PROCEEDINGS OF SCIENCE

Stars like γ Cassiopeia: close to us and enigmatic

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The results of our analysis of the optical spectra of γ Cas type stars under the large observation program *Line Profile Variability in the Spectra of OBA Stars and the Nature of their X-Ray emission* and the results of a study of the archival X-ray spectra of these stars based on the XMM-Newton satellite observations are presented. A fast variability of the line profiles in the optical spectra of γ Cas type stars on scales from several minutes to hours, as well as a similar fast variability of their X-ray light curves are detected.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

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PoS(MUTO2022)044

1. Introduction

One of the most enigmatic groups of stars is the classical Be stars of the main sequence, which include rapidly rotating BIII-V stars of III-V luminosity classes with emission lines. Despite more than 150 years of history of studying these objects, their nature remains mysterious. The appearance of emission lines in the spectra of Be stars is associated with the formation of a decretion disk in the equatorial plane, the formation mechanisms of which are debatable. The role of the magnetic field in the formation of the disk is considered undoubted, although so far no Be star magnetic fields have been detected. γ Cas type stars (γ Cas analogs) belong to a small group ($\sim$1%) among Be stars. These stars are basically similar in their properties to the progenitor of the class, γ Cas. A group of γ Cas type stars includes Oe/Be stars with an anomalously hard X-ray emission. Their X-ray luminosity reaches $10^{32} - 10^{33}$ erg s^{-1}. In the present paper we analyse our recent optical observations of selected γ Cas type stars and compare the optical and X-ray variability of these enigmatic objects.

The present paper is organized as follows. In Section 2 the basic knowledge on γ Cas type stars and a list of these objects are given. Section 3 describes the optical observations of selected γ Cas type stars and their line profiles and X-ray flux variability. Some conclusions are given in Section 4.

2. An ensemble of γ Cas type stars

The criteria for Be stars to be in a group of γ Cas type stars were formulated by Naze & Motch [3]. These stars are characterized by an X-ray luminosity $\log L_{\rm X}(0.5-10\,\mathrm{keV}) = 31.6-33.2$, which is 1-2 orders of magnitude higher than the typical values for other Be stars and about one and a half orders of magnitude lower than those for massive X-ray binaries with Be components. X-ray spectra of γ Cas type stars are characterized by hardness $HR > 1.6$, where HR is the ratio of the fluxes in hard (2-10 keV) and soft (0.5-2 keV) energy bands. Such hardness corresponds to an anomalously high temperature of hot plasma of about 5-20 keV and even higher [3]. At the same time, the optical spectra of γ Cas type stars do not stand out among the spectra of other Be stars [3].

The unusually powerful X-ray and gamma emission of γ Cas type stars in comparison with other Be stars stimulated the development of different models of their X-rays formation. The simplest of them is the assumption that the X-ray spectrum is described by a combination of several thermal components. For example, the spectrum of the star HD 130437 (CQ Cir) can be represented by a combination of components with temperatures 3.4 ± 0.7 keV and 34 ± 10 keV [4]. Similar fits with very high component temperatures are also typical for other γ Cas type stars. The standard mechanism of plasma heating by shock waves in the stellar wind does not allow reaching temperatures above 3-5 keV. At the same time, the accretion onto the compact component in a binary system could lead to such high temperatures.

According to [5] accretion onto a nearby unidentified white dwarf can be a source of hard X-rays. Postnov et al. [6] suggested that the cause of hard X-ray emission from γ Cas type stars is accretion onto a neutron star at the propeller stage.

