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The lack of X-ray pulsations in the extreme helium star BD+37°442 and its possible stellar wind X-ray emission

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ABSTRACT

We report the results of a new *XMM–Newton* observation of the helium-rich hot subdwarf BD+37°442 carried out in 2016 February. The possible periodicity at 19 s seen in a 2011 shorter observation is not confirmed, thus dismissing the evidence for a binary nature. This implies that the observed soft X-ray emission, with a luminosity of a few 10^{31} erg s^{-1}, originates in BD+37°442 itself, rather than in an accreting neutron star companion. The X-ray spectrum is well fit by thermal plasma emission with a temperature of 0.22 keV and non-solar element abundances. Besides the overabundance of He, C and N already known from optical/UV studies, the X-ray spectra indicate also a significant excess of Ne. The soft X-ray spectrum and the ratio of X-ray to bolometric luminosity, $L_X/L_{BOL} \sim 2 \times 10^{-7}$, are similar to those observed in massive early-type stars. This indicates that the mechanisms responsible for plasma shock-heating can work also in the weak stellar winds (mass-loss rates $\dot{M}_W \leq 10^{-8}$ $M_\odot$ yr^{-1}) of low-mass hot stars.

Key words: stars: individual: BD+37°442 – subdwarfs.

1 INTRODUCTION

The luminous ($L \sim 2.5 \times 10^4$ $L_\odot$) helium-rich O-type star BD+37°442 is one of the few hot subdwarfs that have been detected in the X-ray band. X-rays from hot subdwarfs can have two different origins: they can be produced by accretion on to a neutron star or white dwarf companion or they can be emitted by shock-heated plasma in their stellar wind, as it occurs in early-type stars of higher mass and luminosity. In both cases, X-ray observations of hot subdwarfs are useful because they provide a way to study the relatively weak winds of these low-mass stars (see Mereghetti & La Palombara 2016, for a review).

X-rays from BD+37°442 were discovered with an *XMM–Newton* observation carried out in 2011 (La Palombara et al. 2012). The spectrum was fit by the sum of a blackbody with temperature kT = 45 ± 10 eV plus a faint power law with photon index $\Gamma \sim 2$, giving a luminosity between $\sim 10^{32}$ and $\sim 10^{35}$ erg s^{-1} (for $d = 2$ kpc; Bauer & Husfeld 1995). The large uncertainty on the luminosity, due to the poorly constrained spectral parameters, left open both of the above possibilities for the origin of the X-ray emission in BD+37°442. The *XMM–Newton* data also showed a periodicity at 19.2 s (with a statistical significance of 3.2σ) pointing to the presence of a compact companion. However, no evidence for a binary nature had been reported in the literature (Faÿ, Honeycutt & Warren 1973; Kaufmann & Theil 1980; Dworetsky, Whitelock & Carnochan 1982) and a recent campaign of high-resolution optical spectroscopy did not reveal radial velocity variations (Heber et al. 2014). This means that either the orbital plane has a very small inclination and/or the orbital period is of the order of months, or that BD+37°442 is indeed a single star and the reported signal was spurious.

Here we report the results of a longer follow-up *XMM–Newton* observation of BD+37°442 that we obtained in order to clarify the origin of its X-ray emission.

2 DATA ANALYSIS

BD+37°442 was observed with the *XMM–Newton* satellite for 72 ks on 2016 February 1. The three CCD cameras of the EPIC instrument were operated in imaging mode with a time resolution of 73 ms for the pn camera (Strüder et al. 2001) and of 0.9 s for the two MOS cameras (Turner et al. 2001). The medium thickness filter was used for all cameras. The data were processed with SAS v15. We used only single- and double-pixel events for the pn (pattern ≤ 4) and single- and multiple-pixel events for the MOS (pattern ≤ 12).

For the timing analysis, we extracted the source counts from a circle of radius 15 arcsec and converted their arrival times to the Solar system barycenter. We used only the events in the energy range from 0.15 to 2 keV, as it was done for the 2011 data by La

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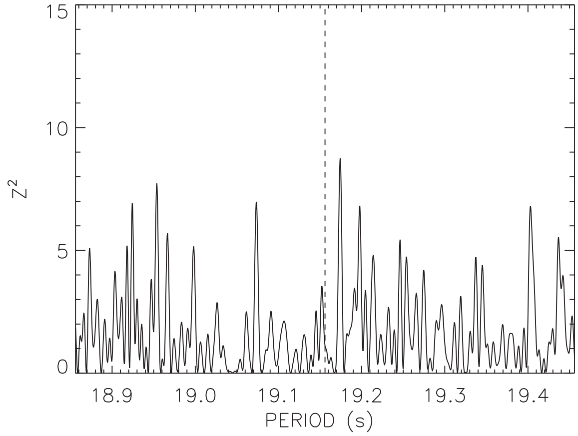

Figure 1. Distribution of the Z^2 statistics versus trial period for the 2016 observation of BD+37°442. The dashed line indicates the period detected in the 2011 data.

