Research Article

Elizaveta B. Ryspaeva* and Alexander F. Kholtygin

A possible nonthermal X-ray emission from γ Cas analogues stars

<https://doi.org/10.1515/astro-2021-0018>

Received Oct 19, 2021; accepted Dec 02, 2021

Abstract: We analyze the archival XMM-Newton X-ray observations of 15 γ Cas analogue stars and two candidates for such objects. The EPIC spectra of the considered stars in the range of 0.2–8 keV were extracted and fitted by different models. Our estimates show that assuming the X-ray emission from γ Cas analogues to be totally thermal, their model plasma temperatures can reach anomalously high values. However including an additional power components to the model spectra leads to significant decreasing of the plasma temperatures. The spectral index of the power component is about 1.5, and the fraction of this in the total model flux is rather large (50–90%). Moreover, it decreases with expanding temperature of the X-ray emitting plasma as compared to typical OB stars. We conclude that γ Cas analogues can produce nonthermal X-ray emission within the framework of the Chen & White (1991) model, while if the nonthermal X-rays from typical OB stars exists, they should be generated by different processes.

Keywords: stars, X-rays, spectra

1 Introduction

The γ Cas analogues are enigmatic Oe and Be stars with very strong X-ray emission and X-ray luminosities up to $L_X \sim 10^{32} \text{ erg s}^{-1}$. Supposing that the X-ray emitting plasma is thermal, its temperature can reach 10–20 keV and more. These values are higher than those for typical OB stars but smaller than typical temperatures for High Mass X-ray Binaries (HMXB). Such stars demonstrate variations of their X-ray emission on a timescale from a few minutes to a few years. The γ Cas analogues are supposed to have the circumstellar Keplerian decretion disks that manifest themselves via strong emission lines in the optical spectra (Naze *et al.*, 2020).

The phenomenon of γ Cas analogues still remains debated. The large-scale magnetic field of stars is unlikely to be responsible for the γ Cas analogue X-rays, because the formation of Keplerian decretion disks is incompatible with the presence of a strong dipolar magnetic fields (Grunhut *et al.*, 2012; ud-Doula *et al.*, 2018). But localized small-scale magnetic fields can interact with instability-

generated fields of the disk, leading to flaring X-ray emission (Robinson *et al.*, 2002).

According to Hamaguchi *et al.* (2016) and Postnov *et al.* (2017) the X-rays from these enigmatic stars can be generated due to the accretion onto a compact companion. Smith *et al.* (2016) also consider an interaction of the star and disk magnetic fields as a possible source of X-rays. Later Ryspaeva & Kholtygin (2020) proposed that γ Cas analogues can be the sources of nonthermal X-rays, which are formed in a framework of Chen & White (1991) theory. In such case X-ray emission is “produced through the inverse Compton mechanism when the stellar UV photons are scattered by relativistic electrons accelerated by shocks in the stellar wind near the star”¹.

In the present paper we test and develop the results by Ryspaeva & Kholtygin (2020) analyzing a more extended sample of objects. The paper is organized by the following manner. Section 2 describes the observations used and their reduction. The applied X-ray models are described in Section 3. Results of spectral fits are presented in Section 4. A comparison of the X-ray spectra of γ Cas analogues with those of typical OB stars is given in Section 5. The general conclusions are given in Section 6.

Corresponding Author: Elizaveta B. Ryspaeva: Crimean Astrophysical Observatory, Nauchnyy, Crimea, Russia; Email: e.ryspaeva@yandex.ru

Alexander F. Kholtygin: Saint-Petersburg State University, Saint-Petersburg, Russia

¹ This is a quote from Chen & White (1991) paper.

2 Observations and data reduction

We reanalyzed the archival *XMM-Newton* X-ray observations of 15 γ Cas analogues and two candidates for such objects HD 42054 and HD 120678. The log of observations is presented in Table 1.

Table 1. Log of observations.

Star	ObsID	Data	Exposition, s
HD42054	402121401	2007-04-11	15709
HD44458	820310301	2018-09-08	15900
HD45314	670080301	2012-04-14	26226
HD45995	820310401	2018-09-24	13000
HD110432	504730101	2007-09-04	80677
HD119682	551000201	2009-03-06	57270
HD120678	820310601	2019-03-10	50000
HD120991	402121801	2007-01-25	10951
HD130437	840910401	2019-09-20	7300
HD157832	551020101	2008-09-05	21920
HD161103	201200101	2004-02-26	17823
	691760101	2012-09-08	22917
HD162718	840910501	2019-03-22	19800
HD183362	840200401	2019-10-03	9000
HD212571	720390701	2013-11-17	54500
HD316568	206590201	2004-09-05	20915
	402280101	2006-09-10	44112
SA049725	201200201	2003-12-09	11515
V2156Cyg	840910601	2019-11-30	18000

We extracted and analyzed the low-resolution stellar spectra from the EPIC (“European Photon Imaging Camera”) images. The data reduction was performed using the SAS 19.0 software following the recommendation of the SAS team².

First of all we made the preliminary pipeline of observation data files by the *emproc* script for EPIC-MOS1/EPIC-MOS2 data, and by the *epproc* script for EPIC-PN data. The filtration of the EPIC-images from background flares was performed with the *tabgtigen* and *esfilter* tasks. The stellar spectra were extracted from the “clean” images by the *evselect*, *arfgen*, and *rmfgen* procedures. The spectra of sources were obtained from the circle region with a radius of not less than $15'$ centered on the stellar coordinates. They were taken from the SIMBAD³ database and corrected by the images. The background spectra were obtained from the regions of the same size in the places free of other bright

sources. The background spectral correction was performed using the *specgroup* task.

For each star from our sample we have got three low-resolution spectra extracted from the EPIC-PN, EPIC-MOS1, EPIC-MOS2 images. The EPIC-PN, EPIC-MOS1, and EPIC-MOS2 spectra obtained on different dates were merged using the *epicspeccombine* command. The stars HD 161103 and HD 316568 were observed twice and their spectra obtained on different dates were also merged.

