DISCOVERY OF A COMPACT COMPANION TO THE HOT SUBDWARF STAR BD +37° 442

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ABSTRACT

We report the results of the first X-ray observation of the luminous and helium-rich O-type subdwarf BD +37° 442 carried out with the XMM-Newton satellite in 2011 August. X-ray emission is detected with a flux of about $3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.2–1 keV) and a very soft spectrum, well fit by the sum of a blackbody with temperature $kT_{BB} = 45^{+3}_{-2}$ eV, and a power law with a poorly constrained photon index. Significant pulsations with a period of 19.2 s are detected, indicating that the X-ray emission originates in a white dwarf or neutron star companion, most likely powered by accretion from the wind of BD +37° 442.

Key words: pulsars: general – stars: individual (BD +37 442) – subdwarfs – X-rays: binaries – X-rays: stars

1. INTRODUCTION

Hot subdwarfs are evolved, low-mass stars that have lost most of their hydrogen envelope and are now in the stage of helium-core burning (see Heber 2009 for a review). From the spectroscopic point of view, we distinguish the cooler B-type subdwarf (sdB) stars, with effective temperature $T_{\text{eff}} < 40,000$ K, and the hotter O-type (sdO) stars, with $T_{\text{eff}} > 40,000$ K (Hirsch et al. 2008). Most sdB stars are helium-poor and display no or only weak helium lines, while most sdO stars are helium-rich and show He$^+$ and He$^0$ lines. While the sdBs form a homogenous group, the sdOs show a wide spread in temperature ($T_{\text{eff}} = 40,000–100,000$ K), gravity ($\log(g) = 4–6.5$), and helium abundance (Heber & Jeffery 1992; Heber et al. 2006). Historically, sdO stars were divided into “luminous” and “compact” sdOs, depending on their value of log(g).

One possible mechanism responsible for the loss of the massive hydrogen envelopes of hot subdwarfs is mass transfer in a binary. Indeed, there is substantial evidence that many hot subdwarfs are in close binary systems (Maxted et al. 2001; Napiwotzki et al. 2004; Copperwheat et al. 2011). In particular, a large fraction of binaries is found among sdB stars. Models of binary evolution (Han et al. 2002) predict that many of the subdwarf companions should be white dwarfs (WDs). Indeed, a few sdB+WD are known (Koen et al. 1998; Maxted et al. 2000; Edelmann et al. 2005), and recent optical studies of single-lined spectroscopic binaries yielded several new candidates (Geier et al. 2010). The presence of a compact companion (a WD, neutron star (NS), or black hole) could be revealed by the detection of X-ray emission powered by accretion, if the subdwarf mass-donor can provide a sufficiently high accretion rate. Short Swift/XRT observations of candidate sdB+WD/NS binaries, selected from the Geier et al. (2010) sample, gave X-ray luminosity upper limits of $\sim 10^{30}–10^{31}$ erg s$^{-1}$ (Mereghetti et al. 2011a). These limits confirm that sdB stars have rather weak stellar winds unable to provide enough accretion rate.

Although the fraction of binaries among sdO stars is not as high as for the sdBs, the prospects to find X-ray emitting companions are more promising for these stars. In fact, at least a few luminous sdO stars show evidence for stellar winds with mass-loss rate $M \sim 10^{-7}–10^{-10}$ $M_\odot$ yr$^{-1}$ (Jeffery & Hamann 2010). Among these, the bright star HD 49798 is known as a soft X-ray source, with a strong periodic modulation at 13.2 s, for more than 15 years (Israel et al. 1997). More recent X-ray observations with XMM-Newton showed that the compact companion of HD 49798 is a massive (1.28 ± 0.05 $M_\odot$) white dwarf (Mereghetti et al. 2009). To our knowledge, no other X-ray detections of sdO stars have been reported up to now.

Prompted by our findings on HD 49798, we carried out an X-ray observation of another bright sdO star. Our target is BD +37° 442 (Rebeirot 1966), a luminous sdO which is often referred to as an “extreme helium star” because of its complete lack of hydrogen (while HD 49798 has about 20% (by mass) of hydrogen): it shows evidence for significant mass-loss rate (Jeffery & Hamann 2010) and stellar parameters similar to those of HD 49798 (see Table 1), but with the notable difference that, up to now, no evidence of binary nature was reported. Here we present the results of the first X-ray observations of BD +37° 442, which indicate the presence of a compact companion, either a WD or an NS.