Palombara et al. (2012). This resulted in 1519 pn counts and 485 MOS counts. We estimate that the background contributes about 22 per cent and 17 per cent of these counts, respectively.

In order to take into account a possible spin-up or spin-down of the source during the ~4.5 yr between the two *XMM–Newton* observations with plausible values of $|\dot{P}| \lesssim 3 \times 10^{-10}$ s s^{-1}, we considered possible periods in the range from 19.1 to 19.2 s (the value measured in 2011 was $P_0 = 19.156 \pm 0.001$ s). Using the sum of the pn and MOS counts, we found a maximum value of the Z^2 statistics (Buccheri et al. 1983) of 8.74, for a period $P = 19.174$ s (see Fig. 1). However, the corresponding probability of chance occurrence, taking into account the number of sampled periods, is too large to claim a significant detection.

Through Monte Carlo simulations we found that a sinusoidal modulation with pulsed fraction of 33 per cent, as found in the 2011 data, has a probability of 99.9 per cent of being detected at a significance above 5σ in an observation with the same duration and counting statistics as the 2016 one. The corresponding probability for a pulsed fraction of 25 per cent (the lower bound of the 2σ uncertainty of the 2011 value) is 84 per cent. Therefore, the lack of a detection in the new data strongly suggests that either the pulsations in BD+37°442 disappeared (i.e. the pulsed fraction decreased making them undetectable) or the peak at 19.2 s appearing in the 2011 periodogram was caused by a statistical fluctuation.

For the spectral analysis, we used circular extraction regions with radii of 20 arcsec for the source and 50 arcsec for the background. Time intervals of high background were excluded. We merged the spectra from the three cameras into a single EPIC spectrum and produced the appropriate response matrix using the task `multi-xmmselect`. Following exactly the same procedures, we extracted also the EPIC spectrum of BD+37°442 from the 2011 data, which we reprocessed using SAS v15.

The effective exposure times of the 2016 and 2011 spectra are 48 and 28 ks, respectively. By comparing the two spectra, we found no evidence that the flux or spectral shape changed between the two observations. Therefore, we performed the spectral analysis by jointly fitting the 2011 and 2016 data in the 0.2–2 keV energy range using the XSPEC software.

Simple models (power law, blackbody, thermal bremsstrahlung) modified by interstellar absorption could not fit the data (values of reduced χ^2_ν >2.5). Thermal plasma emission models with abundances fixed at Solar values (Anders & Grevesse 1989) were also rejected, but they could give satisfactory fits if some of the abundances were let free to vary. For simplicity, and considering that the quality of the data does not allow us to constrain a large number of spectral parameters, we considered only a single-temperature plasma described by the APEC model.

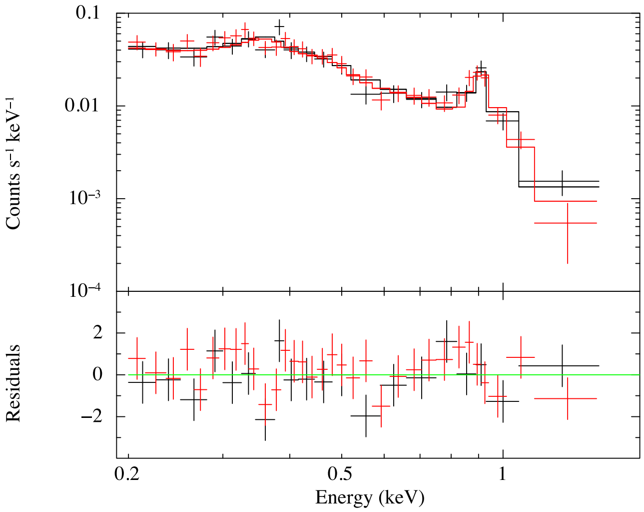

Figure 2. Joint fit of the EPIC 2011 (black) and 2016 (red) spectra of BD+37°442 with a thermal plasma model. The corresponding best-fitting parameters are given in the Model A column of Table 1. Top panel: data and best-fitting model. Bottom panel: residuals in units of σ.

Table 1. Results of the joint fits of the 2011 and 2014 EPIC spectra of BD+37°442 with two different assumptions for the element abundances.

