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BINARIES γ CAS ANALOGS: OPTICAL AND X-RAY VARIABILITY

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ABSTRACT

γ Cas analogs constitute a small group of Be stars characterized by unusual X-ray spectra and high X-ray luminosities, $L_X \sim 10^{31}$–10^{33} erg s^{-1}. This is 2–3 orders of magnitude higher than for typical Be stars, yet lower than that observed in massive X-ray binaries with Be components. Compared to classical Be stars, these objects exhibit unusually hard X-ray spectra.

In the present paper, we present results from the analysis of the spectral and photometric variability of binary γ Cas analogs in both optical and X-ray bands. Notably, the periods of regular optical and X-ray variability appear to be similar. This suggests that at least part of the X-ray emission arises from interactions between local magnetic fields of the Be stars and the magnetic fields of their decretion disks.

X-ray flares are expected to result from the reconnection of magnetic field lines. For the stars BZ Cru and π Aqr, several thousand flare events were identified in the X-ray light curves obtained with the *XMM-Newton* satellite. Moreover, regular variations in X-ray brightness with periods of 50–90 seconds have been detected for the γ Cas analogs HD 45314, HD 45995, NGC 6649 9, and V558 Lyr. These periods may correspond to the rotation periods of white dwarfs in binary Be+WD systems.

We propose that the hard component of X-ray emission from γ Cas stars is generated via the accretion of disk material onto a rapidly rotating white dwarf.

Key words: stars: emission-line, Be – stars: binaries: individual: γ Cas – stars

1 INTRODUCTION

The γ Cas analogs constitute a small group of Be stars exhibiting X-ray luminosities 1–2 orders of magnitude higher than those of ordinary Be stars, along with anomalously high plasma temperatures ($kT \sim$ 10–20 keV or more) in their X-ray emitting regions. Despite these extreme X-ray properties, the optical spectra of γ Cas analogs do not differ significantly from those of other Be stars. These stars possess Keplerian decretion disks, which give rise to strong emission lines in their optical spectra (Naze et al. 2020a).

The hardness of the X-ray spectra of γ Cas analogs—defined as the ratio of hard (2–8 keV) to soft (0.2–2 keV) X-ray flux—exceeds 1.6. Long-term X-ray observations show significant variability in the stellar X-ray fluxes, which has been attributed to changes in the mass and density of the circumstellar disks (Rauw et al. 2018; Naze et al. 2022a).

The origin of X-ray emission in γ Cas analogs remains uncertain. Recent modeling of Be star outflows by Bogovalov et al. (2021) and (Bogovalov & Petrov 2022) reproduces the formation of a fast polar wind and a slow, highly turbulent equatorial outflow. At rotational velocities 0.5–1% above critical, a quasi-Keplerian disk with a size of 10–15 stellar radii forms at the equator.

Several mechanisms have been proposed to explain the X-ray emission. Postnov et al. (2017) suggested accretion of Be star material onto a neutron star in the propeller mode, while Hamaguchi et al. (2016) considered accretion onto a magnetic white dwarf. Ryspaeva & Kholtygin (2021) proposed contributions from non-thermal X-ray radiation. Another hypothesis is that X-rays are generated by interactions between the Be star's local magnetic fields and the disk magnetic field (Robinson et al. 2002), a mechanism considered the dominant process by Smith et al. (2016).

A large fraction of γ Cas analogs are found in binary systems (Naze et al. 2022b). More recently, Gies et al. (2023) proposed that the bright and hard X-ray flux in this subgroup

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may result from gas accretion onto an orbiting white dwarf (WD) companion, a scenario further supported by Gunderson et al. (2025). In the present paper, we compare the variability of the optical and X-ray spectra for several known binary γ Cas analogs to investigate how rapid optical and X-ray variations can provide insights into the origin of their X-ray emission.

The present paper is organized in the following manner. The properties of known binary γ Cas analogs are summarized in Section 2. In Section 3, we analyze the variability of spectral line profiles in these stars. Section 4 is devoted to the study of X-ray light curve variability. Finally, in Section 5, we discuss the impact of binarity on the mechanisms of X-ray formation.

2 BINARY γ CAS ANALOGS

To date, 26 stars have been identified as γ Cas analogs, along with 2 candidate objects. A list of 24 confirmed γ Cas analogs and the candidate stars is provided by Kholtygin et al. (2022a). The star 2XMMJ 180816.6−191939 (Naze et al. 2020a) and the bright star ζ Tau (Naze et al. 2020b) should also be added to this list. In Table 1, we present the known binary γ Cas analogs with established orbital parameters.

