Bull. Soc. R. Sci. Liège, 2024, **93**(3), 250–255 *Peer-reviewed conference paper*
doi:10.25518/0037-9565.12333

ζ Tau, a Post-interaction Binary

Yaël NAZÉ[1,2,*], Christian MOTCH[3], Gregor RAUW[2], Myron A. SMITH[4] and Jan ROBRADE[5]

[1] F.R.S.-FNRS Senior Research Associate
[2] GAPHE, Université de Liège, Allée du Six-Août 19c, B–4000 Liège, Belgium
[3] Université de Strasbourg, 11 rue de l'Université, UMR 7550, F–67000 Strasbourg, France
[4] NSF OIR Lab, 950 N Cherry Ave, Tucson, AZ 85721, USA
[5] Universität Hamburg, Gojenbergsweg 112, D–21029 Hamburg, Germany
[*] Corresponding author: ynaze@uliege.be

Paper presented at the 41st Liège International Astrophysical Colloquium on
"The eventful life of massive star multiples," University of Liège (Belgium), 15–19 July 2024.

Abstract

Be stars are usually thought to be born in binary interactions. The presence of the companion has been proposed to play a role in the peculiar X-ray emission recorded for a subgroup of Be stars called the γ Cas analogs. In this contribution, we report on a multiwavelength investigation of one of them, the Be binary ζ Tau. Using data from TESS, *Chandra*, *SRG/eROSITA*, and *XMM-Newton*, we derive the high-energy properties as a function of time and orbital phase. The results are then used to test the proposed γ Cas models.

Keywords: X-rays: stars, stars: Be, stars: individual: ζ Tau

1. Introduction

The Be category was originally defined by the detection of Balmer emission lines in the spectrum of some non-supergiant B-type stars. Such emissions were found to be linked to the presence of circumstellar decretion disks around the stars. The origin of these disks and even of the Be stars themselves has been a subject of debate for decades. In this context, it has long been proposed that the formation of Be stars could involve binary interactions (van Bever and Vanbeveren, 1997) although the exact incidence of this scenario remained unclear. Several observational studies recently brought further support to the binary scenario through, e.g., the analysis of runaway fractions and SED turndowns, or the detection of stripped companions (Boubert and Evans, 2018; Klement et al., 2019; Wang et al., 2021).

In the X-ray range, a subgroup of Be stars appears particularly remarkable (for a review, see Smith et al. 2016). They are collectively called γ Cas analogs, from their prototype (the first identified Be star, γ Cas). Their X-ray emission is particularly bright and hard, in clear contrast with other groups of Be stars. Indeed, "normal" OB stars, and Be stars in particular, are usually quite faint and soft X-ray emitters, while Be+WD in nova stage are very bright and extremely soft, and Be+NS systems are very bright, very hard, and usually non-thermal in X-rays (see Nazé and Robrade 2023 and references therein). The nature of this peculiar high-energy emission is debated, with several proposed scenarios: (1) star-disk interactions through small-scale magnetic fields, (2) accretion onto a WD, (3) accretion onto a NS, and (4) collision between the Be disk and the wind from a sdO companion. The last two scenarios could be discarded, for both observational and theoretical reasons (Smith et al., 2017; Nazé et al., 2022b; Rauw, 2024).

A bright object of the Winter night sky, ζ Tau is a binary system with $P \sim 133$ d composed of a B1Ve star and a low-mass ($\sim 1\,M_{\odot}$) object of unknown nature (Ruždjak et al., 2009). It was recently found to belong to the class of γCas analogs (Nazé et al., 2022b). Its X-ray emission suffers from a high absorption, which is probably linked to the high inclination (70–90°) of the disk. Thanks to new observations, we were able to monitor the X-ray emission throughout the orbit and we summarize here the results of our analysis (Nazé et al., 2024b).