Parameter	Model A	Model B
N_H (10^{20} cm^{-2})	$2.7^{+1.4}_{-0.9}$	<7
kT (keV)	$0.22^{+0.01}_{-0.02}$	0.23 ± 0.01
X_{He}	0.99 (fixed)	0.96 (fixed)
X_C	0.005	0.025 (fixed)
X_N		0.003 (fixed)
X_{Ne}	0.0005	0.0025
X_{Si}		0.0008 (fixed)
X_{Fe}		0.0006 (fixed)
Flux (10^{-14} erg cm^{-2} s^{-1})	$5.5^{+1.1}_{-0.6}$	$3.4^{+0.3}_{-0.1}$
χ^2_ν/d.o.f.	0.94/48	0.90/49

Notes. Abundances are given in mass fraction; the flux refers to the 0.2–2 keV range and is corrected for the absorption; errors are at 1σ.

We found strong evidence for an overabundance of C and Ne, the latter being required to fit the significant excess of emission visible in the spectra at ~0.9 keV. The derived C and Ne abundances were found to depend on that of He, which was however poorly constrained by the X-ray data. Therefore, considering that BD+37°442 is an extreme He-rich star, we fixed the abundance of this element to a mass fraction of $X_{He} = 0.99$. In this case, we obtained a good fit with temperature kT = 0.22 keV, absorption $N_H = 2.7 \times 10^{20}$ cm^{-2} and solar abundances relative to hydrogen for all the other elements (see Fig. 2 and Model A in Table 1). From optical studies we know, however, that also other elements are overabundant in this star. Indeed, an equally good fit was obtained with the abundances of He, C, N, Si and Fe fixed at the values of Jeffery & Hamann (2010), but also in this case an overabundance of Ne was required (Model B in Table 1). The two models result in slightly different

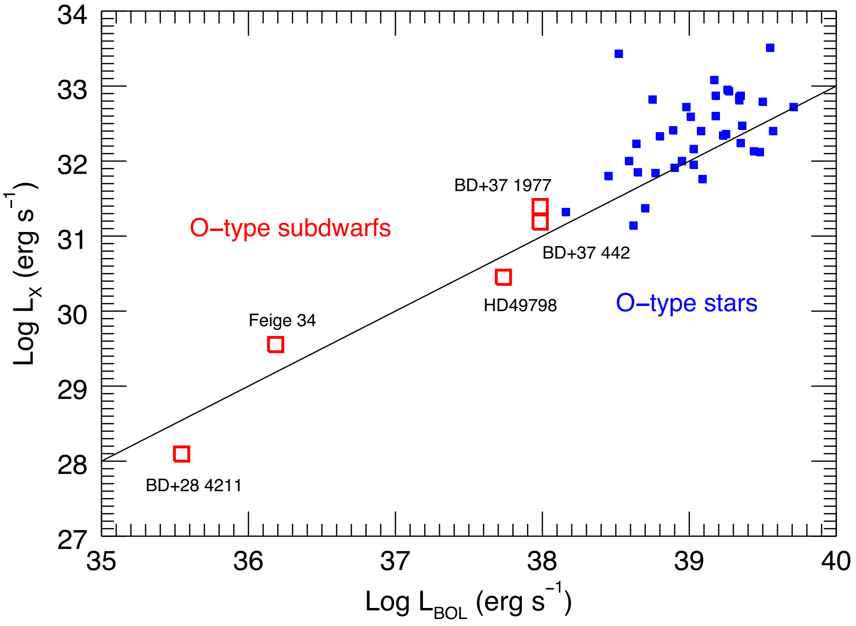

Figure 3. X-ray versus bolometric luminosity for O-type subdwarfs (open red squares) and normal O-type stars (small blue squares). The line indicates the relation $L_{\rm X}/L_{\rm BOL} = 10^{-7}$.

values of the unabsorbed flux, both of a few 10^{-14} erg cm^{-2} s^{-1} (0.2–2 keV), which, for a distance of 2 kpc (Bauer & Husfeld 1995), correspond to X-ray luminosities in the range $\sim$(1.5–3) $\times$ 10^{31} erg s^{-1}.

We performed also spectral fits fixing the interstellar absorption at $N_H = 6.2 \times 10^{20}$ cm^{-2}, based on the BD+37°442 reddening of $E(B-V) = 0.09$ (Jeffery & Hamann 2010) and the relation derived by Güver & Özel (2009). In the case of Model A, we obtained a good fit ($\chi^2_\nu = 1.03$) with similar abundances and a slightly lower temperature kT = 0.20 ± 0.01 keV, while Model B resulted in a worse fit to the data ($\chi^2_\nu = 1.7$).

