MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

A nature of the X-ray and optical emission from gamma Cassiopeia stars

A. Kholtygin[1], I. Yakunin[1,2], E. Ryspaeva[1,3], and D. Mokshin[1]

[1] Saint-Petersburg University, 7-9 University Emb., St. Petersburg, 199034 Russia
[2] Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhny Arkhyz, 369167 Russia
[3] Crimean Astrophysical Observatory of the Russian Academy of Sciences, Nauchnyi, 298409 Russia

Abstract. To test the origin of the X-ray and optical emission from the γ Cas-type stars, we analyzed their optical spectra obtained on the 6-m telescope BTA, the 1.25-m telescope of the Crimean station of the State Astronomical Institute (SAI, Moscow), the 2.5-m telescope SAI25 of SAI, and the photometric TESS light curves. We compare the optical variability of the γ Cas-type stars with variations of their X-ray luminosity. An overlap between the periods of line profile variations in the spectra of γCas stars and the variations in their X-ray brightness allows us to assume that a significant fraction of X-rays emits from the same place where the optical radiation comes from. The γ Cas-type stars HD 45314, HD 45995 and NGC 6649 9 demonstrate the ultrafast X-ray brightness variations with the periods of about 50–90 seconds, which may be the rotation periods of white dwarfs components of binary systems. Thus, we can assume that at least for these stars the X-ray emission goes partly due to accretion onto rapidly rotating white dwarfs. The anomalously hard X-ray emission from the γ Cas stars can be interpreted by assuming that the contribution of non-thermal X-ray emission is generated as a result of a reconnection of the local magnetic field lines of the Be star and its decretion disk.

Keywords: stars: general, emission-line, Be; X-rays: stars

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1 Introduction

The most enigmatic group of B stars is the classical Be stars including the rapidly rotating BIII–V stars of III–V luminosity classes with emission lines in their spectrum. Be stars lose gas and angular momentum into a circumstellar decretion disk (Rivinius et al. 2013). Some Be stars spin up at the stage of mass transfer in an interacting binary system (Pols et al. 1991), and the former donor star stands as a stripped, compact remnant (hot subdwarf, neutron star or white dwarf). Close binaries with compact component are known as Be X-ray systems with strong X-rays, while the most of Be stars are low X-ray sources with luminosities close to that of normal B-type stars (Nazé et al. 2022).

The nature of these objects remains mysterious despite more than 150 years of studying them. Emission lines in spectra of Be stars are associated with a decretion disk in the equatorial plane, the formation mechanism of which is unknown up to date. Even more enigmatic objects are γ Cas-type stars (γ Cas analogs) which belong to a small group (about 1%) among Be stars. This type includes Oe/Be stars with anomalously hard X-rays. Their X-ray luminosity is about 10^{31}–10^{33} erg/s. In the present paper we analyse our recent optical observations of selected γ Cas-type stars and compare them with their TESS photometry and X-rays.

The present paper is organized in the following way. In Section 2 the basic knowledge on these stars is given. Section 3 describes our optical observations of selected γ Cas-type stars and their line profile variations (LPVs). X-rays variability of the γ Cas-type stars are analysed in Section 4. A possible nature of γ Cas X-ray and optical luminosity is considered in Section 5.

2 An ensemble of γ Cas-type stars

To date, 26 stars of the γ Cas-type and two candidates of them are known. A list of 24 known γ Cas stars together with a list of candidates is presented by Kholtygin et al. (2022a). The bright star ζ Tau (Nazé et al. 2022) and the star 2XMMJ 180816.6−191939 (Nazé et al. 2020) should be added to this list. The estimated total number of γ Cas-type star in the Milky Way is nearly 5000 objects (Kholtygin et al. 2023a).

According to Nazé et al. (2022), eight of γ Cas-type stars are binaries. The new member of the γ Cas-type group ζ Tau is also a binary star (Ruždjak et al. 2009). Stars HD 44458 (FR CMa), HD 110432 (BZ Cru), HD 119682, HD 161103 (V3892 Sgr) and HD 162718 (V771 Sgr) are considered by Nazé et al. (2022) as presumably binary. This means that more than half (16 out of 26) of γ Cas stars are binary or suspected binary.