Futhermore, we extracted light curves with a 200 s step from the EPIC images in the energy bands of 0.2–8 keV and 2–8 keV. Stellar and background light curves were extracted from the same regions as stellar and background spectra using the *evselect* procedure. Background light curves were subtracted by the *epiclccorr* task. A visual inspection of light curves did not showed fast changes of count rate during the observations.

3 X-rays spectral models

We fit stellar spectra in the 0.2–8 keV energy band by different models within the “XSPEC 12.10.0”⁴ package. The EPIC-PN, EPIC-MOS1, EPIC-MOS2 spectra are fitted simultaneously. First we approximate spectra by the sums of models APEC (Astrophysical Plasma Emission Code by Smith *et al.* (2001)) or MEKAL (Mewe *et al.*, 1985, 1986; Liedahl *et al.*, 1995)⁵ Both models describe the X-ray emission from hot gas with the atoms ionized by electron impact. These models are characterized by the following parameters:

- kT is the plasma temperature in keV;
- $norm$ is the normalized parameter that depends on the emission measure EM and determines a fraction of plasma with the temperature kT :

$$norm = \frac{10^{-14}}{4\pi d^2} \cdot EM, \quad (1)$$

where the emission measure

$$EM = \int n_e n_H dV. \quad (2)$$

Here d is the distance to the source (in cm), n_e and n_H are the electron and hydrogen number densities (in cm^{-3}) respectively.

- *Abundance* is the metal abundance parameter in X-ray emitted plasma in solar units based on data from the list of Anders & Grevesse (1989), we used

² www.cosmos.esa.int/web/xmm-newton

³ <http://simbad.u-strasbg.fr/Simbad>

⁴ <https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

⁵ Thereafter – thermal models.

this parameter as common in sums of all models for a given star.

Also we use the model of plane-parallel post-shock wave PSHOCK of Borkowski *et al.* (2001). This model describes nonstationary thermal X-ray emission from the hot plasma heated by shock waves. This model is characterized by the same parameters as the APEC/MEKAL and the additional ionization timescale parameter τ_u (in s cm^{-3}). The parameter

$$\tau_u = T_{\text{char}} \cdot n_e \quad (\text{s} \cdot \text{cm}^{-3}). \quad (3)$$

where n_e is the postshock electron number density and T_{char} is the characteristic time. In the original model PSHOCK of Borkowski *et al.* (2001) developed for the supernova remnants T_{char} is the remnant's age t_0 . For the stellar winds we can specify the value of T_{char} to be equal to the plasma cooling time.

For all combinations of the considered models we estimated the average plasma temperature

$$\langle kT \rangle = \frac{\sum_{i=1}^n T_i \cdot \text{norm}_i}{\sum_{i=1}^n \text{norm}_i}. \quad (4)$$

Here T_i is the temperature of the hot plasma for the contributed model with the number i , n is the number of the model, and norm_i is the normalized parameter (1) for the corresponding plasma component. Average plasma temperatures $\langle kT \rangle$ for γ Cas analogues are close to the highest temperature in the case of a two-temperature model.

To search for the possible nonthermal contributions to the common X-ray fluxes in the spectra of γ Cas analogues we fit their X-ray spectra by sums of the APEC, MEKAL or PSHOCK models with the addition of a power law (PL) component. Last model describes nonthermal emission. Together with the spectral index G and the amplitude norm_{PL} of the PL we calculated a fraction of the power component in the whole model flux $H_{\text{total}}(0.2-8 \text{ keV})$ in the 0.2-8 keV range:

$$F_{\text{PL}} = \frac{H_{\text{PL}}(0.2-8 \text{ keV})}{H_{\text{total}}(0.2-8 \text{ keV})}, \quad (5)$$

where $H_{\text{PL}}(0.2-8 \text{ keV})$ is the model flux for the PL component only.

Likewise we test whether the hypothesis of Chen & White (1991) is valid for the γ Cas analogues. Chen & White supposed that the nonthermal X-rays from the stars should be described by the power law with the spectral index $G = 1.5$. For this reason we considered the models with both fixed and free parameter G .

To take into account interstellar absorption and possible circumstellar absorption of X-rays, the sums of additive

models were multiplied on the TBABS model of Wilms *et al.* (2000). Last model presents the cross section for X-ray absorption by the interstellar medium (ISM) as a sum of cross sections for X-ray absorption by the gas, grains, and molecules in the ISM. The TBABS model is characterized by the single parameter of hydrogen column density N_{H} in 10^{22} cm^{-2} . To estimate a value of the possible local X-ray absorption by the circumstellar disk or/and stellar wind we subtracted from our N_{H} parameters the interstellar values, which are calculated via the expression of Gudennavar *et al.* (2012):

$$N_{\text{H}}^{\text{G}} = E(B-V) \cdot 6.12 \cdot 10^{21} \text{ cm}^2. \quad (6)$$

In the cases when the hydrogen column density N_{H} determined in our fitting appeared to be less than the value of N_{H}^{G} calculated from Eq. 6 we fixed $N_{\text{H}} = N_{\text{H}}^{\text{G}}$ and multiplied the sum of models by the additional photoelectric absorption model PHABS of Balucinska-Church & McCammon (1992) to determine the local column density $N_{\text{H}}^{\text{local}}$.