3 DISCUSSION AND CONCLUSIONS

The non-detection of a significant periodicity at 19.2 s in the new data (which have a higher counting statistics than the previous ones) casts doubts on the presence of a neutron star companion in BD+37°442. This result, coupled to the lack of radial velocity variations in the optical spectra (Heber et al. 2014), leads us to conclude that BD+37°442 is most likely a single star. Indeed, one of the scenarios proposed to explain the origin of extreme helium-rich stars is that they result from the merger of a binary composed of a He white dwarf and a more massive CO white dwarf. The lighter white dwarf is disrupted and a single He-enriched star is formed (Jeffery, Karakas & Saio 2011).

If BD+37°442 is a single star, the observed X-ray emission cannot be powered by mass accretion on to a neutron star companion, with the interesting consequence that it has to originate in BD+37°442 itself. The X-ray emission from massive O-type stars is related to the presence of powerful radiation-driven winds. X-rays are produced in the winds of single stars by shock-heated plasma resulting from various instabilities (see e.g. Oskinova 2016, and references therein). An empirical correlation has been found between the X-ray and bolometric luminosities of early-type stars: $L_{\rm X} \sim 10^{-7} L_{\rm BOL}$ (Pallavicini et al. 1981; Nazé 2009). The X-ray luminosity we derived for BD+37°442 corresponds to a value of $L_{\rm X}/L_{\rm BOL} \sim 2 \times 10^{-7}$, fully consistent with the observed dispersion around the above average relation.

It is thus natural to ascribe the X-rays observed in BD+37°442 to the same, or similar, processes that are at work in the stellar winds of massive early-type stars. There is in fact evidence from UV and optical spectroscopy that BD+37°442, despite its low luminosity compared to normal O-type stars, has a stellar wind. The inferred mass-loss rate is $\dot{M}_{\rm W} = 3 \times 10^{-9}$ M$_\odot$ yr^{-1} (Jeffery & Hamann 2010), in good agreement with the predictions of the most recent theoretical models of radiatively driven winds in low luminosity hot stars (Krtička, Kubát & Krtičková 2016).

In Fig. 3, we plot the X-ray and bolometric luminosities of the five sdO stars that have been detected in the X-ray range. For comparison, the values for a sample of normal O stars seen in the *ROSAT* All Sky Survey (Berghoefer, Schmitt & Cassinelli 1996) are also shown in the figure. BD+37°1977 (La Palombara et al. 2015) is another single, He-rich star very similar to BD+37°442 for what concerns its optical spectrum, composition and mass-loss properties (Jeffery & Hamann 2010). These two stars lie very close in the $L_{\rm X}$–$L_{\rm BOL}$ plane. The same is true for the spectroscopic binary HD 49798, which is in a 1.55 d orbit with a neutron star or white dwarf companion (Mereghetti et al. 2009, 2013). For this star, we plot in Fig. 3 the X-ray luminosity observed when the compact companion is eclipsed by the sdO star and likely due to wind emission; out of the eclipse the luminosity is a factor of 10 higher and pulsations at 13.2 s are observed.[1] The X-ray spectra of these three stars are similar, except for the presence of a harder component in HD 49798, which might be related to its binary nature. The two other sdO stars plotted in Fig. 3 (Feige 34 and BD +28°4211; La Palombara et al. 2014) are

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[1] The presence of this X-ray periodicity in HD 49798 is certain. The pulsations were discovered with high statistical significance in 1992 with the *ROSAT* satellite (Israel et al. 1997) and subsequently detected in all the *XMM–Newton* observations of this source carried out in 2002–2014 (Mereghetti et al. 2016).

less luminous and their faint X-ray emission has not been studied in detail. It is however remarkable that they lie on the extrapolation of the average L_X–L_{BOL} relation observed at higher luminosity.

The temperature found in the spectral fits of BD+37°442 is in the lower range of the values seen in the sample of O-type stars observed with the *XMM–Newton* EPIC instrument, when a single-temperature plasma is sufficient to describe their low-resolution X-ray spectra (Nazé 2009). This might be related to the weaker wind of BD+37°442 compared to that of normal O-type stars. It is also interesting to note that the weak-wind O-type dwarf μ Col (HD 38666), with a mass-loss rate $\dot{M}_W = 10^{-9.5\,\pm\,0.7}$ $M_\odot$ yr^{-1} (Martins et al. 2005) similar to that of BD+37°442, has an X-ray emitting wind with higher temperature (kT $\sim$ 0.4 keV; Huenemoerder et al. 2012), despite its lower wind velocity ($v_\infty = 1200$ km s^{-1} wrt $v_\infty = 2000$ km s^{-1}; Jeffery & Hamann 2010). However, we caution that the temperatures derived from low-resolution spectroscopy of faint X-ray sources, such as the hot subdwarfs discussed here, might be affected by the uncertainties in the element abundances. Instruments with large collecting area and high spectral resolution are needed to address these issues in more detail and fully exploit the study of subdwarfs in the context of a more general understanding of stellar wind in hot stars.

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