2. OBSERVATIONS AND DATA ANALYSIS

BD +37° 442 was observed with XMM-Newton on 2011 August 21, starting at 23:35:19 UT (MJD = 55794.983). The three EPIC cameras, i.e., one pn (Strüder et al. 2001) and two MOS (Turner et al. 2001), were operated in full frame mode, with time resolution of 73 ms for the pn and of 2.6 s for the two MOS cameras; the effective source exposure time was, respectively, of ~33 ks and ~28 ks. For all cameras the medium thickness filter was used.

We used version 11.0 of the XMM-Newton Science Analysis System (SAS) to process the event files. The observation was affected by high instrumental background only for a short time interval of ~1.2 ks, which we removed for the spectral analysis. We selected only the events with pattern in the range 0–4 (i.e., mono- and bi-pixel events) for the pn camera and 0–12 (i.e., from 1 to 4 pixel events) for the two MOS.

The images obtained with the three cameras clearly show that BD +37° 442 is emitting in the X-ray range: in fact, a source is significantly detected at the coordinates R.A. = 01h58m33.4s, Decl. = +38°34′22″, which differ by only 1°8 from the position of BD +37° 442. This difference is consistent with the ~2″ rms astrometric accuracy of XMM-Newton. The source net count

4 http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.ps.gz
subtracted light curves of Figure 2, the periodicity is visible also in the separate data sets, i.e.,

\[ \text{of chance occurrence, after taking into account the number of events,} \]

and (1.9 ± 0.2) × 10^{-3} counts s^{-1} for the pn and each of the two MOS, respectively. BD +37° 442 is not detected above 2 keV, suggesting a soft spectrum, as confirmed by the spectral analysis presented below.

For the timing analysis, we used the data of the whole observation and the three EPIC cameras, extracting the events from a circular region with radius 15′′ centered at the source position. We converted the arrival times to the solar system position. We converted the arrival times to the solar system center. We assumed a source distance of 2 kpc. This value is subject to a large uncertainty because the value of \( R_{BB} \) is only poorly constrained and depends on the blackbody temperature \( kT_{BB} \) or \( R_{BB} \).

The effective temperature (K)

\[ \text{for the spectral analysis we considered only the} \]

\[ \text{of the \( 0.2–1 \) keV component, corrected for the}\]

\[ \text{for which 28% can be ascribed to the power-law component. The}\]

\[ \text{to bolometric blackbody luminosities between 6 \times 10^{31} \text{ erg s}^{-1} \text{ cm}^{-2}} \]
Figure 2. Background-subtracted light curves of BD +37° 442 in the energy range 0.15–2 keV, folded at the best-fit period $P = 19.156$ s. From top to bottom: pn data, sum of MOS1 and MOS2 data, total data (pn+MOS1+MOS2).

Figure 3. Top panel: pn spectrum of BD +37° 442 with the best-fit power-law (dashed line) plus blackbody (dotted line) model. Bottom panel: residuals (in units of $\sigma$) between data and model.

- The highest luminosity is obtained for the lowest temperature. The 0.2–10 keV luminosity of the power-law component is in the range $(1.8–3.2) \times 10^{31}$ erg s$^{-1}$.

3. DISCUSSION

Our XMM-Newton observation of BD +37° 442 has provided the first detection of X-ray emission from this O-type subdwarf. Shocks in the radiation-driven stellar winds of main sequence, giant, and supergiant early-type stars give rise to soft X-rays, with a typical ratio of X-ray to optical flux of the order of $\log(f_{\text{X}}/f_{\text{bol}}) = -6.45 \pm 0.51$ (Nazé 2009). It is not known if this relation also holds for low luminosity stars. The only other sdO star possibly detected in X-rays is HD 49798, which is in a binary system with an X-ray emitting white dwarf. In this system, the X-ray flux of $f_X = 4.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, visible when the accreting WD companion is in eclipse, corresponds to $\log(f_{\text{X}}/f_{\text{bol}}) = -7.4$ and could be due to emission from the sdO (Mereghetti et al. 2011b). For BD +37° 442 we measure $\log(f_{\text{X}}/f_{\text{bol}}) = -6.63$, consistent with the above values, but the significant periodic modulation at 19.156 s clearly indicates that most of, or possibly all, the detected flux originates in a compact companion star, rather than in BD +37° 442 itself. The periodic modulation can be explained equally well as the spin period of an NS or a WD.