Besides we calculated three model independent characteristics of the studied spectra:

- absorbed X-ray luminosities in intervals 0.2-8 keV and 2-8 keV

$$L_X(0.2-8 \text{ keV}) = 4\pi d^2 H(0.2-8 \text{ keV}), \quad [\text{erg s}^{-1}], \quad (7)$$

and

$$L_X(2-8 \text{ keV}) = 4\pi d^2 H(2-8 \text{ keV}), \quad [\text{erg s}^{-1}], \quad (8)$$

- hardness ratio (e.g. Naze *et al.*, 2014)

$$HR = \frac{H(2-8 \text{ keV})}{H(0.2-2 \text{ keV})}, \quad (9)$$

- fraction of hard luminosity

$$F_{\text{HL}} = \frac{H(2-8 \text{ keV})}{H(0.2-8 \text{ keV})}. \quad (10)$$

4 Fitting X-ray spectra

A list of the considered stars along with their spectral types, distances, color excesses $E(B-V)$ and the above model independent parameters of X-rays is given in Table 2. The distances d to the stars are calculated by the parallaxes, which were defined in the Gaia DR2 online catalogue (2018)⁶. Color excesses are extracted from the “Stilism” interface⁷

⁶ <http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/345>

⁷ <http://stilism.obspm.fr>

Figure 1. The best fits of stellar spectra by thermal models. The contributions of individual components into the total model X-ray spectra are shown by color lines. For the model spectrum of HD 162718 (*bottom panel*), confidence ranges of plasma temperature are presented.

(Capitanio *et al.*, 2017), but E(B-V) for HD 316568 is taken from Marshall *et al.* (2006).

The results of our spectral fitting are presented in Tables 3–7. Table 3 shows the results of the model fits for combinations of two thermal models APEC or MEKAL. For stars marked with † we are unable to estimate $N_{\text{H}}^{\text{local}}$. For these stars the interstellar value N_{H} obtained within the TBABS model given in the table. A value of 1.0 for the *Abundance* means that this parameters are fixed in one solar unit. A reduced χ^2/n statistics and degrees of freedom (in brackets) are given in the last column of table.

Figure 1 provides the fits of X-rays by thermal models for the selected γ Cas analogues with the labeled contributions of the components with different temperatures. As can be

Figure 2. The same as in Figure 1 but for APEC/MEKAL+PSHOCK models.

Figure 3. The same as in Figure 1 but for APEC/MEKAL+PL models.

seen from the figure and from data in Table 3 it is mandatory to use high plasma temperature, since an excess of X-ray radiation in the 2-8 keV range can be reproduced only for extremely high plasma temperatures up to $kT \sim 40$ keV.

Figure 4. The same as in Figure 1 but for APEC/MEKAL+PL models with fixed spectral index $G = 1.5$.

Table 4 shows the results of the model fits for combinations of both one of the thermal models APEC/MEKAL and

the PSHOCK. The ionization parameter τ_u is tabulated in Column 7 of the table.

Figure 2 demonstrates the fits of X-rays by the APEC/MEKAL+PSHOCK models for the same objects as in Figure 1 excluding HD 44458. Analyzing this figure and the data of Table 4 one can conclude that as for the purely thermal APEC/MEKAL model combinations high temperatures of the shocked plasma are mandatory for most stars. As such temperatures for shocks in the stellar winds of OB stars are hardly achievable we can suggest that the applicability of the combination of APEC/MEKAL+PSHOCK models for describing X-ray spectra of all γ Cas analogues is doubtful.

The results of our spectral fitting by two PSHOCK models only are given in Table 5. Such approximation can be used only for 6 stars. Moreover in this approach similar to the APEC/MEKAL+PSHOCK model combination too high plasma temperatures kT_{shock} are needed. It means that PSHOCK+PSHOCK model is also hardly applicable to describe the X-ray spectra of γ Cas analogues.

Parameters of the spectral fit for the thermal models with a contribution of the PL component are given in Table 6. In this table asterisks indicates spectral fits when the Fe 6.4 keV K_α line is absent in the model spectrum. Analyzing the data of Table 6 we can conclude that the fixation of the G value leads to decreasing fraction of the power component F_{PL} in the total X-ray model flux.

Table 2. List of targets, their parameters, and model independent characteristics of X-ray spectra.

Star	Sp.Type	d, pc	E(B-V)	HR, rel. un.	$L_X(0.2-8 \text{ keV})$, $10^{32} \text{ erg s}^{-1}$	$L_X(2-8 \text{ keV})$, $10^{32} \text{ erg s}^{-1}$	F_{HL} %
HD 42054	B5Ve	337	0.012	1.13±0.05	0.44±0.02	0.23±0.01	52.48±4.66
HD 44458	B1.5IVe	624	0.108	1.98±0.04	0.94±0.05	0.62±0.04	66.37±7.79
HD 45314	O9:npe	2100	0.331	4.29±0.27	6.2±0.22	5±0.23	80.88±6.58
HD 45995	B1.5Vne	668	0.122	1.78±0.30	0.69±0.04	0.44±0.04	64.32±9.53
HD 110432	B0.5IVpe	301	0.326	3.02±0.29	1.2±0.03	0.89±0.05	74.32±6.02
HD 119682	B0Ve	1692	0.320	2.70±0.03	4.22±0.25	3.06±0.21	73.06±9.30
HD 120678	O9.5Ve	2485	0.421	2.28±0.55	1.16±0.19	0.8±0.19	73.62±28.44
HD 120991	B2Ve	7949	0.070	1.80±0.13	242.48±11.5	152.42±9.51	63.19±6.92
HD 130437	B1Ve	1741	0.447	5.31±0.60	16.72±1.99	13.93±1.91	85.89±21.65
HD 157832	B2ne	1104	0.140	3.42±0.30	4.29±0.32	3.3±0.3	77.88±12.80
HD 161103	B0.5III/IVe	1209	0.752	3.74±0.13	3.36±0.11	2.63±0.08	78.44±4.95
HD 162718	B3/5ne	768	0.310	5.29±0.32	3.37±0.06	2.8±0.04	83.13±2.67
HD 183362	B3Ve	580	0.036	2.27±0.27	0.79±0.07	0.55±0.07	70.96±15.15
HD 212571	B1III-IVe	240	0.059	3.15±0.07	0.68±0.01	0.51±0.01	75.04±2.57
HD 316568	B3	2175	0.540	2.64±0.75	0.71±0.16	0.51±0.16	81.02±40.79
SAO 49725	B0.5III/IVe	2680	-	3.89±0.41	8.36±0.49	6.66±0.45	80.26±10.09
V2156 Cyg	B1.5V:nnep	934	0.311	7.79±0.12	0.90±0.06	0.79±0.05	88.54±11.46

Table 3. Results from the spectral fits for the APEC/MEKAL models.