In Table 1, the orbital period $P_{\rm orb}$ in days, the masses of the Be stars (M_1) and their low-mass companions (M_2) in solar masses, the orbital inclination i, and the semi-major axes a (calculated using Kepler's third law) are presented. Additionally, five other γ Cas analogs (FR CMa, BZ Cru, V771 Sgr, HD 119682, and HD 161103) are likely binaries, although their orbital parameters are unknown. Thus, more than half of the γ Cas analogs are either confirmed or probable binary systems.

The masses of the Be components in these binaries range from 8 to 13 $M_\odot$, while the masses of their companions, excluding π Aqr, do not exceed the mass limit for white dwarfs (WDs). According to Bjorkman et al. (2002), the secondary mass in π Aqr is $M_2 = 1.8 \pm 0.2\ M_\odot$, whereas Tsujimoto et al. (2023) report a mass below 1.4 $M_\odot$. This indicates that the companion in π Aqr may also be a WD.

The nature of the secondary stars in γ Cas analogs remains uncertain. They could be low-mass main-sequence (MS) stars, subdwarf O or B stars (sdOB), WDs, or neutron stars (NS). Low-mass MS stars may have been formed before the first mass-transfer stage in the close binary, but forming a Be star at this stage is highly unlikely. Be+sdO binaries can form through Case B mass transfer, where the donor fills its Roche lobe during H-shell burning expansion (Shao & Li 2021). During the second mass-transfer stage, the sdO star (with mass $< 1.4\ M_\odot$) loses about 12% of its mass to the Be star and becomes a WD. The resulting post-mass-transfer binary typically has a longer orbital period. Willems & Kolb (2004) show that WD remnants in such systems have masses in the range 0.7–1.4 $M_\odot$, with orbital periods peaking near 200 days. The Be stars in these systems acquire masses of 7–17 $M_\odot$, consistent with the properties of known Be binaries (see Table 1).

To investigate the nature of low-mass companions in Be binaries, Klement et al. (2024) used optical/near-infrared interferometry with the Center for High Angular Resolution Astronomy (CHARA) on 37 Be stars suspected of hosting low-mass spectroscopic companions. Their targets included six γ Cas analogs: γ Cas, FR CMa, HD 45995, V558 Lyr, V782 Cas, and π Aqr. No sdOB or MS companions of the expected spectroscopic mass were detected, leaving elusive WDs as the most likely companions. In contrast, sdOB companions have been detected in other Be binaries.

The flux difference between a Be star and a WD in the H-band (1.63 μm) exceeds 11.5 magnitudes (Gies et al. 2023), making current interferometers unable to detect WDs in Be+WD binaries. Neutron star companions are also excluded for the secondary masses listed in Table 1. Therefore, generalizing the results of Gies et al. (2023), we conclude that all γ Cas analogs are wide (~ 1 au) Be+WD binaries.

3 VARIABILITY OF LINE PROFILES IN SPECTRA OF BINARY γ CAS ANALOGS

Sixteen γ Cas analogs with declinations $\delta > -12^\circ$ can be observed from Russia. We obtained spectra for nine of these stars using the 6-m BTA telescope (Russia), the 1.25-m ZTE telescope at the Crimean station of the Sternberg Astronomical Institute (SAI), Moscow State University, and the 2.5-m SAI25 telescope at the Caucasian Mountain Observatory of SAI. A summary of our observations is provided in Table 1 of Kholtygin et al. (2024a).

The line profiles variations of Balmer lines for all observed Be binaries appear to be typical for γ Cas analogs too, as illustrated in Fig. 1 (two left panels) for the binary star V558 Lyr. Spectra of V558 Lyr were obtained on 18 April 2024 and 14 December 2024 using the 2.5-m SAI25 telescope at the Caucasian Mountain Observatory of the Sternberg Astronomical Institute, Moscow State University, equipped with the low-resolution TDS spectrograph (Potanin et al. 2020).

To study the line profile variations (LPVs) in the stellar spectra, we use the difference line profiles (residuals):

$$d_i(V) = F_i(V) - \langle F(V) \rangle, \qquad (1)$$

where $F_i(V)$ is the flux in the spectral line corresponding to the Doppler shift V, normalized to the continuum in spectrum i, and $\langle F(V) \rangle$ is the flux averaged over all observations. The collection of difference spectra (dynamic spectrum) for the Hα and Hβ lines is presented in Fig. 1 (two right panels).

