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X-ray emission of HD 37479: a Bf?p-star?

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We propose that the B2Vp star HD 37479 belongs to a new peculiar class Bf?p. We determine the base criteria for selection of Bf?p type objects are the presence of a strong emission component in the profiles of hydrogen lines and the spectral variability in lines of He, C, Si ions and Balmer lines, the strong and probably active X-ray emission. We have analysed archival X-ray observations of HD 37479 and compare our results with those for Of?p stars. Based on our analysis we conclude that Sigma Ori E is a typical Bf?p star.

Keywords: Stars: peculiar; individual: HD 37479, HD 148937, HD 191612

1 Introduction

A new peculiar type of massive O stars named as Of?p was introduced by Walborn (1973). The Of?p classification criteria are a variability of line profiles of He I, C III, Si III and Balmer line and emission in C IIIλ 4650 Å. Only five of Of?p stars CPD-28 2561, HD 108, HD 148937, NGC 1624-2 and HD 191612, are known in the Milky Way (Walborn et al. 2010) and recent observations reveal a presence of a strong magnetic field in all Of?p stars (Hubrig et al. 2015, Shultz & Wade 2017, Wade et al. 2012a,b, Hubrig 2010). The Of?p stars appear to be bright X-ray sources (e.g. Wade et al. 2012b). Some Of?p-stars were detected in Magellanic clouds: SMC 159, LMC 164, 2dfs936, Bi57, AV 220 (Munoz et al. 2017). The first four stars from this list appear to be magnetic. The magnetic field of star AV 220 has not yet been detected but it is very likely that this star is also magnetic.

There exists a subgroup of B0–B2 stars and their properties are similar to those of Of?p stars. They have a significant emission contribution into line profiles of Hα and Hβ lines, variable profiles of Balmer lines and lines of He, C, Si ions and strong or moderate magnetic field. This group of stars includes B0 star CPD-62° 6124 (Hubrig et al. 2017b), HD 345439 (Hubrig et al. 2017b, Petit et al. 2013), B2IV-Vp_He star HD 37479 (Oksala et al. 2012) and B1Iab supergiant ρ Leo (Kholtygin et al. 2007).

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We can previously call these stars as Bf?p stars. All Of?p stars possess strong X-ray radiation. So we can suppose as a classification criteria that Bf?p stars are also strong X-ray emitters. We start a new program to investigate the X-ray properties of suspected Bf?p objects. In the present paper we study in detail the B2Vp star HD 37479 to check its X-ray properties. An X-ray observation of σ Ori E was made both by "Chandra" and "XMM-Newton" orbital observatories (Pavallicini et al., 2002, Sanz-Forcada et al, 2004, Skinner et al, 2008). X-ray flares occur for this star so it indicates that σ Ori E can be a binary system.

In our work we have made an independent analysis of the X-ray spectrum of HD 37479 and comprised the result with a spectra of two typical Of?p stars HD 148937 and HD 191612. In Section 2 the main properties of the star are described. In Section 3 the source data and data reduction procedures are presented. The spectra modeling procedure is described in Section 4. Finally, some conclusions are given in Section 5.

2 Main properties of HD 37479

HD 37479 (σ Ori E) is known as a young object (B2IV-Vp_He C) with peculiar properties. Its main parameters are given in Table 1. The coordinates of the star and distance to the star are taken from the SIMBAD database*. The value of the polar magnetic field B_p is taken from a paper by Petit et al. (2013) and the rotation period P is given by Reiners et al. (2000). The total X-ray flux of HD 37479 is estimated by Petit et al. (2013) using the distance given in Table 1.

Table 1 The basic parameters of HD 37479.

Parameter	Value	Ref.
ICRS coord. (ep = J2000)	05 38 47.198 –02 35 40.540	SIMBAD
Spectral type	B2Vp	(Naze et al., 2014)
d	500 pc	(Naze et al., 2014)
B_p	9.6 G	(Petit et al., 2013)
P	1,1908 d	(Reiners et al., 2000)
$\log(L_{\rm X})$	29.19 erg s^{-1}	(Naze et al., 2014)

There is a strong emission component in the profile of H_α line in spectra of HD 37479 (see Fig. 6 in Petit et al. 2013). Oksala et al. (2012) revealed a variability on Hα and Hβ line profile in spectra of this star. This variability is connected with rigid rotation of the stellar magnetosphere which can be described by Rigidly Rotating Magnetosphere model (RRM, Townsend & Owocki, 2005). According to the RRM model the magnetosphere of σ Ori E consists of two bubbles. The magnetosphere rotation can explain the changing of the magnetic field during the rotational phase.