Smith et al. [7] proposed this hypothesis to be questioned since if it is accepted, the number of stars of the γ Cas type will be significantly less than actually observed. Alternatively [8] they

Table 1: List of γ Cas type stars and candidates for these objects

No.	Star Name	RA	DEC	Sp. Type	V/G	d, pc	Ref.
1	γ Cas	0 56 42.53	+60 43 00.26	B0.5IV-Ve	2.39	188	[1]
2	TYC 3681-695-1	1 15 59.05	+59 09 14.21	B1-2 III/Ve	11.36	2948	[1]
3	V782 Cas	2 08 45.44	+65 02 14.73	B2.5III:	7.62	846	[2]
4	HD 44458	6 21 24.72	-11 46 23.67	B1.5IVe	5.55	537	[2]
5	HD 45314	6 27 15.78	+14 53 21.22	O9:npe	6.64	886	[1]
6	HD 45995	6 31 09.56	+11 15 04.95	B1.5Vne	6.14	669	[2]
7	HD 90563	10 25 52.46	-58 47 07.13	OBe	9.86	2514	[2, 3]
8	HD 110432	12 42 50.27	-63 03 31.05	B0.5 IIIe	5.31	438	[1]
9	HD 119682	13 46 32.57	-62 55 24.16	B0.5e	7.90	1652	[1]
10	V767 Cen	13 53 57.24	-47 07 41.39	B2Ve	6.10	686	[2, 3]
11	CQ Cir	14 50 50.25	-60 17 10.36	B1Ve	10.04	1645	[2, 3]
12	HD 157832	17 27 54.81	-47 01 34.40	B1.5Ve	6.66	1013	[1]
13	HD 161103	17 44 45.77	-27 13 44.48	B0.5 III-Ve	9.13	1270	[1]
14	V771 Sgr	17 53 28.44	-24 46 27.64	B3/5ne	9.16	1802	[2, 3]
15	HD 316568	17 54 42.70	-29 43 47.63	B3 E	9.66	1762	[2, 3]
16	GSC2 S300302371	18 30 15.93	-10 45 38.34	Be D	12.78G	2287	[2, 3]
17	NGC6649 9	18 33 28.30	-10 24 08.76	B1-1.5 IIIe	11.76	2111	[1]
18	SS 397	18 33 27.77	-10 35 24.44	B0.5Ve D	11.9	928	[1]
19	3XMM J190144.5 +045914	19 01 44.58	+04 59 14.77	O9e-B3e	16.69G	4386	[2, 3]
20	V558 Lyr	19 27 36.40	+37 56 28.31	B3Ve	6.34	562	[2]
21	SAO 49725	20 30 30.85	+47 51 50.72	B0.5 III-Ve	9.27	2385	[1]
22	V2156 Cyg	21 25 02.44	+44 27 06.38	B1.5V:nnep	8.91	918	[2, 3]
23	pi Aqr	22 25 16.62	+01 22 38.63	B1III-IVe	4.64	239	[2, 3]
24	V810 Cas	23 20 19.02	+55 48 28.08	B2 D	8.59	1485	[2, 3]
	Candidate γ Cas type stars						
26	HD 42054	06 07 03.67	-34 18 43.28	B5Ve	5.84	291	[2, 3]
27	HD 120678	13 52 56.41	-62 43 14.26	O9.5Ve	8.20	1787	[2, 3]

suggested that the interaction between the local stellar magnetic field and the disk magnetic field can better describe the X-ray properties of γ Cas type stars.

In the model by Chen & White [9] the non-thermal X-ray emission resulting from the Compton backscattering of UV stellar photons on relativistic electrons explains the unusually hard X-rays of γ Cas type stars. This model was used by Ryspaeva & Kholtygin [4, 10] for an interpretation of the X-ray spectra of selected γ Cas type stars.