2. Data and Results

ζ Tau was observed several times in the X-ray range. The first dataset is a short Chandra exposure of December 2021 in which the binary appears off-axis and heavily piled-up (Nazé et al., 2022b). The second group of observations comprises four sets of *eROSITA* data (taken over 1 d in each of the four semesters between March 2020 and September 2021). In those data, the binary suffers from contamination by UV/visible photons (optical loading) at low energies (Nazé and Robrade, 2023). The last dataset is composed of two *XMM-Newton* exposures, taken in March/October 2023, which have been carefully designed to avoid both pile-up and optical loading. Stray light from the nearby Crab nebula is seen close to ζ Tau, but this does not affect its analysis. The particularity of the XMM observations is that they were taken at two opposite orbital phases (Be star in front of its companion and the reverse situation - Nazé et al. 2024b). X-ray light curves and spectra were extracted in the usual way for these datasets. To support the X-ray data analysis, we have analysed the optical behaviour of the star using amateur spectra (BeSS, Nazé et al. 2022b, 2024a) and TESS photometry (Sectors 43–45 in 2021 and 71–72 in 2023).

As usual in γCas analogs, the XMM intra-pointing light curves display significant variations on short timescales. Their periodograms reveal an intermittent signal in one of the exposures and an overall decreasing trend in all datasets (with Amplitude $\propto$ freq$^{-0.75}$). Both features are regularly seen in other analogs (see, e.g., Smith et al. 2016). No correlation between hardness and count rate can be detected, although a possible "softness dip" may have been observed towards the end of the first XMM exposure. Periodograms associated to the TESS high-cadence photometry display strong frequency groups, with variations from sector to sector, both common features amongst Be stars. No correlation is seen between the (then decreasing) overall strength of the Hα line and the TESS photometry and nothing particular is seen in the photometry at dates of (or close to) X-ray observations.

The X-ray spectrum of ζ Tau is revealed in detail in the XMM observations. Notably, they unveiled the presence of a faint soft component, the intensity of which appears comparable to that detected in "normal" Be stars. In addition, the iron fluorescence line at 6.4 keV appears similar in both observations and also to values recorded for γ Cas itself. Finally, X-ray spectra from the various facilities show long-term variations to occur. The observed flux in the 2–10 keV range appears in the range $1\text{–}2 \times 10^{-11}$ erg cm^{-2} s^{-1}, and the changes are largest in the 1.5–4.0 keV range. These variations are due to changes in the absorbing column towards the hottest ($kT = 9.1$ keV) plasma component. The absorption variations are clearly not phase-locked, nor are they correlated to changes in the disk as traced by the Hα line (overall strength, depth of the central absorption of the shell profile, peak separation). For example, when the X-ray absorption is highest or lowest, the central absorption depth in Hα is clearly not at an extremum. This is reminiscent of other γ Cas analogs for which no correlation with phase or Hα properties has been detected – in some cases, the peculiar X-ray emission may still exist while Hα is seen in absorption (Smith et al., 2012; Nazé et al., 2019, 2022a; Rauw et al., 2022).

3. Discussion

The behaviour of ζ Tau can now be compared to expectations of the two proposed γ Cas scenarios. First, we examine the star-disk interaction scenario. Using the usual density dependency of Be disks, we modelled the absorption along the line-of-sight for various parameters (notably considering several inclinations – 75, 80, 85, and 90°, basal densities, scale heights, disk sizes). If the X-ray source is located near the equator of the star, the absorbing column may reach very high values (over 10^{25} cm^{-2}). However, the observed columns agree with disk absorptions if the X-ray source is located at moderate elevations ($0.5\text{–}1.0\,R_*$) above the equatorial plane, which is not unexpected in this scenario. The lack of correlations with disk features remains puzzling, but requires more investigation to draw secure conclusions.

