Follow-up observations of X-ray emitting hot subdwarf star: the He-rich sdO BD +37° 1977

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Abstract. We report on the results of the first XMM–Newton satellite observation of the luminous and helium–rich O-type subdwarf BD +37° 1977 carried out in April 2014. X-ray emission is detected with a flux of about \(4 \times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}\) (0.2–1.5 keV), corresponding to a \(f_X/f_{bol}\) ratio \(\sim 10^{-7}\); the source spectrum is very soft, and is well fit by the sum of two plasma components at different temperatures. Both characteristics are in agreement with what is observed in the main-sequence early-type stars, where the observed X-ray emission is due to turbulence and shocks in the stellar wind. A smaller but still significant stellar wind has been observed also in BD +37° 1977; therefore, we suggest that also in this case the detected X-ray flux has the same origin.

Key words. stars: early-type — stars: subdwarfs — stars: individual: BD +37° 1977 — X-rays: stars

1. Introduction

Among the hot subdwarf (sd) stars, which are evolved He-core burning low-mass stars (Heber 2009), the sdO stars are those which show the highest temperatures (T\(_{\text{eff}}\) > 40 kK). Apart from this characteristic, sdO stars (sdOs) are characterized by a wide range of values for the surface gravity (log\(g\) = 4–6.5) and helium abundance (-3.5 \(\lesssim\) log\(n_{\text{He}}/n_{\text{H}}\) \(\lesssim\) 3). Indeed they form a rather heterogeneous class of stars, which includes both He-poor and He-rich stars (Heber & Jeffery 1992, Heber et al. 2006, Hirsch et al. 2008), and ‘luminous’ and ‘compact’ stars, according to their low or high surface gravity, respectively (Napiwotzki 2008). This variety of properties is probably the consequence of different evolutionary histories (Heber 2009, Geier 2015): in the case of the compact stars, the He-poor ones are post-EHB stars, while the origin of the He-rich ones might be either the merging of two He-core or C/O-core white dwarfs (Iben 1990, Saio & Jeffery 2000, 2002) or the so-called late hot-flasher scenario (Brown et al. 2001); instead the luminous sdO stars are post-AGB stars. Evolutionary models suggest that most sdO stars are the outcome of the evolution of single stars, but some of them could descend from binary systems which underwent a common-envelope phase; in this case it is possible that the sdO stars has a compact companion, typically a white dwarf (WD).

Up to now, sdO stars have been deeply investigated in the optical/UV domain, where several of them are rather bright; on the other hand, only few of them are known as X-ray sources. In the case of the binary HD 49798, the detection of pulsed (\(P = 13.18\) s) soft X-rays (Israel et al. 1997) indicates that this emission originates from accretion onto a compact object, most likely a massive white dwarf (Mereghetti et al. 2009). For this binary we detected an evident X-ray emission also when the compact companion is eclipsed by the sdO star, suggesting the possibility of intrinsic X-ray emission of the sdO star (Mereghetti et al. 2013). Another sdO star recently detected at X-rays is BD +37° 442: the XMM–Newton observation of this He-rich star revealed soft X-ray emission, with a spectrum similar to that of HD 49798, and a possible periodicity of 19.16 s (at 3 \(\sigma\) confidence level), which suggests that also BD +37° 442 has a compact companion (La Palombara et al. 2012). In order to enlarge the sample of sdO stars observed at X-rays, we performed with Chandra HRC-I a survey of a complete flux-limited sample of sdO stars and discovered three additional X-ray emitting stars (La Palombara et al. 2014): the luminous and He-rich sdO star BD +37° 1977 (Jeffery & Hamann 2010) and the compact (log\(g\) > 6) and He-poor stars Feige 34 and BD+28° 4211 (Thejll et al. 1991, Zanin & Weinberger 1997).