The presence of a non-thermal component in the X-ray spectra of γ Cas type stars remains an important problem. Rauw et al. [11] believe that the X-ray spectrum of these stars is purely thermal, based on the results of Shrader et al. [12]. These authors describe the X-ray spectrum of γ Cas itself in the region of 0.6-100 keV using the data from the Suzaku and Integral satellites and a thermal model with a temperature of 14 keV and with the addition of Gaussian profiles of the fluorescence

Table 2: List of our observations of γ Cas type stars

Star	Nsp	Exp, s	Telescope	Spectrograph	Dates
γ Cas	1576	2	1.25-m ZTE	A-sp	13-14.09.2020
	150	60	6-m BTA	MSS	4.11.2020
	138	60	6-m BTA	MSS	1-2.02.2021
	2460	1.5	1.25-m ZTE	A-sp	7-8.09.2021
HD 45314	20	600	6-m BTA	MSS	5-8.1.2020
HD 45995	208	30	1.25-m ZTE	A-sp	10.10.2021
SAO 49725	432	7	6-m BTA	SCORPIO	17-18.08.2021
V2156 Cyg	7	20	6-m BTA	SCORPIO	18.08.2021
π Aqr	1250	5	1.25-m ZTE	A-sp	10.10.2021

iron line and the emission lines of helium and hydrogen-like iron. At the same time, the analysis of Torrejon et al. [13] of the spectra of the γ Cas type star HD 110432, obtained by Chandra and Suzaku satellites, showed that their X-ray spectra can be described both by a multi-component model with component temperatures up to 33 keV, and by an additional power-law component with a photon index of 1.5 – 1.6 and lower temperatures.

By now over twenty γ Cas type stars are known. The list of all known stars of such type and 2 candidates for these objects are listed in Table 1. The names of the stars in the list are tabulated in Column 2. The coordinates of the stars are given in Columns 3-4. In Columns 5 -7 the spectral types, V values, and the distance to the stars are given. The references to the lists of known or newly identified γ Cas type stars are presented in the last column.

Be stars and γ Cas type stars, as a small group of Be stars, are rather weak radio sources. Their radio emission is determined mainly by their stellar winds. In the catalogue of Radio Stars[1] the radio fluxes are given only for the brightest γ Cas type stars. The maximal radio flux for γ Cas is 100 mJy at 90 GHz, while for π Aqr the maximal flux is 12 mJy at 10.6 GHz.

Recently Wang & Loeb [14] studied the non-thermal emission due to the interaction between magnetized Jupiter-like exoplanets and the wind from their host star. The supersonic motion of planets through the wind forms a bow shock accelerating the electrons that produce non-thermal radiation in a wide wavelength range. The authors estimated the expected radio synchrotron emission from a Jupiter-like planet which is detectable by the VLA and the SKA at 1 – 10 GHz out to a distance of 100 pc. Our estimations show that the possible contribution to the total radio flux of γ Cas type stars due to the mechanism proposed by Wang & Loeb does not exceed 0.15 mJy. Such a small flux is hardly detectable among the strong flux of the thermal radio emission. At the same time Wang & Loeb show that inverse Compton scattering of the stellar radiation results in X-ray emission detectable by Chandra X-ray Observatory out to 150 pc.

Many Be disk formation models require these stars to have magnetic fields (e.g. [15]). At the same time, no magnetic fields were detected for any Be star. Searching for the magnetic fields of γ Cas type stars as part of the Be stars group also gave no results. One can note only the detection of the magnetic field of Be star λ Eri at the level of 3-4 standard deviations [16], but this result needs to be independently confirmed. The authors point out the possible presence of regular variations of

[1]https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=VIII/99

the B_l component of the magnetic field with a period of about 13.6 minutes. This periodicity may indicate the presence of local magnetic fields on the stellar surface.

Grunhut et al. [17, 18] suggested, based on the measurements of the magnetic field of OBA stars by the MIMES project and the complete absence of significant measurements of a magnetic field in Be stars, that the absence of such measurements is not related to the method or to the accuracy of the polarimetric observation analysis but indicates that all such stars are non-magnetic.

ud-Doula et al. [19] simulate the interaction of the already formed Keplerian decretion disk of a Be star with a dipole magnetic field. It is shown that even at a polar field value of 10 G the disk can be destroyed, and for the polar fields of 100 G, corresponding to the upper limit obtained from measurements of the magnetic field of Be stars, the disk will be destroyed in a few days. Thus, the authors suggest that the presence of even a small regular magnetic field in a B star prevents the formation of a disk.