In addition Caballero et al. (2016) showed the binarity of the star using the observation on Calar Alto telescope. The authors proposed HD 37479 to be a close binary system consisting of a main B star and a K dwarf. K dwarf has a mass $2.0^{-0.2}_{+0.1} M_\odot$, and a distance between the companions is about 130 AU.

*simbad.u-strasbg.fr/simbad

3 Observation and data reduction

We have analysed archival X-ray observation obtained by the "Chandra" space observatory. For comparison of σ Ori E with peculiar Of?p stars we analysed observation of HD 148937 and HD 191612 obtained by the same satellite. Log of observation is given in Table 2.

Table 2 Log of observations. In the first column the object names are given. In the second column we put the observation ID numbers. The dates of the observation and exposition in seconds are presented in the third and fourth columns respectively.

Object	ObsID	Obs.date	Exp. (s)
HD 37479	3738	12.08.2003	92130
HD 148937	10982	5.06.2010	100040
HD 191612	17489	9.05.2015	44490
	16653	4.07.2015	38510
	17694	12.07.2015	36340
	17655	12.05.2015	24030

Our data analysis of X-ray observational data is made using the CIAO 4.7 software and following the recommendation of "Chandra" team[†]. We extracted the spectra of stars with *specextract* tool. Four spectra from the different sets of HD 191612 observations were combined. After we fitted 0.5–8 keV range of background subtracted stellar spectra with "Sherpa" package[‡].

4 Spectral analysis

For spectra approximation we used the plasma models APEC[§] and MEKAL[¶].

The parameters of our approximations are presented in Table 3. In the 1st column the code of the plasma model used is given. WABS letters mean that to take into account the interstellar absorption we multiply the model data on that calculated in WABS[‖] interstellar absorption model. The designation APEC+APEC means that we use the two component APEC plasma model. Analogously via MEKAL+MEKAL we designate two temperature MECAL plasma model.

In the 2nd column the hydrogen column density used in the WABS model is given. Each component both in APEC and MECAL model is determined by their temperature kT and the emission measure EM. Instead of EM, the parameter $norm$ described by the relation

$$norm = \frac{10^{-14}\, EM}{4\pi d^2} \tag{1}$$

[†] cxc.harvard.edu/ciao
[‡] cxc.harvard.edu/sherpa
[§] cxc.cfa.harvard.edu/sherpa/ahelp/xsapec
[¶] cxc.cfa.harvard.edu/sherpa/ahelp/xsmekal
[‖] cxc.cfa.harvard.edu/sherpa/ahelp/xswabs

Table 3 The parameters of spectra fitting for program stars.