We applied the CLEAN Fourier analysis method (Roberts et al. 1987) to the time series of difference line profiles $d(V, t_i)$ in the spectra of binary γ Cas analogs, corresponding to all observation times t_i. In Table 2, we list the periods P of the revealed regular components in the LPVs for the binary γ Cas analog V558 Lyr. The corresponding false-alarm probability (FAP) levels α are given in the last row of the table.

Similar regular components of LPVs with periods ranging

Table 1. Parameters of binary γ Cas analogs

Star Name	$P_{\rm orb}$ (d)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	i (deg)	a (au)	Reference
γ Cas	203.36	13	0.98	45	1.63	Naze et al. (2022b), Nemravova et al. (2012)
V782 Cas	122.0	9	0.6–0.7	60–90	1.02	Naze et al. (2022b)
ζ Tau	133.0	11	0.87–1.02	60–90	1.17	Ruzdjak et al. (2009)
HD 45995	103.1	10	1.0 $\pm$ 0.1	46.8	0.96	Naze et al. (2022b)
V558 Lyr	83.3	8	0.7–0.8	60–90	0.77	Naze et al. (2022b)
SAO 49725	137.0	13	0.5–0.7	30–90	1.24	Naze et al. (2022b)
V2156 Cyg	126.6	11	0.7–0.8	60–90	1.12	Naze et al. (2022b)
π Aqr	84.1	15	<1.4	70	0.95	Bjorkman et al. (2002), Tsujimoto et al. (2023)
V810 Cas	75.8	12.5	0.7–0.8	60–90	0.83	Naze et al. (2022b)

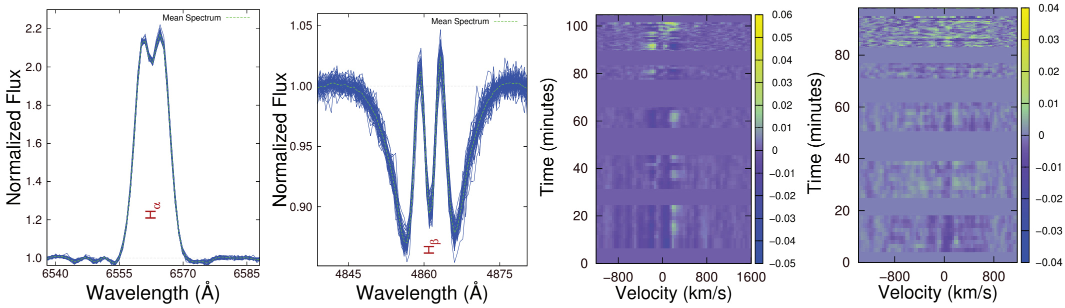

Figure 1. Line profile variations and dynamical spectra of V558 Lyr. Panels (a) and (b) show the Hα and Hβ line profile variations, respectively. Panels (c) and (d) show the corresponding dynamical spectra.

Table 2. Regular components of line profile variations in the spectrum of V558 Lyr

Component number	1	2	3	4
P (min)	1.22 ± 0.02	1.77 ± 0.03	5.00 ± 0.25	21.2 ± 4.6
FAP (α)	10^{-2}	10^{-3}	10^{-2}	10^{-4}

from 1 to 150 minutes and amplitudes of 0.5–2% of the continuum level were also detected in other γ Cas analogs: γ Cas itself (Kholtygin et al. 2021), π Aqr (Kholtygin et al. 2022b), HD 45995 (Kholtygin et al. 2023), and SAO 49725 (Kholtygin et al. 2024b).

The detected periods of LPVs could correspond to high-order non-radial pulsations (NRPs; e.g., Kholtygin & Ryspaeva 2024). However, very short regular components with periods less than 5 minutes were observed for γ Cas (4.02 ± 0.13 min), SAO 49725 (0.89 ± 0.01 min), and π Aqr (4.10 ± 0.10 min). Such short LPV periods are difficult to explain even by high-order NRPs.

By contrast, the rotation periods of isolated white dwarfs can reach ~ 70 s (Kilic et al. 2021), while for the white dwarf in the binary system HD 49798 with an O-type donor, the period is as short as 13.2 s (Mereghetti et al. 2021). We therefore propose that the shortest LPV periods may correspond to, or be multiples of, the rotation periods of white dwarfs in Be+WD binary systems. The existence of these very short periods in binary Be stars provides additional evidence that the companions in these systems are white dwarfs. While the rotation periods of white dwarfs in Be+WD systems can sometimes exceed 5 minutes, identifying such periods among the bulk of NRP periods remains challenging.