3. Optical and X-ray spectra

We observed the northern γ Cas type stars using the 6-meter telescope BTA (Big Telescope Azimuthal) with the low resolution spectrograph SCORPIO [20] and medium resolution spectrograph MSS (Main Stellar Spectrograph) [21]. Our observations of the brightest γ Cas type stars were also made with the 1.25-m telescope in the Crimean station of Sternberg Astronomical Institute, Moscow University with the low resolution spectrograph A-Sp (e.g. [22]) with the exposure time 2-50 s.

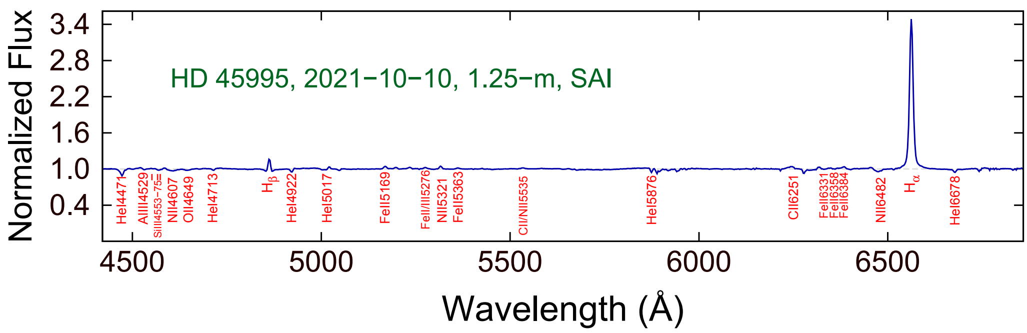

Figure 1: Mean spectrum of HD 45995.

All spectra of γ Cas type stars obtained by us appeared to be similar to those of other Be stars. As an example we plot the mean spectrum of bright γ Cas type star HD 45995 in Fig. 1. This mean spectra is obtained by averaging all 208 spectra observed with the 1.25-m telescope on October 10-11, 2021. To study the line profile variations we use the difference line profile $d(V,t) = F(V,t) - \overline{F}(V)$, where $F(V,t)$ is the continuum normalized line flux for the spectrum obtained at time t, $\overline{F}(V)$ is the mean flux in the line at the velocity V. Instead of the wavelength λ we use the Doppler shifts V from the laboratory wavelength λ_0 of the line, where $V = c \cdot (\lambda - \lambda_0)/\lambda_0$, and c is the speed of light.

The pattern of the line profile variations (LPVs) is seen in Fig. 2, which shows all the normalized profiles of lines HeI 4471 and HeI 5876 in the spectra of HD 45995 (left panels). Dynamical spectra $d(V,t)$ for these lines are also plotted in Fig. 2 (right panels).

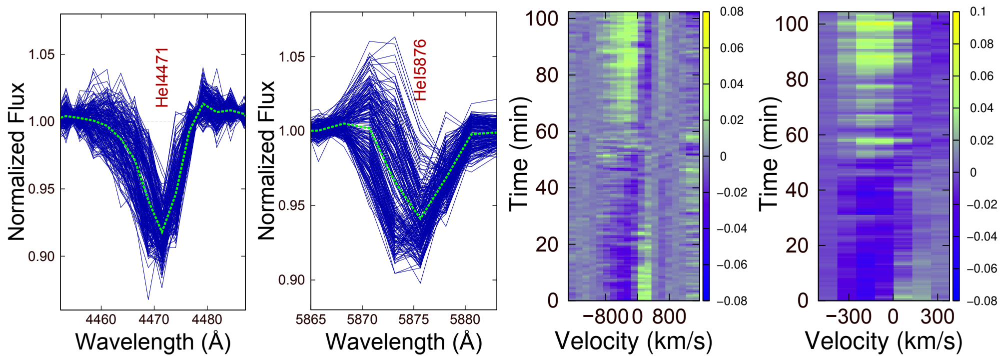

Figure 2: Left panels: all HeI 4471 and HeI 5876 line profiles obtained by us. The mean spectra are shown by dashed lines. Right panels: dynamical spectra for these lines.