In this paper we report on the results of a follow-up observation of BD +37° 1977, performed with XMM–Newton, which allowed us to investigate in detail the spectral and timing properties of the X-ray emission discovered with Chandra. This star was identified as an sdO star by Wolff et al. (1974), who detected several emission He lines but no H lines in its blue spectrum. Their spectroscopic analysis gave a surface gravity log\(g\) \(\lesssim\) 4.5 and a temperature \(T\) \(\lesssim\) 50 kK; comparable values (\(T \approx\) 55 kK and log\(g\) \(\approx\) 4.0) were estimated from the low res-
olution IUE spectrum (Darius et al. 1979), which also gave an estimate of the star luminosity (log$L_{bol}/L_{\odot} = 4.4$). There is no evidence for a compact companion for BD +37° 1977. The possible detection of an infrared excess (at 2-μm wavelength) was ruled out with a confidence level of about 2σ. The analysis of the infrared data suggests that BD +37° 1977 is a M-type dwarf with a mass of 0.15-0.5 M\(_{\odot}\) and a distance of 4.4 kpc. No evidence of periodic signals was found for the five individual observations.

### Table 1. Main parameters of the sdO stars BD +37° 1977, BD +37° 442, and HD 49798.

| Parameter                  | Symbol | BD +37° 1977 Value | Reference | BD +37° 442 Value | Reference | HD 49798 Value | Reference |
|----------------------------|--------|---------------------|-----------|-------------------|-----------|---------------|-----------|
| Surface gravity            | $g$    | $\sim 4.0$          | 1         | $4.00 \pm 0.25$   | 4         | 4.35          | 6         |
| Luminosity ($L_{bol}$)     | $L$    | $25.000$            | 1         | $25.000$          | 1         | 14.000        | 6         |
| Effective Temperature (K)  | $T_{eff}$ | $48.000$           | 2         | $48.000$          | 2         | 46.500        | 6         |
| Magnitudes                 | $U$    | 8.67                | 3         | 8.57              | 5         | 6.76          | 7         |
| $B$                        | 9.93               | 3                   | 9.73               | 5                   | 8.02          | 7         |
| $V$                        | 10.17              | 3                   | 10.01              | 5                   | 5.67          | 7         |
| Distance (kpc)             | $d$    | $\sim 2.7$          | 2         | $2.0^{+0.6}_{-0.9}$ | 4         | 0.65 ± 0.10  | 8         |
| Terminal wind velocity (km s⁻¹) | $v_\infty$ | $2.000$               | 2         | $2.000$          | 2         | 1.350         | 9         |
| Mass–loss rate ($M_\odot$ yr⁻¹) | $\dot{M}$    | $10^{-8.2}$         | 2         | $10^{-8.5}$       | 2         | $10^{-8.5}$  | 6         |

References: 1 - Darius et al. (1974); 2 - Jeffery & Hamann (2010); 3 - Jordi et al. (1991); 4 - Bauer & Hhusfeld (1995); 5 - Landolt (1973); 6 - Hamann (1978); 7 - Landolt & Uomoto (2007); 8 - Kudritzki & Simon (2007); 9 - Hamann et al. (1981)

### 2. Observations and data analysis

BD +37° 1977 was observed with XMM–Newton in April 2014. At that time the source was visible only for the first ∼ 20 ks of each XMM–Newton orbit: therefore, five different observations were performed, between April 14 and 24 (see Table 2). The three EPIC cameras, i.e. one pn (Strüder et al. 2001) and two MOS (Turner et al. 2001), were always operated in full frame mode, with time resolution of 73 ms for the pn and of 2.6 s for the two MOS cameras; taking into account all the observations, the total effective exposure time was, respectively, of ∼ 34.5 ks and ∼ 50 ks. For all cameras the medium thickness filter was used.

We used version 13.5 of the XMM–Newton Science Analysis System (SAS) to process the event files. For the data 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. For each camera, we merged together the data of the five observations and accumulated the images in various energy ranges. We found that BD +37° 1977 is significantly detected at the coordinates R.A. = 9h 24m 26s, Dec. = +36° 42′ 52.8″, which differ by 0.7″ from the position of BD +37° 1977. This difference is consistent with the ∼ 2″ r.m.s. astrometric accuracy of XMM–Newton. In each of the five observations a point source is clearly detected below 0.5 keV, while considering the five observation merged together the source is detected up to ∼ 1.5 keV (Fig. 1). This implies that the source spectrum is very soft. All the observations were partly affected by high instrumental background. However, since the spectrum of the instrumental background is rather hard, the background contamination has a limited impact on the source spectral analysis: therefore, we considered the whole data set, without rejecting the time intervals with the highest particle background. The source net count rate in the 0.15–1.5 keV range is (1.7 ± 0.2) × 10⁻³ cts s⁻¹ and (2.5 ± 0.3) × 10⁻³ cts s⁻¹ for the pn and each of the two MOS, respectively.