The mass of Be components in γ Cas-type binaries is 8–13 $M_\odot$, while the masses of the satellites do not exceed one solar mass excluding the binaries π Aqr (HD 212571). The mass of the secondary in this system is $2.4 \pm 0.5\, M_\odot$ (Nazé et al. 2022).

3 Optical observations

In Russia 17 stars of γ Cas subclass with $\delta > -12°$ can be observed. We obtained spectra of nine of these stars at the 6-m telescope BTA, 1.25-m telescope ZTE in the Crimean station of the Sternberg Astronomical Institute (SAI) of Moscow State University and at 2.5-m telescope SAI25 of the Caucasian Mountain Observatory of SAI. The list of our observations is given in Table 1.

Table 1. Log of γ Cas observations.

Star	Spectral Type	V mag	N_{sp}	Exp s	Telescope	Spectrograph	Date yyyy.mm.dd	N_{sp}^{tot}
γ Cas	B0.5IVpe	2.39	150	60	BTA	MSS	2020.11.04	4324
			138	60	BTA	MSS	2021.02.01–02	
			1576	2	ZTE	A-Sp	2020.09.13–14	
			2460	1.5	ZTE	A-Sp	2021.09.07–08	
ζ Tau	B1IVe	3.03	51	120	BTA	MSS	2023.01.12	51
HD 45314	O9:npe	6.64	20	600	BTA	MSS	2020.08.05–08	20
HD 45995	B1.5Vne	6.14	17	300	BTA	MSS	2023.01.12	225
			208	30	ZTE	A-Sp	2021.10.10	
SS 397	B0.5Ve	11.9	48	120	BTA	SCORPIO	2024.06.24	48
V558 Lyr	B3Ve	6.34	29	180/300	BTA	MSS	2023.12.01	861
			182	120	SAI25	TDS	2024.04.18	
			650	30	ZTE	A-Sp	2023.06.22–23	
SAO 49725	B0.5III/IVe	9.27	432	5	ZTE	SCORPIO	2021.08.17–18	432
V2156 Cyg	B1.5Ve	8.91	7	20	BTA	SCORPIO	2021.08.18	19
			12	600	BTA	MSS	2023.01.12	
π Aqr	B1III-IVe	4.64	1250	5	BTA	A-Sp	2023.01.12	1250

The total number of γ Cas-type stars spectra is 7230. The BTA spectra were obtained with the Main Stellar Spectrograph (MSS, Panchuk et al. 2014) and the SCORPIO spectrograph (Afanasiev & Moiseev 2005). The spectrograph A-Sp (Ikonnikova et al. 2021) was used to obtain the ZTE spectra, while SAI25 spectra were obtained with the spectrograph TDS (Potanin et al. 2020)[1].

These spectra were analysed by Kholtygin et al. (2021a,b, 2022b,c, 2023a,b). The regular variations of the line profiles in spectra of studied stars with periods

[1] https://obs.sai.msu.ru/cmo/sai25/tds/

4–300 minutes have been detected. Authors supposed that these variations are connected with high modes of the non-radial pulsations.

4 X-ray spectra and X-ray light curves

We analyzed the archival X-ray observations of γ Cas-type stars, obtained by the XMM-Newton and Chandra space observatories. Log of the observations and the procedure of data reduction can be found in the paper by Ryspaeva & Kholtygin (2021).