The second scenario involves an accreting white dwarf (WD), and many such objects are known. Only a few of them are paired with Be stars, however, and those systems are very bright and extremely soft (in other words, nova-like), contrary to γ Cas analogs (Kennea et al. 2021 and references therein). Other accreting WDs have different configurations, with short periods (often below 2 d) and the WD paired with a low-mass star (either overfilling its Roche lobe or providing the accretion material through its wind). Depending on the strength of the WD magnetic field, the accreted material can fall directly on the WD surface, fill a truncated disk before falling onto it, or form a disk around it. Temperatures recorded for such accreting WDs, the strength of their iron lines, and the frequency behaviour of their short-term variability are comparable to those reported for γ Cas analogs. While the observed absorbing column in ζ Tau appears comparable to those regularly observed for magnetic WDs, the link with inclination (since only the edge-on ζ Tau system shows such a high absorption) and the absence of stable short-term periodicity (despite the detection of intermittent features) in γ Cas analogs strongly disfavor such cases. For non-magnetic cases, the absorption is usually smaller, except at high accretion rates but then the soft X-ray emission dominates, contrary to observations of γ Cas stars. Only a small group of symbiotic stars, the so-called δ-type objects, appear to display highly absorbed hard X-rays, although they do so at somewhat lower inclinations too. In addition, while "shots" are ubiquitous in γCas analogs, they are much rarer in accreting WDs and the few exhibiting them display a different spectral behaviour during "flaring". It thus remains to be seen whether all γCas characteristics (temperature, absorption, variability, luminosity) can be accounted for with an accreting WD.

The wealth of available observations of γCas analogs is putting strong constraints on both scenarios envisaged to explain them. However, up to now, adequate theoretical predictions are not available. Indeed, modelling of large-scale magnetic fields and Be disks have been performed, but not of small-scale fields. Similarly, models of accreting WDs coupled to low-mass stars in tight orbits exist, but that is not the case of WDs coupled to distant high-mass stars with decretion disks. Such modelling efforts, adapted to γCas configurations, are now urgently needed, to fully assess the compatibility of the proposed scenarios with the X-ray and optical observations.

Acknowledgments

YN and GR acknowledge support from ESA, the FNRS and BELSPO (Belgium), MAS from Chandra grant #362675 to Catholic University of America, and JR from DLR grant 50QR2105.

Further Information

Authors' ORCID identifiers

0000-0003-4071-9346 (Yaël NAZÉ)
0000-0002-4298-5624 (Christian MOTCH)
0000-0003-4715-9871 (Gregor RAUW)
0000-0003-4240-4794 (Myron SMITH)
0000-0002-4939-8940 (Jan ROBRADE)

Author contributions

YN led the data analysis. She reduced the optical and *XMM*/*Chandra* data while JR reduced the *eROSITA* data. All authors contributed to the interpretation of the results.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

Boubert, D. and Evans, N. W. (2018) On the kinematics of a runaway Be star population. *MNRAS*, **477**(4), 5261–5278. https://doi.org/10.1093/mnras/sty980.

Kennea, J. A., Coe, M. J., Evans, P. A., Townsend, L. J., Campbell, Z. A., and Udalski, A. (2021) Swift J011511.0-725611: discovery of a rare Be star/white dwarf binary system in the SMC. *MNRAS*, **508**(1), 781–788. https://doi.org/10.1093/mnras/stab2632.

Klement, R., Carciofi, A. C., Rivinius, T., Ignace, R., Matthews, L. D., Torstensson, K., Gies, D., Vieira, R. G., Richardson, N. D., Domiciano de Souza, A., Bjorkman, J. E., Hallinan, G., Faes, D. M., Mota, B., Gullingsrud, A. D., de Breuck, C., Kervella, P., Curé, M., and Gunawan, D. (2019) Prevalence of SED turndown among classical Be stars: Are all Be stars close binaries? *ApJ*, **885**(2), 147. https://doi.org/10.3847/1538-4357/ab48e7.

Nazé, Y., Guarro Flo, J., Leduc, A., Stiewing, A., Curry, S., Dupont, X., Bryssnick, E., Diz, H. R., Bertrand, E., Buil, C., Desnoux, V., and Garde, O. (2024a) The recent Hα variations of ζ Tau. *OEJV*, **246**, 1–8. https://doi.org/10.5817/OEJV2024-0246.