Star	$N_{\text{H}}^{\text{local}}$, 10^{22} cm^{-2}	kT_1 , keV	$\log EM_1$, cm^{-3}	kT_2 , keV	$\log EM_2$, cm^{-3}	Abundance, sol. un.	χ^2/n (d.o.f.)
HD 42054	<0.006	0.75±0.05	53.09±0.06	4.08±0.23	54.30±0.01	1.0	1.06 (454)
HD 44458	0.05±0.01	0.99±0.06	53.44±0.07	7.29±1.04	54.66±0.01	1.0	1.31 (446)
HD 45314	0.116±0.036	0.64±0.23	53.56±0.44	14.11±3.08	55.53±0.01	1.0	1.11 (452)
HD 45995	<0.01	1.98±1.30	53.50±0.74	13.13±8.95	54.26±0.19	1.0	1.00 (337)
HD 110432	0.02±0.00	0.80±0.03	53.33±0.05	12.32±0.43	54.876±0.004	0.61±0.05	1.84 (487)
HD 119682 [†]	0.18±0.01	0.81±0.23	53.86±0.19	8.50±0.97	55.36±0.02	0.52±0.15	1.12 (464)
HD 120678	0.57±0.13	0.19±0.05	56.02±0.51	4.81±1.92	54.62±0.07	1.0	0.91 (290)
HD 120991	<0.007	1.00±0.08	55.57±0.11	7.13±0.81	57.05±0.01	1.0	1.23 (445)
HD 130437	0.34±0.07	3.43±0.71	55.64±0.14	34.43±19.63	55.74±0.09	1.0	1.13 (415)
HD 157832	0.14±0.02	1.09±0.17	53.85±0.18	10.13±1.54	55.34±0.02	0.95±0.27	0.92 (445)
HD 161103 [†]	0.36±0.02	0.86±0.10	53.82±0.13	7.77±0.54	55.18±0.01	0.90±0.14	1.01 (474)
HD 162718	0.24±0.03	4.00±3.51	53.88±0.70	38.11±20.78	55.28±0.07	0.88±0.46	1.20 (467)
HD 183362	0.06±0.02	1.18±0.14	53.54±0.28	7.37±1.52	54.56±0.04	0.77±0.34	1.06 (383)
HD 212571	0.171±0.004	1.26±0.07	53.25±0.09	12.70±0.61	54.656±0.005	0.46±0.05	1.19 (488)
SAO 49725 [†]	0.38±0.07	1.06±0.30	54.38±0.38	9.39±2.50	55.63±0.04	0.81±0.38	0.96 (366)

Table 4. The same as in Table 3 but for APEC/MEKAL+PSHOCK models.

Star	$N_{\mathrm{H}}^{\mathrm{local}},$ $10^{22} \mathrm{cm}^{-2}$	$kT_1,$ keV	$\log EM_1,$ cm^{-3}	$kT_{\mathrm{shock}},$ keV	$\log EM_{\mathrm{shock}},$ cm^{-3}	$\tau_u,$ $10^{12}, \mathrm{s} \mathrm{cm}^{-3}$	Abundance, sol. un.	χ^2 (d.o.f.)
HD44458	0.07±0.01	12.39±2.85	54.05±0.21	2.87±0.70	54.55±0.06	1.01±0.45	1.0	1.29 (445)
HD119682	<0.02	0.51±0.16	53.96±0.29	9.02±1.20	55.36±0.02	11.84±9.77	0.45±0.16	1.11 (463)
HD120678	0.26 (fr.)	7.51±3.02	53.69±0.15	1.38±0.61	54.5±0.06	0.26±0.20	1.0	0.86 (290)
HD120991	0.02±0.01	13.36±4.85	56.44±0.34	4.18±0.95	56.87±0.12	1.48±0.66	1.0	1.18 (444)
HD130437	0.56±0.10	3.67±0.97	55.76±0.11	5.26±1.44	55.79±0.12	(9.62±5)·10 ⁻⁴	1.0	1.07 (414)
HD157832	0.17±0.03	0.82±0.24	53.55±0.31	11.10±2.00	55.34±0.01	13.31±10.11	1.0	0.92 (445)
HD161103 [†]	0.39±0.03	0.57±0.09	53.92±0.17	8.95±0.99	55.18±0.01	4.14±2.14	0.77±0.15	0.99 (473)
HD162718	0.30±0.05	2.57±2.22	53.59±0.85	22.24±6.13	55.35±0.02	8.20±7.03	0.46±0.29	1.2 (466)
HD183362	0.16±0.05	0.06±0.03	56.78±1.19	6.78±1.22	54.54±0.03	1.99±0.98	1.0	1.12 (383)
HD212571	0.17±0.01	24.98±2.90	53.94±0.06	4.30±0.30	54.56±0.01	3.00±0.78	1.0	1.35 (488)

Table 5. The same as in Table 3 but for PSHOCK+PSHOCK models.

Star	$N_{\mathrm{H}}^{\mathrm{local}},$ $10^{22} \mathrm{cm}^{-2}$	$kT_1,$ keV	$\log EM_1,$ cm^{-3}	$kT_2,$ keV	$\log EM_2,$ cm^{-3}	$\tau_u,$ $10^{12}, \mathrm{s} \mathrm{cm}^{-3}$	Abundance, sol. un.	χ^2 (d.o.f.)
HD110432	0.05±0.01	0.62±0.05	53.35±0.08	14.58±0.69	54.885±0.004	2.81±0.54	0.43±0.05	1.51 (486)
HD120991	0.61±0.06	0.22±0.02	59.12±0.24	4.90±0.50	57.2±0.03	(5.54±1)·10 ⁻⁴	1.0	1.62 (444)
HD157832	0.17±0.03	0.90±0.26	53.55±0.38	11.94±2.59	55.35±0.03	14.44±13.02	0.74±0.32	0.92 (444)
HD161103 [†]	0.40±0.03	0.70±0.08	53.81±0.16	9.20±1.05	55.18±0.01	2.94±1.23	0.76±0.16	0.98 (465)
HD162718	0.30±0.05	0.58±0.33	53.3±1.08	20.61±4.51	55.35±0.02	8.12±6.88	0.53±0.22	1.2 (466)
HD212571	0.19±0.01	4.98±1.58	53.96±0.27	21.20±5.33	54.57±0.07	3.36±1.07	0.36±0.07	1.1 (487)

Table 6. The same as in Table 3 but for APEC/MEKAL+PL model.