Model	$N_{\rm H}, 10^{22}{\rm cm}^{-2}$	kT_1, keV	$norm_1, 10^{-5}$	kT_2, keV	$norm_2, 10^{-5}$	Abundance	χ^2 (d.o.f)
			HD 37479 (FF)				
WABS·(APEC+APEC)	$0.012^{\dagger}$	$0.34^{-0.04}_{+0.46}$	$3.22^{-0.91}_{+0.64}$	$1.33^{-0.06}_{+0.27}$	$6.40^{-0.68}_{+0.69}$	1	0.78 (73)
WABS·(MEKAL+MEKAL)	$0.012^{\dagger}$	$1.33^{-0.6}_{+0.11}$	$9.26^{-1.26}_{1.69}$	$0.47^{-0.17}_{+0.13}$	$4.20^{-0.71}_{+0.83}$	1	0.71 (73)
			HD 191612 (FF)				
WABS·(APEC+APEC)	$0.32^{\dagger}$	$0.76^{-0.06}_{+0.05}$	$30.72^{-3.60}_{+3.12}$	$2.27^{-0.24}_{+0.27}$	$48.33^{-4.35}_{4.92}$	1	0.62 (120)
WABS·(MEKAL+MEKAL)	$0.32^{\dagger}$	$2.17^{-0.18}_{+0.23}$	$54.12^{-4.39}_{+4.39}$	$0.62^{-0.05}_{0.05}$	$0.36^{-3.85}_{+3.85}$	1	0.61 (120)
			HD 148937 (FF)				
WABS·(APEC+APEC)	$0.39^{\dagger}$	$0.81^{-0.02}_{+0.02}$	$147.38^{-6.05}_{+6.05}$	$2.55^{-0.12}_{+0.12}$	$181.76^{-8.86}_{+8.86}$	1	0.82 (244)
WABS·(MEKAL+MEKAL)	$0.39^{\dagger}$	$0.66^{-0.02}_{+0.02}$	$172.84^{-6.99}_{+6.99}$	$2.43^{-0.11}_{+0.11}$	$205.60^{-8.80}_{+8.80}$	1	0.80 (244)
			HD 37479 (FV)				
WABS·(APEC+APEC)	$0.012^{\dagger}$	$1.17^{-0.16}_{+0.13}$	$20.65^{-5.14}_{+8.03}$	$0.45^{-0.13}_{+0.21}$	$9.07^{-3.63}_{+19.65}$	$0.15^{-0.07}_{+0.13}$	0.68 (72)
WABS·(MEKAL+MEKAL)	–	–	–	–	–	–	–
			HD 191612 (FV)				
WABS·(APEC+APEC)	$0.32^{\dagger}$	$2.37^{-0.26}_{+0.27}$	$40.98^{-8.48}_{+8.68}$	$0.76^{-0.05}_{+0.05}$	$20.88^{-7.14}_{+10.40}$	$1.53^{-0.53}_{+0.86}$	0.61 (119)
WABS·(MEKAL+MEKAL)	$0.32^{\dagger}$	$2.28^{-0.20}_{+0.30}$	$43.75^{-10.28}_{+10.32}$	$0.62^{-0.04}_{+0.04}$	$22.65^{-8.35}_{+11.95}$	$1.65^{-0.61}_{+1.06}$	0.61 (119)
			HD 148937 (FV)				
WABS·(APEC+APEC)	$0.39^{\dagger}$	$0.82^{-0.02}_{+0.02}$	$200.29^{-32.64}_{+41.67}$	$2.57^{-0.13}_{+0.15}$	$193.98^{-11.89}_{+12.56}$	$0.72^{-0.13}_{+0.15}$	0.81 (243)
WABS·(MEKAL+MEKAL)	$0.39^{\dagger}$	$0.66^{-0.02}_{+0.02}$	$222.92^{-36.88}_{+47.24}$	$2.43^{-0.12}_{+0.12}$	$219.90^{-13.54}_{+13.97}$	$0.76^{-0.14}_{+0.16}$	0.80 (243)

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Table 3 (continued)

Model	$N_{\rm H}, 10^{22}{\rm cm}^{-2}$	kT_1, keV	$norm_1, 10^{-5}$	kT_2, keV	$norm_2, 10^{-5}$	Abundance	χ^2 (d.o.f)
			HD 37479 (VF)				
WABS·(APEC+APEC)	$0.27^{-0.23}_{+0.19}$	$1.21^{-0.14}_{+0.12}$	$10.94^{-2.42}_{+1.80}$	$0.26^{-0.04}_{+0.08}$	$29.47^{-24.68}_{+74.33}$	1	0.73 (77)
WABS·(MEKAL+MEKAL)	–	–	–	–	–	–	–
			HD 191612 (VF)				
WABS·(APEC+APEC)	–	–	–	–	–	–	–
WABS·(MEKAL+MEKAL)	$0.32^{-0.10}_{+0.10}$	$0.62^{-0.05}_{+0.06}$	$35.51^{-12.82}_{+17.74}$	$2.17^{-0.18}_{+0.23}$	$54.12^{-4.52}_{+4.39}$	1	0.62 (119)
			HD 148937 (VF)				
WABS·(APEC+APEC)	$0.85^{-0.04}_{+0.04}$	$1.95^{-0.06}_{+0.07}$	281^{-11}_{+11}	$0.24^{-0.01}_{+0.02}$	3739^{-114}_{+139}	1	0.97 (243)
WABS·(MEKAL+MEKAL)	$0.39^{-0.06}_{+0.06}$	$0.66^{-0.02}_{+0.03}$	174^{-38}_{+43}	$2.43^{-0.11}_{+0.12}$	206^{-10}_{+9}	1	0.81 (243)
			HD 37479 (VV)				
WABS·(APEC+APEC)	-	–	–	–	–	–	–
WABS·(MEKAL+MEKAL)	–	–	–	–	–	–	–
			HD 191612 (VV)				
WABS·(APEC+APEC)	$0.80^{-0.11}_{+0.10}$	$1.80^{-0.34}_{+0.15}$	$55.52^{-15.26}_{+21.55}$	$0.20^{-0.03}_{+0.04}$	890^{-579}_{+2075}	$1.70^{-0.70}_{+1.08}$	0.64 (118)
WABS·(MEKAL+MEKAL)	–	–	–	–	–	–	–
			HD 148937 (VV)				
WABS·(APEC+APEC)	$0.27^{-0.03}_{+0.04}$	$2.57^{-0.15}_{+0.20}$	204^{-2}_{+16}	$0.90^{-0.04}_{+0.03}$	157^{-3}_{+4}	$0.58^{-0.11}_{+0.13}$	0.79 (242)
WABS·(MEKAL+MEKAL)	$0.96^{-0.16}_{+0.03}$	$1.90^{-0.07}_{+0.07}$	342^{-3}_{+31}	$0.20^{-0.01}_{+0.08}$	10684^{-8495}_{+583}	$0.76^{-0.15}_{+0.18}$	0.86 (242)