Nazé, Y., Motch, C., Rauw, G., Smith, M. A., and Robrade, J. (2024b) X-raying the ζ Tau binary system. *A&A*, **688**, A181. https://doi.org/10.1051/0004-6361/202449737.

Nazé, Y., Rauw, G., Bohlsen, T., Heathcote, B., Mc Gee, P., Cacella, P., and Motch, C. (2022a) X-ray response to disc evolution in two γ Cas stars. *MNRAS*, **512**(2), 1648–1657. https://doi.org/10.1093/mnras/stac314.

Nazé, Y., Rauw, G., and Smith, M. (2019) Surprises in the simultaneous X-ray and optical monitoring of π Aquarii. *A&A*, **632**, A23. https://doi.org/10.1051/0004-6361/201936307.

Nazé, Y., Rauw, G., Smith, M. A., and Motch, C. (2022b) The X-ray emission of Be+stripped star binaries. *MNRAS*, **516**(3), 3366–3380. https://doi.org/10.1093/mnras/stac2245.

Nazé, Y. and Robrade, J. (2023) *SRG/eROSITA* survey of Be stars. *MNRAS*, **525**(3), 4186–4201. https://doi.org/10.1093/mnras/stad2399.

Rauw, G. (2024) Fluorescent Fe K line emission of γ Cas stars. I. Do γ Cas stars host propelling neutron stars? *A&A*, **682**, A179. https://doi.org/10.1051/0004-6361/202348076.

Rauw, G., Nazé, Y., Motch, C., Smith, M. A., Fló, J. G., and Lopes de Oliveira, R. (2022) The X-ray emission of γ Cassiopeiae during the 2020–2021 disc eruption. *A&A*, **664**, A184. https://doi.org/10.1051/0004-6361/202243679.

Ruždjak, D., Božić, H., Harmanec, P., Fiřt, R., Chadima, P., Bjorkman, K., Gies, D. R., Kaye, A. B., Koubský, P., McDavid, D., Richardson, N., Sudar, D., Šlechta, M., Wolf, M., and Yang, S. (2009) Properties and nature of Be stars. 26. Long-term and orbital changes of ζ Tauri. *A&A*, **506**(3), 1319–1333. https://doi.org/10.1051/0004-6361/200810526.

Smith, M. A., Lopes de Oliveira, R., and Motch, C. (2016) The X-ray emission of the γ Cassiopeiae stars. *AdSpR*, **58**(5), 782–808. https://doi.org/10.1016/j.asr.2015.12.032.

Smith, M. A., Lopes de Oliveira, R., and Motch, C. (2017) Is there a propeller neutron star in γ Cas? *MNRAS*, **469**(2), 1502–1509. https://doi.org/10.1093/mnras/stx926.

Smith, M. A., Lopes de Oliveira, R., Motch, C., Henry, G. W., Richardson, N. D., Bjorkman, K. S., Stee, P., Mourard, D., Monnier, J. D., Che, X., Bücke, R., Pollmann, E., Gies, D. R., H Schaefer, G., ten Brummelaar, T., McAlister, H. A., Turner, N. H., Sturmann, J., Sturmann, L., and Ridgway, S. T. (2012) The relationship between γ Cassiopeiae's X-ray emission and its circumstellar environment. *A&A*, **540**, A53. https://doi.org/10.1051/0004-6361/201118342.

van Bever, J. and Vanbeveren, D. (1997) The number of B-type binary mass gainers in general, binary Be stars in particular, predicted by close binary evolution. *A&A*, **322**, 116–126. https://ui.adsabs.harvard.edu/abs/1997A&A...322..116V.

Wang, L., Gies, D. R., Peters, G. J., Götberg, Y., Chojnowski, S. D., Lester, K. V., and Howell, S. B. (2021) The detection and characterization of Be+sdO binaries from HST/STIS FUV spectroscopy. *AJ*, **161**(5), 248. https://doi.org/10.3847/1538-3881/abf144.