Star	$N_{\mathrm{H}}^{\mathrm{local}},$ $10^{22} \mathrm{cm}^{-2}$	$kT_1,$ keV	$\log EM_1,$ cm^{-3}	G	$norm_{\mathrm{PL}},$ 10^{-4}	$F_{\mathrm{PL}},$ %	χ^2 (d.o.f.)
HD42054	0.06±0.01	1.28±0.05	53.41±0.07	1.97±0.06	5.27±0.38	81.9±0.2	1.37 (454)
*	<0.003	2.88±0.33	54.23±0.06	1.5	1.03±0.47	24.8±0.1	1.53 (455)
HD44458*	0.14±0.02	0.92±0.14	53.33±0.12	1.90±0.07	4.04±0.30	91.6±0.4	1.21 (446)
	0.06±0.01	2.76±0.41	54.31±0.11	1.5	1.74±0.24	59.8±0.2	1.38 (447)
HD45314	0.10±0.03	7.31±4.10	55.03±0.31	1.37±0.16	1.05±0.29	70.4±0.1	1.11 (452)
	0.11±0.03	10.15±4.31	55.11±0.29	1.5	0.90±0.49	53.1±0.02	1.11 (453)
HD45995	<0.012	2.94±1.05	54.14±0.23	1.5	0.66±0.38	44.5±0.1	1.00 (338)
HD119682 [†]	0.020±0.017	0.77±0.56	53.53±0.24	1.65±0.06	1.97±0.17	95.9±0.3	1.16 (465)
*	0.17±0.01	4.65±1.07	54.87±0.14	1.5	1.11±0.20	64.1±0.1	1.16 (466)
HD120678*	0.26 (fr.)	0.78±0.14	53.67±0.17	2.10±0.23	0.21±0.04	77.4±1.4	0.86 (291)
*	0.26 (fr.)	0.65±0.06	54.00±0.06	1.5	0.12±0.01	62.0±2.8	0.91 (292)
HD120991	0.09±0.04	8.07±2.74	56.73±0.17	2.32±0.42	4.03±0.72	58.7±1.1	1.17 (445)
	0.01±0.01	3.91±0.54	56.82±0.08	1.5	2.01±0.47	45.2±0.1	1.23 (446)
HD130437	0.81±0.34	0.45±0.30	56.08±0.79	2.06±0.18	14.49±3.80	93.8±0.6	1.04 (415)
	0.37±0.07	3.34±0.74	55.60±0.15	1.5	4.41±0.90	61.4±0.1	1.70 (416)
HD157832*	0.16±0.02	1.19±0.16	53.98±0.18	1.49±0.07	3.98±0.33	91.8±0.2	0.97 (446)
*	0.16±0.01	1.18±0.24	54.05±0.20	1.5	4.01±0.11	92.6±0.3	0.97 (447)
HD161103 [†] *	0.38±0.02	0.94±0.08	53.82±0.10	1.61±0.04	2.54±0.13	92.1±0.5	1.25 (475)
*	0.35±0.02	1.00±0.06	53.86±0.08	1.5	2.23±0.04	90.9±0.6	1.29 (476)
HD162718	0.25±0.03	15.14±7.99	54.83±0.28	1.42±0.11	4.17±1.55	62.9±0.02	1.21 (468)
*	0.34±0.04	0.51±0.26	53.67±0.51	1.5	7.77±0.18	97.8±0.3	1.23 (469)
HD183362*	0.11±0.03	1.30±0.19	53.50±0.17	1.71±0.12	2.80±0.39	85.3±0.2	1.10 (384)
*	0.07±0.01	1.43±0.21	53.70±0.18	1.5	2.18±0.12	80.0±0.4	1.12 (385)
HD212571	0.19±0.01	6.20±1.15	54.06±0.07	1.52±0.02	12.28±0.68	72.5±0.01	1.30 (489)
	0.188±0.003	5.98±0.57	54.04±0.06	1.5	12.32±0.60	73.9±0.0	1.31 (490)
SAO49725	0.33±0.05	4.90±2.34	55.26±0.24	1.29±0.38	0.60±0.39	51.7±0.2	0.97 (367)
	0.34±0.04	5.08±2.74	55.20±0.29	1.5	0.67±0.44	54.9±0.1	0.98 (371)

Table 7. The same as in Table 3 but for by PSHOCK+PL models.