For the timing and spectral analysis, we used the data of the whole observation and the three EPIC cameras; we extracted the source events from a circular region with radius 15″ centered at the source position, while the corresponding background events were accumulated on circular areas free of sources and radii of 30″ and 120″ for the pn and the two MOS cameras, respectively. We converted the arrival times to the solar system barycenter, then we combined the three datasets in a single event list. The background–subtracted light curve of BD +37° 1977 does not show any variability on time scales from hundreds of seconds to the observation length. We looked for possible periodicities in the X-ray emission, but we found no evidence of periodic signals; this search was unsuccessful not only for the five individual observations, but also when considering together all of them. In all cases we estimated an upper limit of ∼ 30 % on the pulsed fraction, for a sinusoidal modulation between 1 and 5000 s. For the spectral analysis we considered first the pn data, since the source soft spectrum and the lower sensitivity of the MOS cameras at low energies strongly reduced the count statistics. We verified that the addition of the MOS data gave consi-

1 http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.ps.gz
Table 2. List of observations of BD +37° 1977 performed by XMM–Newton.

| Revolution | Observation ID | Start time (YYYY-MM-DD hh:mm:ss) | Effective exposure |
|------------|----------------|----------------------------------|--------------------|
|            |                | pn (ks)                          | MOS (ks)           |
| 2627       | 0740140301     | 2014-04-14@15:00:25              | 4.2                |
| 2629       | 0740140501     | 2014-04-18@14:43:21              | 7.0                |
| 2630       | 0740140401     | 2014-04-20@15:45:37              | 7.9                |
| 2631       | 0740140601     | 2014-04-22@14:36:30              | 9.9                |
| 2632       | 0740140701     | 2014-04-24@14:06:44              | 5.5                |

Fig. 1. EPIC pn image of the sky region around BD +37° 1977 in the energies ranges 0.15-0.5 (left), 0.5-1.5 (centre), and 1.5-10 keV (right). The green circle (15′′ radius) indicates the source position.

tent results. We generated the response matrix and ancillary file using the SAS tasks rmfgen and arfgen. To ensure the applicability of the χ² statistics, the spectrum was rebinned with a minimum of 30 net counts per bin; then, we fitted them using XSPEC (V 12.7.0). We only used the energy range 0.2–1.5 keV since at higher energies the background dominates and the source flux is negligible. In the following, all the spectral uncertainties and upper limits are given at the 90 % confidence level for one interesting parameter, and we assume a source distance of 2.7 kpc (Jeffery & Hamann 2010); we adopted the results of Anders & Grevesse (1989) for the solar abundances of the atomic elements.

The source spectrum is very soft and we tried to describe it with different models (see Table 3). The fit with an absorbed power law (PL) is formally acceptable (χ² < 2) but gives a very large and unrealistic photon index (Γ ≃ 5), while a fit with a blackbody model is rejected by the data (χ² > 2). An absorbed power law plus blackbody gives a good fit, but with unrealistic (for the power-law photon index) or unconstrained (for the blackbody normalization) values of the model parameters. We note that while this model is physically motivated for BD +37° 442, where the observed X-ray flux can be attributed to accretion onto a compact companion, this is not the case for BD +37° 1977, for which no evidence of a compact companion has been found. For this reason, we consider in the following the possibility that the X-ray emission detected in BD +37° 1977 has the same origin of that observed in the normal, giant and supergiant early-type O stars.

For a large sample of this type of stars observed with XMM–Newton the spectrum can be described by the sum of different thermal plasma components (MEKAL in XSPEC), with temperatures between ≃ 0.1 and ≃ 5 keV (Naze 2009). Therefore, we tried to use the same approach also in the case of BD +37° 1977. We clearly found that, assuming solar abundances, with this model it was not possible to obtain an acceptable fit, even if we considered the sum of two MEKAL components at different temperatures (Fig. 2 and Table 3). Therefore, we modified the model abundances by taking into account the values of the single chemical elements considered by Jeffery & Hamann (2010). Since there are no abundance measurements for BD +37° 1977, they adopted the same overabundance of He, C, N, Si, and Fe obtained by Bauer & Husfeld (1995) for BD +37° 442, which is very similar from the spectroscopic point of view.