Ultraviolet spectra of BD +37° 442, acquired with the IUE satellite, show N v and C iv resonance lines with P Cygni-like profiles, indicating the presence of a stellar wind (Rossi et al. 1984). A more recent analysis of UV and optical spectra of BD +37° 442 has been reported by Jeffery & Hamann (2010), who derived a mass-loss rate of $3 \times 10^{-9} M_\odot$ yr$^{-1}$ and a wind terminal velocity of $v_\infty = 2000$ km s$^{-1}$. It is possible that part of the sdO stellar wind is captured by its compact companion, giving rise to accretion powered X-ray emission. The density and velocity of the wind material at the position of the compact object can be computed assuming a canonical wind velocity law with radial dependence $v(R) = v_\infty(1 - 1/R)^{\beta}$, where $R$ is the radial distance in units of stellar radii and the index $\beta$. 


The blackbody emitting radius derived from the best fit, \( R_{\text{BB}} = 39.9^{+62}_{-28} \) km (for \( d = 2 \) kpc), is only marginally consistent with a neutron star. However, this parameter is strongly correlated with the poorly constrained slope of the power law spectral component and an acceptable fit can be obtained, e.g., with \( \Gamma = 1.5 \), \( kT_{\text{BB}} \sim 58 \) eV, and \( R_{\text{BB}} \sim 10 \) km. Alternatively, the accreting companion could be a WD, if the sdO extends to (or close to) the Roche lobe, thus yielding an accretion rate larger than what we computed assuming wind accretion (or in the unlikely case that the adopted distance is largely overestimated). The observed spectrum is much softer than the typical spectrum of neutron stars in classical X-ray binaries, which however have very different companion stars and accrete at higher rates. It should also be considered that we can observe the low-temperature emission from BD +37° 442 (and HD 49798, see below) only because these sources are at high Galactic latitude, where interstellar X-ray absorption is very small.

Up to now BD +37° 442 was believed to be a single star: no evidence for a companion has been seen in spectroscopic (Fayé et al. 1973; Kaufmann & Theil 1980; Dworetsky et al. 1982) or photometric data (Landolt 1968, 1973), and infrared observations did not show any excess emission (Thejell et al. 1995). On the other hand, some of the very few published radial velocity measurements are inconsistent with a single value, hinting to a possible binary motion. A radial velocity \( V_r = -156.4 \pm 1.1 \) km s\(^{-1}\) is given in the original discovery paper (Rebeiro 1966), while Drilling & Heber (1987) found \( V_r = -94 \pm 1 \) km s\(^{-1}\). New accurate radial measurements are needed to determine the parameters of this binary.

The X-ray properties of BD +37° 442 are very similar to those of the only other X-ray source associated with an sdO star: HD 49798. In this binary a massive white dwarf accretes matter from the stellar wind of its subdwarf companion (Mereghetti et al. 2009). Also in the case of HD 49798 the X-ray emission is pulsed, with a period (13.2 s) similar to that we have discovered in BD +37° 442, and the soft spectrum is well described by the sum of a blackbody with \( kT_{\text{BB}} = 39 \) eV and a power law with \( \Gamma = 1.6 \) (Mereghetti et al. 2011b). HD 49798 has an orbital period of 1.55 days, first discovered through radial velocity measurements of the sdO optical emission (Thackeray 1970), and an X-ray luminosity of \( 10^{32} \) erg s\(^{-1}\) (at \( d = 650 \) pc).

The fact that the only two sdO stars observed with sensitive X-ray instruments turned out to be binaries with a compact companion is noteworthy. Although it is premature to draw conclusions from such small numbers, this might suggest that the fraction of sdO binaries is larger than currently believed on the basis of optical observations. Note that, contrary to late-type companions, which can give a detectable contribution in the spectral and photometric data, WDs and NSs are too faint and completely outshined in the optical/UV by the sdO emission. Both BD +37° 442 and HD 49798 belong to the subclass of luminous, He-rich sdOs, whose origin and evolutionary link with other classes of stars is still unclear (Napiwotzki 2008; Justham et al. 2011). In this respect, X-ray observations might provide important information to complement optical/UV data. Besides the potential of discovering other sdO binaries through the detection of pulsations, the high sensitivity of current satellites like XMM-Newton and Chandra can probe the X-ray emission of single sdOs, and test whether their wind emission scales as in early-type stars of higher luminosity.

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