Star	$N_{\text{H}}^{\text{local}}$, 10^{22} cm^{-2}	kT , keV	$\log EM$, cm^{-3}	τ_{U} , $10^{12} \text{ s cm}^{-3}$	G	$norm_{\text{PL}}$, 10^{-4}	F_{PL} , %	χ^2 (d.o.f.)
HD 42054	0.16 ± 0.05	6.86 ± 1.64	54.16 ± 0.05	1.16 ± 0.36	3.59 ± 0.31	3.68 ± 1.33	34.3 ± 2.4	1.20 (453)
HD 44458	0.09 ± 0.01	3.45 ± 0.59	54.24 ± 0.12	1.46 ± 0.60	1.5	1.73 ± 0.27	53.9 ± 0.7	1.28 (446)
HD 120678	0.26(fr.)	1.21 ± 0.51	53.61 ± 0.18	1.41 ± 1.33	1.90 ± 0.29	0.18 ± 0.05	69.8 ± 2.4	0.86 (290)
	0.26(fr.)	1.64 ± 0.80	53.72 ± 0.13	0.26 ± 0.19	1.5	0.11 ± 0.01	57.6 ± 3.2	0.87 (291)
HD 120991	0.07 ± 0.02	11.49 ± 5.94	56.65 ± 0.20	2.02 ± 1.15	2.04 ± 0.25	3.56 ± 0.87	60.0 ± 0.3	1.12 (444)
	0.03 ± 0.01	5.28 ± 0.95	56.73 ± 0.12	2.44 ± 1.03	1.5	2.03 ± 0.54	45.8 ± 0.5	1.17 (445)
HD 157832*	0.38 ± 0.12	21.20 ± 8.41	55.36 ± 0.02	0.99 ± 0.54	4.25 ± 0.77	3.28 ± 2.30	17.7 ± 1.3	0.90 (444)
	0.18 ± 0.02	11.42 ± 3.62	55.05 ± 0.19	2.14 ± 1.20	1.5	1.75 ± 0.99	39.7 ± 0.3	0.92 (446)
HD 161103†	0.39 ± 0.04	15.38 ± 7.63	54.99 ± 0.10	1.80 ± 0.82	1.90 ± 0.48	0.99 ± 0.57	28.8 ± 0.1	1.06 (474)
	0.36 ± 0.04	8.67 ± 1.27	54.99 ± 0.09	2.12 ± 0.73	1.5	0.66 ± 0.30	26.7 ± 0.2	1.06 (475)
HD 212571	0.21 ± 0.01	12.40 ± 2.90	54.11 ± 0.08	2.58 ± 0.67	1.56 ± 0.04	11.95 ± 0.87	67.2 ± 0.2	1.13 (488)
	0.203 ± 0.005	8.72 ± 0.89	54.05 ± 0.07	2.72 ± 0.72	1.5	11.80 ± 0.76	70.3 ± 0.2	1.15 (489)
SAO 49725	0.42 ± 0.14	11.62 ± 6.68	55.22 ± 0.32	1.57 ± 1.28	1.5	0.59 ± 0.41	46.0 ± 0.5	0.95 (370)

Figure 5. The same as in Figure 1 but for PSHOCK+PL models.

Figure 3 shows the examples of the fits of X-ray spectra by APEC/MEKAL+PL model. The analogical fits of spectra of the same stars but with the fixed value $G = 1.5$ are presented in Figure 4. Analyzing these figures, one can conclude that an additional PL component makes it possible to describe the X-ray spectra of γ Cas analogues with acceptable temperatures of hot plasma.

Parameters of the fit for the model combination PSHOCK+PL are given in Table 7. Both free and fixed values of the spectral index $G = 1.5$ are used. For all the stars excluding HD 157832 we use fixed $Abundance = 1.0$. For HD 157832 we accept the parameter $Abundance = 0.54 \pm 0.25$. Also as for the APEC/MEKAL+PL combination the models with the PL component allows us to decrease the plasma temperatures to the acceptable temperatures.

Figure 5 demonstrates the fits of X-ray spectra by APEC/MEKAL+PL model with parameters given in Table 7. We are not able to fit spectra of V 2156 Cyg and HD 316568 stars because these spectra are very faint and noisy. We calculate only model independent characteristics of X-rays from these objects.

5 Comparison with typical OB stars

As it follows from the previous section, X-ray spectra of γ Cas analogues can be described by thermal models with anomalously high plasma temperatures. Meanwhile the spectra of 10 stars can be fitted by the APEC/MEKAL+PSHOCK models, spectra of 6 stars can be fitted by the PSHOCK+PSHOCK models.

In model spectra with the PSHOCK component, plasma temperature can also reach great values ~ 20 keV. It means that using the PSHOCK model only or in combination with the thermal models hardly allows to describe the X-ray spec-

tra with acceptable for OB stars plasma temperature about 1 keV for γ Cas analogues. Instead adding the power component PL to the sums of thermal models significantly reduced plasma temperature for most of considered stars. In many such approximations kT not more than 10 keV. According to Vink *et al.* (2009) terminal wind velocity of HD 45314 $v_\infty = 2410 \text{ km s}^{-1}$. Hence the upper limit of plasma temperature for this star should be about 7 keV. Therefore, if other γ Cas analogues have similar v_∞ , than $kT < 10 \text{ keV}$ can be acceptable for such objects.

Spectra of 13 stars in the APEC/MEKAL+PL model have a power component with the spectral index $G \sim 1.2$, 14 spectra can be fitted by thermal models with a PL component with the fixed $G = 1.5$. In both cases $F_{\text{PL}} \sim 50 - 90\%$. In many model spectra fluxes described by the PL component at energies of more 2 keV are higher than the corresponding fluxes for the APEC/MEKAL or PSHOCK model. Adding the PL component to the model spectra reduces plasma temperature to values below 1 keV for some γ Cas analogues. This value is typical for OB stars. But model spectra with such temperatures do not contain the Fe K_α line at 6.4 keV, which is presents in X-ray spectra of γ Cas analogues.

Spectra of 7 stars can be fitted by the PSHOCK+PL model. In the recent cases the ionization timescale $\tau_u \sim 10^{12} - 10^{13} \text{ s cm}^{-3}$, this is higher by one order than that for typical OB stars (Ryspaeva & Kholtygin, in prep.).

To check the possibility of generation of nonthermal X-rays by γ Cas analogues and other mechanisms of origin of their X-rays, we trace possible correlations between the defined characteristics of target stars' spectra. We compare the obtained dependences with similar ones for typical OB stars considered by Ryspaeva & Kholtygin (in prep.). The results of our regression analysis are presented in Table 8. The best correlations are shown in Figures 6–9.

A fraction of hard luminosity F_{HL} for γ Cas analogues increases with HR . This correlation continues the similar dependence for typical OB stars as it is shown in the bottom panel of Figure 6.