Assuming these abundances, a single thermal component provides an acceptable fit (χ² < 2) but leaves large residuals at the high energies. Hence we considered a model composed by the sum of two absorbed components, at different temperatures. We checked that the estimated interstellar absorption is negligible and consistent with 0. Therefore we fixed it at N_H = 10^{20} cm⁻², which is the total absorption value across the Galaxy in the direction of BD +37° 1977. In this way we found a good fit (χ² = 0.71 for 13 degrees of freedom, Fig. 3) with kT₁ =
120±30 eV and $kT_2 = 840^{+350}_{-210}$ eV. The total flux in the energy range 0.2–1.5 keV is $f_X = (4.0^{+1.2}_{-0.3}) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$; although 78 % of the flux is due to the low-temperature component, the high-temperature component is significant at 3σ confidence level. The measured flux corresponds to a source luminosity $L_X = (3.3^{+0.5}_{-0.3}) \times 10^{34}$ erg s$^{-1}$. The fit leaves some residuals at ~ 650 eV, thus suggesting the presence of the O VIII emission line (Fig. 3). This could be due to an underestimate of the real Oxygen abundance, since in our model we fixed it at the Solar value. Therefore we repeated the spectral fit with the same model but leaving the Oxygen abundance free to vary. In this way we obtained an improvement of the spectral fit (Fig. 4) and we found that the best-fit abundance value is 310±250 times the Solar value: although it is not well constrained, this is consistent with the expected Oxygen overabundance in BD +37° 1977.

### 3. Discussion

The XMM–Newton observation of BD +37° 1977 enabled us to constrain the flux and spectrum of the X-ray emission recently discovered by Chandra (La Palombara et al. 2014). The measured flux $f_X \approx 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ confirms the estimate provided by the Chandra detection. It implies a luminosity $L_X \approx 3.3 \times 10^{34}$ erg s$^{-1}$. Since the bolometric luminosity of BD +37° 1977 is $L_{bol} \approx 25,000 L_\odot$ (Darius et al. 1979; Jeffery & Hamann 2010), the corresponding ratio is $L_X/L_{bol} \approx 10^{-6.5}$. This value is consistent with the 'canoni-

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**Table 3. Summary of the best-fit parameters of BD +37° 1977 obtained with different spectral models.**

| Parameter | Unit | Value |
|-----------|------|-------|
| $N_H$     | cm$^{-2}$ | $(3.5^{+1.0}_{-0.7}) \times 10^{20}$ |
| $\Gamma$  |       | 5.0$^{+1.7}_{-1.1}$ |
| $\chi^2$  |       | 1.76 |
| Degrees of freedom |       | 14 |

**Power law**

| $N_H$     | cm$^{-2}$ | $(9.9^{+6.6}_{-4.7}) \times 10^{20}$ |
| $kT$      | eV       | $67^{+12}_{-12}$ |
| $\chi^2$  |       | 2.46 |
| Degrees of freedom |       | 14 |

**Blackbody**

| $N_H$     | cm$^{-2}$ | $(2.0^{+1.0}_{-0.8}) \times 10^{21}$ |
| $kT$      | eV       | $22^{+16}_{-12}$ |
| $\chi^2$  |       | 0.76 |
| Degrees of freedom |       | 12 |

**Power law + Blackbody**

| $N_H$     | cm$^{-2}$ | $(1.8^{+1.2}_{-1.1}) \times 10^{20}$ |
| $kT_1$    | eV       | $81^{+0}_{-11}$ |
| $kT_2$    | eV       | $800^{+350}_{-210}$ |
| $\chi^2$  |       | 2.15 |
| Degrees of freedom |       | 12 |

**Mekal + Mekal**

| $N_H$     | cm$^{-2}$ | $1 \times 10^{20}$ (fixed) |
| $kT_1$    | eV       | 120±30 |
| $kT_2$    | eV       | $840^{+350}_{-210}$ |
| $\chi^2$  |       | 0.71 |
| Degrees of freedom |       | 13 |