4 X-RAY LIGHT CURVES VARIABILITY

A comparison of the X-ray and optical variability can provide insights into the origin of the extremely hard X-rays in γ Cas analogs. We reanalyzed archival X-ray light curves of known γ Cas analogs obtained with the *XMM-Newton* satellite. Currently, X-ray observations are available for 15 γ Cas analogs for which optical spectral observations have also been obtained.

Particularly interesting results were obtained for the bright star π Aqr. The CLEAN spectrum of the X-ray light curves of π Aqr, observed with *XMM-Newton* on 21 January 2020, is presented by Kholtygin & Ryspaeva (2024) (their Fig. 3, left panel). Four regular components with periods ranging from 35 minutes to 8 hours 37 minutes were revealed.

The most intriguing result is the correspondence between the periods of optical and X-ray variations. In the CLEAN spectrum of the X-ray light curve of γ Cas obtained with *XMM-Newton* on 5 February 2004 (ObsID 201220101), we detected 10 regular components with periods ranging from 29.6 min to 10 h 4 min across different energy bands. These components are plotted in Fig. 2.

The ninth period of the X-ray light curve, $P_9 = 36.69 \pm 1.24$ min, is very close to the period of the optical LPVs in γ Cas, $P = 37.11 \pm 3.59$ min. It is also notable that the periods

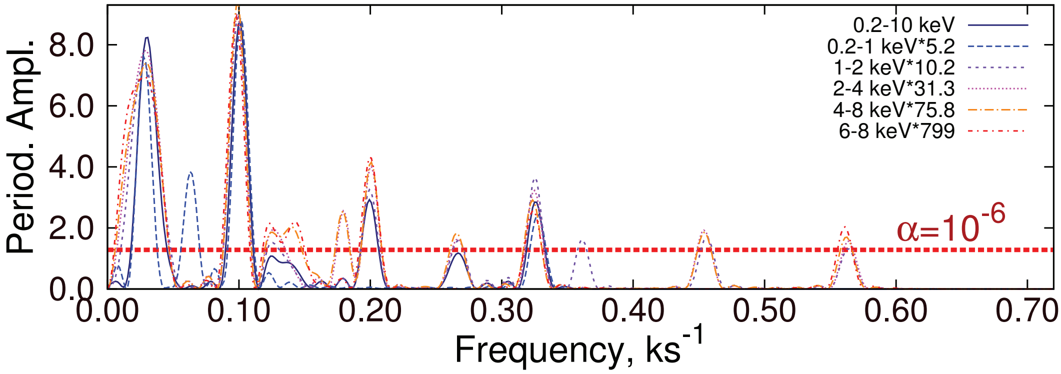

Figure 2. Amplitude of the CLEAN periodogram of the γ Cas X-ray light curve obtained with the *XMM-Newton* satellite on 5 February 2004 for different energy bands. The dashed line marks the false-alarm probability (FAP) level of 10^{-6}.

of the components corresponding to different energy bands are nearly identical, as seen in Fig. 2.

For HD 45995 and V558 Lyr, very short X-ray variation periods were detected: 48.5±0.5 s and 1.16±0.02 min, respectively. The latter is very close to the period of 1.22±0.02 min of the optical LPVs given in Table 2. The similar fast X-ray variations were detected for HD 45314 and NGC 6649 9. This closeness of periods supports the hypothesis that these periods correspond to the rotation period of the white dwarf in the V558 Lyr binary system.

5 A NATURE OF THE X-RAY EMISSION IN THE BINARY γ CAS ANALOGS

Our analysis shows that the X-ray fluxes of all analysed γ Cas analogs exhibit regular components with periods up to 5–8 hours, corresponding to the characteristic timescales of variability in the optical spectra. The periods of optical and X-ray variations in γ Cas analogs are also similar to the typical periods of non-radial pulsations (NRPs) in Be stars (Rivinius et al. 2003). This correspondence indicates that the X-ray and optical radiation are, at least in part, generated in spatially close regions.