Given the whole X-ray emission from γ Cas analogues is thermal, their plasma temperature from the APEC/MEKAL model also increases with a hardness ratio. The correlation coefficient of such dependence is similar to that for typical OB stars (Ryspaeva & Kholtygin, in prep.) but approximation parameters are different.

The bottom panel of Figure 7 demonstrates the fits of dependencies kT vs HR both for typical OB stars and γ Cas analogues and dependence between the lowest model kT in the two-temperature model spectra of γ Cas analogues (squared markers). Approximation of the dependence kT vs. HR for OB type stars is not correct for the lowest model temperature of γ Cas analogues.

At the same time no dependences between HR and plasma temperature from thermal models with the added PL or PSHOCK component from the PSHOCK+PSHOCK model are found. Thus the X-ray emission from γ Cas analogues can be principally thermal but it should be formed by another way than X-rays for typical hot stars.

For the APEC/MEKAL model with additional PL component F_{PL} grows with extending of F_{HL} if the spectral index is fixed at $G = 1.5$. Top panel of Figure 8 illustrates this dependence. In the same time such dependence is a continuation of similar correlation for model spectra of typical OB stars, but with free parameter G^8 . The approximation parameters of both dependences are very close. Herewith

⁸ We were unable to fit X-ray spectra of typical OB stars by thermal or/and PSHOCK models with additional power component with fixed $G=1.5$ (Ryspaeva & Kholtygin, in prep.)

Table 8. The results of fitting the dependences between different characteristics of X-rays from γ Cas analogues (set γ in the table) and typical OB stars (set OB). For set $\gamma^\dagger$ we exclude 3 objects of the temperature with the greatest errors.

Fit	Set of objects	R	N	FAP	α	β
$F_{\text{HL}} = \alpha \cdot HR^\beta$	γ	0.71±0.22	17	<0.048	0.59±0.15	0.24±0.08
	OB	0.60±0.09	79	<2·10 ⁻⁶	0.39±0.12	0.55±0.11
	γ +OB	0.73±0.06	96	<2·10 ⁻⁶	0.40±0.12	0.56±0.10
$kT_{\text{APEC}} = \alpha \cdot HR^\beta$	γ	0.77±0.08	15	<0.04	3.82±1.20	1.06±0.24
	γ , $kT < 30 \text{ keV}$	0.63±0.14	13	<0.08	5.15±2.27	0.66±0.23
	$\gamma^\dagger$	0.80±0.02	12	(1.8±0.9)·10 ⁻³	3.31±0.68	0.97±0.30
	γ	-0.80±0.03	13	(1.2±0.9)·10 ⁻³	0.85±0.05	-0.14±0.01
$F_{\text{APEC+PL}} = \alpha \cdot kT^\beta$	γ	0.68±0.01	14	(7.4±1.1)·10 ⁻³	0.35±0.05	0.54±0.04
$F_{\text{APEC+PL}} = \alpha \cdot HR^\beta$	γ , $G = 1.5$ (fr.)	0.66±0.09	14	<0.03	1.67±1.67	1.64±0.69
$F_{\text{APEC+PL}} = \alpha \cdot F_{\text{HL}}^\beta$	OB	0.43±0.02	62	<0.008	0.25±0.01	0.54±0.19
$F_{\text{APEC+PL}} = \alpha + F_{\text{HL}} \cdot \beta$	γ +OB	0.68±0.02	75	<2·10 ⁻⁶	0.22±0.03	0.69±0.13
	γ +OB, $G = 1.5$ (fr.)	0.61±0.02	76	<2·10 ⁻⁶	0.25±0.02	0.56±0.11

Figure 6. Dependence between the fraction of hard luminosity and hardness ratio for γ Cas analogues (*top panel*) and for typical OB stars together with them (*bottom panel*).

Figure 7. Dependence between the average plasma temperature and hardness ratio for γ Cas analogues (*top panel*) and for typical OB stars together with them (*bottom panel*).

Figure 8. Dependence between the fraction of power component and fraction of hard luminosity for γ Cas analogues (*top panel*) and for typical OB stars together with them (*bottom panel*).

Figure 9. Dependence between the fraction of power component vs. plasma temperature from the APEC/MEKAL+PL model (*top panel*) and vs. hardness ratio (*bottom panel*) for γ Cas analogues.

the dependence F_{PL} vs. F_{HL} for model spectra of OB stars and γ Cas analogues combined with free spectral index G takes place too.

Furthermore, we revealed a decreases of the fraction of power components F_{PL} of the model spectra of γ Cas analogues with growing plasma temperature unlike for typical OB stars (Ryspaeva & Kholtygin, 2020). This can be seen in Figure 9 (top panel). Whereas F_{PL} of γ Cas analogues grows with the hardness ratio HR if spectral index is fixed at $G=1.5$. F_{PL} in spectra of typical OB stars is unlike to depend on HR since the correlation coefficient $R \sim 0.4$ (Ryspaeva & Kholtygin, in prep.) is low. We can propose, that if the nonthermal X-rays from γ Cas analogues and from typical OB stars exist, they should be generated by different mechanisms.

6 Discussion and conclusion

On basis of our analysis of the EPIC-spectra of 15 stars of enigmatic class of γ Cas analogues we can made the following essential conclusions.

Assuming the purely thermal origin of X-ray emission from the studied objects we need the extremely hot plasma. At the same time in the model spectra with an additional power component the spectral index $G \sim 1.2$, the PL component dominates at hard energies (more 2 keV). This can be interpreted that the X-ray spectra of γ Cas analogues have the nonthermal component produced through the inverse Compton scattering of UV-photons by relativistic electrons in an agreement with the hypothesis of Chen & White (1991).

But since in the 2-8 keV energy region in spectra of γ Cas analogues there can be present a few spectral lines, the thermal contribution to X-rays for these energies may be important. In the cases of the presence of both PL and thermal components with a plasma temperature of about a few keV in the model spectrum we can propose that thermal X-rays are produced in the framework of the models of Hillier *et al.* (1993), Feldmeier *et al.* (1997) or due to *hybrid* model of Cassinelli & Swank (1983), Waldron & Cassinelli (2009). X-ray emission from γ Cas analogues can not be formed according to MCWS model (Babel & Montmerle, 1997; ud-Doula & Owocki, 2002), because they unlike to have strong large-scale magnetic fields.