**Mekal + Mekal**

| $N_H$     | cm$^{-2}$ | $1 \times 10^{20}$ (fixed) |
| $kT_1$    | eV       | $100^{+40}_{-20}$ |
| $kT_2$    | eV       | $840^{+570}_{-250}$ |
| Oxygen Abundance |       | 310±250 |
| $\chi^2$  |       | 0.64 |
| Degrees of freedom |       | 12 |
cal’ relation $L_X \sim 10^{-7} \times L_{bol}$ obtained for the normal, giant and supergiant early-type O stars, which are known since a long ago as X-ray sources (Pallavicini et al. 1981; Sciortino et al. 1990; Güdel & Nazé 2009). The hypothesis of intrinsic origin for the X-ray emission of BD +37° 1977 is further supported by the spectral analysis. In fact, considering the likely possibility of non-Solar composition, the spectrum can be successfully described by the sum of two thermal plasma components, as in normal early-type stars.

It is interesting to compare the properties of the three sdOs for which X-ray spectral information is available (Table 4). The spectrum of HD 49798 during the eclipse phase can be described by the sum of three thermal plasma components (Mereghetti et al. 2013). While the hottest component is re-

The spectrum of HD 49798 during the eclipse phase can be for which X-ray spectral information is available (Table 4). Its flux $f_X \simeq 6.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ implies a luminosity $L_X \simeq 2.9 \times 10^{31}$ erg s$^{-1}$ (for a distance of 2 kpc), hence a X-ray/bolometric luminosity ratio $L_X/L_{bol} = 10^{-6.3}$.

These results indicate that the X-ray emission from these three luminous sdO stars is similar to that of normal O-type stars, which have luminosities up to a few $10^{33}$ erg s$^{-1}$. In these stars the X-ray emission is due to turbulence and shocks in their strong embedded winds (Lucy & White 1980; Owocki et al. 1988). Since the mass-loss rate in the radiation-driven winds of early type stars scales with the bolometric luminosity, and the X-ray emission originates in the stellar wind, a correlation between $L_X$ and $L_{bol}$ is not surprising (see, e.g., Owocki et al. 2013). In this respect it is interesting to note that the three X-ray emitting sdOs are among the few hot subdwarfs for which evidence of mass loss has been reported (Jeffery & Hamann 2010). Our results indicate that, even if the winds of sdO stars are rather weak (e.g. $M = 10^{-8.2} M_\odot$ yr$^{-1}$ for BD +37° 1977 according to the estimate of Jeffery & Hamann 2010), they can produce X-ray emitting shocks, as in more luminous O type stars. In this framework, we note that our findings for sdO stars are supported by the methodology used and the results obtained by Cohen et al. (2014), who investigated the X-ray spectra of O-type stars with very low mass-loss rates.

Fig. 4. Top panel: EPIC pn spectrum of BD +37° 1977 with the best-fit model composed by the sum of two thermal plasma components, with abundances from Jeffery & Hamann (2010) and free Oxygen abundance. Bottom panel: residuals (in units of $\sigma$) between data and model.
Table 4. Summary of the best-fit parameters of the three sdO stars observed with XMM–Newton, when their spectrum is described with multi-temperature thermal-plasma components (MEKAL in XSPEC).

| Source                  | $kT_1$  | $kT_2$  | $kT_3$  | log($L_X/L_{bol}$) | Reference                  |
|-------------------------|---------|---------|---------|--------------------|----------------------------|
| HD 49798 (in eclipse)   | 0.13 ± 0.02 | 0.71 ± 0.15 | 5 (fix) | -7.1              | Mereghetti et al. (2013)  |
| BD +37° 442             | 0.17 ± 0.02 | 0.72 ± 0.22 | -        | -6.3              | This work                  |
| BD +37° 1977            | 0.13 ± 0.01 | 0.79 ± 0.15 | -        | -6.5              | This work                  |

Fig. 5. Level of the X-ray flux (or its upper limit for the undetected sources) of the sdO stars observed at X-rays, as a function of their bolometric magnitude. The upper and lower blue lines (corresponding to $f_X/f_{bol} = 10^{-6.2}$ and $f_X/f_{bol} = 10^{-7.2}$, respectively) include the range of expected values for the main-sequence early-type stars; the red line corresponds to $f_X/f_{bol} = 10^{-6.7}$, which is the best-fit relation found by Nazé (2009) for this type of stars.

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