To search the periodic components of LPVs in the spectra of HD 45995 the CLEAN method [23] was used. We found regular line profile variations with periods 37 ± 13 min and 34 ± 11 min for H_α, H_β, and HeI lines. These periods are close to those for γ Cas and π Aqr [22, 24].

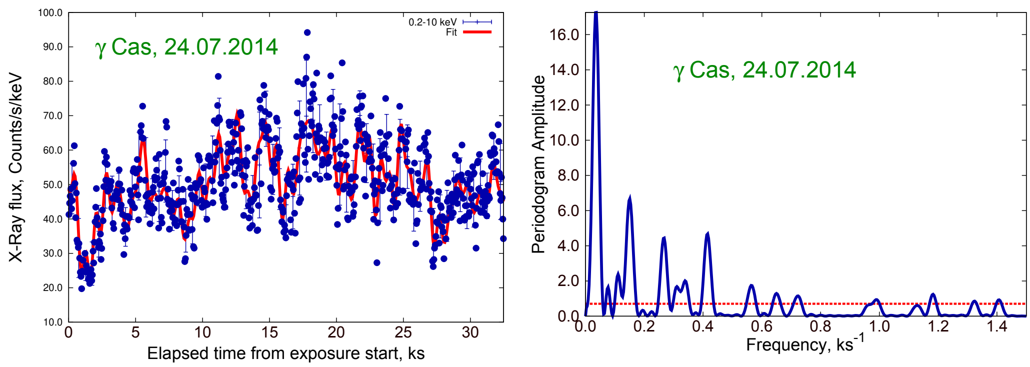

Figure 3: Left panel: X-ray light curve of γ Cas on July 24, 2014 (blue points) and its fit (thick red line). Right panel: Fourier spectrum of the X-ray variations. The solid dashed red line shows the FAP= 10^{-3} level.

All γ Cas type stars are strong X-ray sources. The appearance of hard X-rays in γ Cas type stars is not fully understood. To shed light on the nature of the X-rays in γ Cas type stars one could compare their optical and X-ray variability.

Recently Kholtygin et al. [25] analysed the variability of X-ray fluxes in the 0.2-8 keV range for BZ Cru. They found regular variations of the X-Ray fluxes with periods from 31 to 273 minutes, corresponding to the characteristic times of the optical spectra variability [22, 24].

In the present paper we analysed the changes of the X-Ray fluxes of γ Cas itself using the archive observations of the stars by the XMM satellite on July 24, 2014. In Fig. 3 the X-ray light curve and the corresponding Fourier spectrum for γ Cas are shown. At the FAP= 10^{-3} level 14 regular components in the X-ray light curve with periods from 12 to 492 minutes are found.

4. Conclusion

Some conclusions can be made from our analysis of the spectra of γ Cas type stars:
All investigated γ Cas type stars are characterized by rapid regular variability of the optical and

X-ray spectra with periods from minutes to hours.
The anomalously high X-ray fluxes of γ Cas type stars in the energy range of 2-8 keV can be explained within the framework of the hypothesis of the contribution of possible non-thermal X-ray emission resulting from the inverse-Compton scattering of UV photons by relativistic electrons.
The period of line profile variations in the optical spectrum of γ Cas type stars corresponds to the periods of their X-ray light curve. Radio observations of γ Cas type stars could elucidate the possibility of the formation of their non-thermal radio and non-thermal X-ray radiation.

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