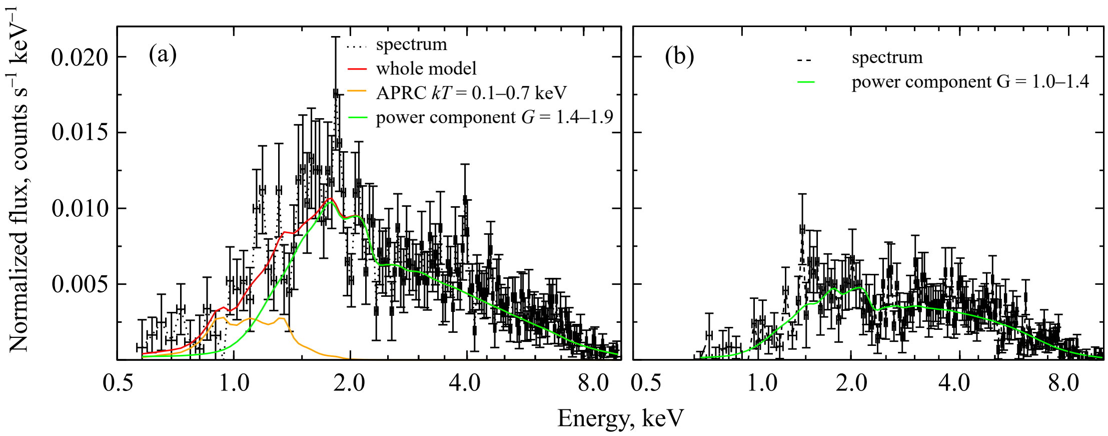

Fig. 1. The best fits of HD 90563 spectrum by APEC+PL (a) and pure PL models (b). The contributions of individual components into the total model X-ray spectrum are marked by colors. Left panel: observations on 2021.01.21. Right panel: joint observations from 2021.06.30 to 2021.08.07.

We approximated the X-rays spectra using `XSPEC 12.10.0` package in 0.2–8 keV energy band. The spectra were approximated by the sums of models `APEC` (Astrophysical Plasma Emission Code by Smith et al. 2001). In order to reach a better fit of the observed spectra we also used an additional power component (Power law, PL) which probably describes the contribution of the non-thermal X-rays.

For all analysed spectra the contribution of the PL component appeared to be significant as it is illustrated in Fig 1a. Moreover, in certain epochs, X-ray spectra can be described by only the PL component (see Fig 1b). It means that the contribution of the non-thermal X-ray emission into the total spectra of γ Cas-type stars seem to be very large as it was pointed out by Ryspaeva & Kholtygin (2021) earlier.

Together with the spectra we extracted X-ray light curves from the XMM EPIC images in the energy ranges of 0.2–8 keV and 2–8 keV for all known γ Cas-type stars.

The periods of optical, TESS photometric, and X-ray variability appeared to be close and correspond to the typical periods of non-radial pulsations (NRPs) of Be stars. It means that the X-ray emission of such stars is formed at least partly in the same place where the optical emission is generated.

5 A nature of optical and X-ray emission of γ Cas stars

There are two main scenarios for the physical cause of the production of hard X-rays of these stars. In the first one, hard X-rays are generated due to the interactions between local magnetic fields on the Be star and those at its decretion disk. In the second one, the matter from the Be star accretes onto a degenerate secondary star WD. Postnov et al. (2017) proposed a scenario in which the binary companion is a rapidly spinning neutron star. Smith et al. (2017) argue that this scenario does not account for the number and observational properties of the γ Cas-type stars.

In support of the first scenario, one can point to the correspondence between the periods of optical and X-ray variability pointed out in Section 4. If such a scenario were to be true, the X-ray emission from γ Cas stars should be flared. The analysis of the X-ray light curves shows that this is precisely the nature of the radiation of stars of this type (e.g., Smith et al. 2012).

The binarity of many of the γ Cas-type stars (Nazé et al. 2022) supports the second scenario. Our analysis shows that γ Cas-type stars HD 45314, HD 45995 and NGC 6649 9 demonstrate the fastest X-ray brightness variations with the periods of about 50–90 seconds, which may be the rotation periods of white dwarfs, components of binaries (Kholtygin et al. 2023b).

The scenario for the formation of Be + WD binary systems is described by Gies et al. (2023). In the case B of mass transfer in the interacting binary the donor filled its Roche surface during the expansion due to the ignition of H-shell burning, and the Be + sdO binaries are probably formed (Pols et al. 1991). After a period of time close to the main-sequence (MS) lifetime of the nearby Be star, the sdO stars will initiate its He-shell burning and again grow in radius and luminosity (e.g., Laplace et al. 2020).

This stage of enlargement leads to a second Roche filling and mass transfer (case BB by Delgado & Thomas 1981). If the remnant after this second mass transfer stage has a core mass lower than $1.4\,M_{\odot}$, then the remnant will rapidly evolve to CO WD or WNe WD (Dewi et al. 2002).

In conclusion, it can be said that the generation of X-ray emission from γ Cas-type stars most likely occurs in a hybrid scenario. The flare part of the total X-ray flux is formed by the interaction of the local stellar magnetic fields and the magnetic field of the disk, while the hard part is generated due to an accretion onto a rapidly rotating white dwarf.

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