Since the optical radiation in these stars is formed either in the Be star itself or in the circumstellar decretion disk, the regular component of their X-rays may originate in the same regions or in the interface between the disk and the stellar photosphere. From a comparison of the periods of optical and X-ray variability, it is possible to conclude that the mechanism proposed by Smith et al. (2016), in which X-rays are generated by the interaction of local magnetic fields of the Be star with the decretion disk, significantly contributes to the total X-ray emission of these stars.

On the other hand, the presence of regular components in both optical and X-ray variations that are close to, or multiples of, the rotation periods of white dwarfs in binary γ Cas analogs supports the hypothesis that part of the X-ray emission arises from accretion of matter from the decretion disk onto a rapidly rotating white dwarf. One of the most intriguing and still unresolved questions is whether the white dwarfs in these binaries are magnetic. Addressing this question requires high-resolution polarimetric observations, which could also help to determine whether the less massive component in a γ Cas binary could be a neutron star.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Afraimovich E. L., Demyanov V. V., Kondakova T. N., 2003, PS Solut., **7**, 109
Bjorkman K. S., Miroshnichenko A. S., McDavid D., Pogrosheva T. M., 2002, ApJ, 573, 812
Bogovalov S. V., Petrov M. A., Timofeev V. A., 2021, MNRAS, 502, 2409
Bogovalov S., Petrov M., 2022, Universe, 8, 591
Gies D. R., Wang L., Klement R., 2023, ApJL, 942, L6
Gunderson S. J., Huenemoerder D. P., Torrejon J. M., et al., 2025, ApJ, 978, 105
Hamaguchi K., Oskinova L., Russell C. M. P., et al., 2016, ApJ, 832, 140

Kilic M., Kosakowski A., Moss A. G., 2021, ApJL, 923, L6
Kholtygin A. F., Burlak M. A., Tsiopa O. A., 2021, Astron. Tsirk., 1649
Kholtygin A. F., Ryspaeva E. B., Moiseeva A. V., 2022a, in The Multifaceted Universe: Theory and Observations, SAO RAS, id. 44
Kholtygin A. F., Burlak M. A., Milanova Y. V., et al., 2022b, Astron. Tsirk., 1652
Kholtygin A. F., Yakunin I. A., Burlak M. A., Ryspaeva E. B., 2023, Astrophys. Bull., 78, 557
Kholtygin A. F., Yakunin I. A., Ryspaeva E. B., Mokshin D. N., 2024a, in Proc. VAK-2024, Modern Astronomy, in press
Kholtygin A. F., Yakunin I. A., Bukharinov et al., 2024b, Astrophys. Bull., 79, 437
Kholtygin A. F., Ryspaeva E. B., 2024, Geomagnetism and Aeronomy, 64, 1267
Klement R., Rivinius T., Gies D. R., et al., 2024, ApJ, 962, 70
Mereghetti S., Pintore F., Rauch T., et al., 2021, MNRAS, 504, 920
Naze Y., Motch C., Rauw G., et al., 2020a, MNRAS, 493, 2511
Naze Y., Pigulski A., Rauw G., Smith M. A., 2020b, MNRAS, 494, 958
Naze Y., Rauw G., Bohlsen T., et al., 2022a, MNRAS, 512, 1648
Naze Y., Rauw G., Smith M. A., Motch C., 2022b, MNRAS, 516, 3366
Nemravova J., Harmanec P., Koubsky P., et al., 2012, A&A, 537, A59
Potanin S. A., Belinski A. A., Dodin A. V., et al., 2020, Astron. Lett., 46, 836
Postnov K., Oskinova L., Torrejon J. M., 2017, MNRAS, 465, L119
Rauw G., Naze Y., Smith M. A., et al., 2018, A&A, 615, A44
Rivinius Th., Baade D., Stefl S., 2003, A&A, 411, 229
Robinson R. D., Smith M. A., Henry G. W., 2002, ApJ, 575, 435
Roberts D. H., Lehar J., Dreher J. W., 1987, AJ, 93, 968
Ruzdjak D., Bozic H., Harmanec P., et al., 2009, A&A, 506, 1319
Ryspaeva E., Kholtygin A., 2021, Open Astronomy, 30, 132
Shao Y., Li X.-D., 2021, ApJ, 908, 67
Smith M. A., Lopes de Oliveira R., Motch C., 2016, Adv. Space Res., 58, 782
Tsujimoto M., Hayashi T., Morihana K., Moritani Y., 2023, PASJ, 75, 177
Willems, B., Kolb, U., 2004, A&A, 419, 1057