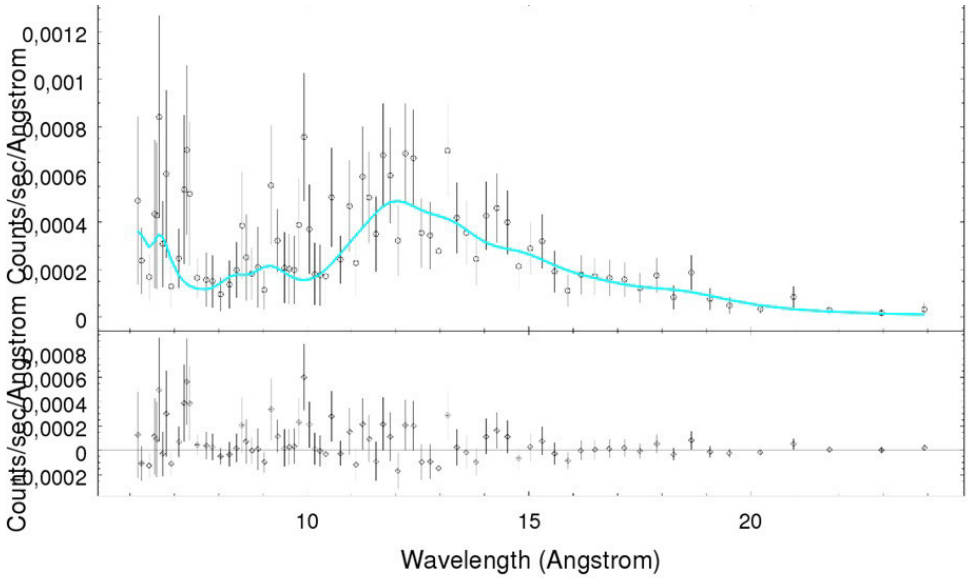


Figure 1 The fit of the X-ray spectra of HD 37479 by the model WABS*(APEC+APEC) with a free parameter of N_H (top panel). The corresponding residuals are given in the bottom panel.

is used. Here d is the distance to the object in pc. Parameters kT_1 and $norm_1$ for the first plasma component are given in columns 3 and 4. The corresponding values kT_2 and $norm_2$ for the second plasma component are given in columns 5 and 6.

A parameter "Abundance" in the 7th column is the ratio of the model element abundances normalized to the solar value given by Lodders (2003). The last column includes the χ^2 value of the model fit, which characterizes the approximation accuracy and number of degrees of freedom (d.o.f).

We used four possible types of the model fit with fixed or varied values of hydrogen column density N_H and the parameter "Abundance". Fixed values of hydrogen column density N_H are taken from Naze et al. (2014). The absence of the fit parameter in the table row means that the corresponding model cannot describe the observed X-ray spectrum with a sufficient accuracy.

In Table 3, the code of the fit is given after the star name. The code **FF** corresponds to the model with fixed N_H and "Abundance" parameter. Code **FV** means that N_H is fixed and "Abundance" is varied. The meaning of codes **VF** and **VV** is evident.

The value $\chi^2 < 1$ for all fits is presented in Table 3. It means that the quality of the fit for all stars considered by us is good and depends weakly on the model code. An example of the X-ray spectrum fit for HD 37479 is given in Fig. 1.

The X-ray emission of Of?p stars is described within the framework of the Magnetic Confined Wind Shock model (MCWS, Babel & Montmerle, 1997; ud-Doula & Owocki, 2002). As we can see from fit parameters given in Table 3 the X-ray spectra of σ Ori E can be described with the model parameters which are similar to those which

are typical for Of?p stars. It probably means that the X-ray emission of HD 37479 can be also presented in a framework of MCWS model. It may also mean that the presence of strong X-ray emission can be used as a classification criterion for Bf?p stars.

5 Summary

Based on our analysis of the X-ray spectra of σ Ori E in a comparison with the X-ray spectra of Of?p-stars we can conclude that the X-ray spectrum of this star can be described by the same MCWS models, which describe the X-ray spectra of Of?p stars. It means that the strong X-ray emission can be considered as one of the classification criteria for Bf?p stars.

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