In our sample there are two candidates for γ Cas analogues HD 42054 and HD 120678. We estimated the characteristics of their X-ray spectra to be similar to those for γ Cas analogues. Therefore, we suggest these stars to be the members of this group of enigmatic objects.

Funding information: The authors state no funding involved.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

References

- Anders E, Grevesse N., 1989. Abundances of the elements: Meteoritic and solar. *Geochim Cosmochim Acta*. 53:197-234.
- Balucinska-Church M, McCammon D. 1992. Photoelectric Absorption Cross Sections with Variable Abundances. *ApJ*. 400:699-700.
- Babel J, Montmerle T. 1997. X-ray emission from Ap-Bp stars: a magnetically confined wind-shock model for IQ Aur. *A&A*. 323:121-138.
- Borkowski KJ, Lyerly WJ, Reynolds SP. 2001. Supernova Remnants in the Sedov Expansion Phase: Thermal X-Ray Emission. *ApJ*. 548:820-835.
- Capitanio L, Lallement R, Vergely *et al.* 2017. Three-dimensional mapping of the local interstellar medium with composite data. *A&A*. 606:A65.
- Cassinelli JP, Swank JH. 1983. X-ray spectra of Orion OB supergiants. *ApJ*. 271:681-690.
- Chen W, White R. 1991. Nonthermal X-ray emission from winds of OB supergiants. *ApJ*. 366:512-528.
- Feldmeier A, Kudritzki R-P, Palsa R, Pauldrach AWA, Puls J. 1997. The X-ray emission from shock cooling zones in O star winds. *A&A*. 320:899-912.
- Grunhut JH, Wade GA, MiMeS Collaboration. 2012. The incidence of magnetic fields in massive stars: an overview of the MiMeS survey component. *AIP Conf. Proc.* 1429:67-74.
- Gudennavar SB, Bubbly SG, Preethi K, Murthy J. 2012. A compilation of interstellar column densities. *ApJ Suppl Ser.* 199:8.
- Hamaguchi K, Oskinova L, Russell CMP, Petre R, Enoto T, Morihana K, *et al.* 2016. Discovery of Rapidly Moving Partial X-ray Absorbers within Gamma Cassiopeiae. *ApJ*. 832:140.
- Hillier DJ, Kudritzki RP, Pauldrach AW, Baade D, Cassinelli JP, Puls J, *et al.* 1993. The 0.1-2.5 keV X-ray spectrum of the O4f star ζ Puppis. *A&A*. 276:117-128.
- Liedahl DA, Osterheld AL, Goldstein WH. 1995. New Calculations of Fe L-Shell X-Ray Spectra in High-Temperature Plasmas. *ApJ*. 438:L115.
- Marshall DJ, Robin AC, Reyleć, Schultheis M, Picaud S. 2006. Modelling the Galactic interstellar extinction distribution in three dimensions. *A&A*. 453:635-651.
- Mewe K, Gronenschild EHBM, van der Oord GHJ. 1985. Calculated X-radiation from optically thin plasmas. *A&AS*. 62:197-254.
- Mewe K, Lemen JR, van der Oord GHJ. 1986. Calculated X-radiation from optically thin plasmas. VI - Improved calculations for continuum emission and approximation formulae for nonrelativistic average Gaunt factors. *A&AS*. 65:511-536.

- Nazé Y, Petit V, Rinbrand M, Cohen D, Owocki S, ud-Doula A, *et al.* 2014. X-ray emission from magnetic massive stars. *ApJ Suppl Ser.* 215:10.
- Nazé Y, Motch C, Rauw G, Kumar S, Robrade J, Lopes de Oliveira R, *et al.* 2020. Three discoveries of gamma Cas analogs from dedicated XMM-Newton observations of Be stars. *MNRAS.* 493:2511-2517.
- Postnov K, Oskinova L, Torrejón JM. 2017. A propelling neutron star in the enigmatic Be-star Cassiopeia. *MNRAS.* 465:L119-L123.
- Robinson RD, Smith MA, Henry GW. 2002. X-Ray and Optical Variations in the Classical Be Star Cassiopeia: The Discovery of a Possible Magnetic Dynamo. *ApJ.* 575:435-448.
- Ryspaeva E, Kholtygin A. 2020. Contribution of a Non-Thermal Component to the X-Ray Emission of OB Stars. *Astrophys Bull.* 75:127-138.
- Smith RK, Brickhouse NS, Liedahl DA, Raymond JC. 2001. Collisional Plasma Models with APEC/APED: Emission-Line Diagnostics of Hydrogen-like and Helium-like Ions. *ApJ.* 556:L91-L95.
- Smith MA, Lopes de Oliveira R, Motch C., 2016. The X-ray emission of the Cassiopeiae stars. *Adv Space Res.* 58:782-808.
- Vink JS, Davies B, Harries TJ, Oudmaijer RD, Walborn NR. 2009. On the presence and absence of disks around O-type stars. *A&A.* 505:743-753.
- ud-Doula A, Owocki SP. 2002. Dynamical Simulations of Magnetically Channeled Line-driven Stellar Winds. I. Isothermal, Nonrotating, Radially Driven Flow. *ApJ.* 576:413-428.
- ud-Doula A, Owocki SP, Kee ND. 2018. Disruption of circumstellar discs by large-scale stellar magnetic fields. *MNRAS.* 478:3049-3055.
- Waldron WL, Cassinelli JP. 2009. Highly Accelerated Diamagnetic Plasmoids: A New X-Ray Production Mechanism for OB Stellar Winds. *ApJ.* 69:L76-L79.
- Wilms J, Allen A, McCray R. 2000. On the Absorption of X-Rays in the Interstellar Medium *ApJ.* 542:914-924.