\rm W}$ in the range $(2-4)\times10^{-13}$ $M_\odot$ yr^{-1}. This value is inconsistent with the theoretical predictions of Vink and Cassisi (2002) if CD –30°11223 has solar or higher abundances (see Fig. 1).

In Fig. 1 we show also the upper limits on $\dot{M}_{\rm W}$ obtained from the X-ray observations of three sdB binaries which might have NS companions (Mereghetti et al., 2011a). These limits are quite constraining, but subject to the effective presence of a NS in these systems, which is based on the mass limits derived under the assumption that the subdwarf rotates synchronously. Further observations to confirm this are required. On the other hand, the current upper limits derived for the other sdB stars with proposed WD companions are two or three orders of magnitude higher and thus not particularly constraining for the theoretical models.

5. Conclusions and future prospects

The results obtained for the small, but rapidly growing, sample of hot subdwarfs detected in the X-ray range, show the potential of X-ray observations in the study of these objects. Unfortunately, detailed analysis such as those carried out for several normal OB stars cannot be done for these relatively faint sources. For example, the element abundances of the thermal plasma models used to fit the sdO spectra could not be constrained by the X-ray data currently available. Therefore, the abundances had to be fixed to the values derived from optical studies, when available, or otherwise based on informed best guesses.

The increased sensitivity and spectral resolution of future X-ray telescopes will provide much better information on the spectral properties of the X-ray emission and lead to the discovery of many new sources. As an illustration of what could be obtained with *Athena*, the next large X-ray satellite approved by the European Space Agency for a launch in the late 2020s, we have simulated X-ray spectra of BD +37°442 based on the expected performances of the WFI and X-IFU instruments (Rau, 2014; Barret et al., 2014). The analysis of these simulated data (see Fig. 6) indicate that it will be possible to obtain much more accurate measures of the plasma temperatures and constrain within $\sim$10% the abundances of C, N, O, Si and Fe, providing a measure independent of that derived from optical/UV analysis.

It is also important to increase the sample of hot subdwarfs detected in X-rays in order to consolidate the comparison with normal early type stars and to explore possible dependences on different parameters, such as surface gravity, temperature and composition. While future satellites will certainly allow us to reach fainter limiting fluxes, also the current facilities can in principle provide many new detections, since only a very small number of targets have been observed so far. One interesting question is whether isolated sdB stars are X-ray emitters.

More optical/UV studies of the X-ray emitting hot subdwarfs are needed to derive better estimates of their atmospheric and wind parameters. The accurate distances which will soon be provided by the *Gaia* mission will be crucial to reduce many of the uncertainties involved in these estimates. A multi-wavelength approach can be very effective to discover other systems such as HD 49798 and CD –30°11223, in which the presence of a compact companion is certain. Besides their intrinsic interest from the point of view of binary evolution models, such systems will allow us to fully exploit the X-ray data to better characterize the poorly known winds of hot subdwarfs.

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