

THE γ CAS PHENOMENON AS A LINK TO MASSIVE STAR EVOLUTION

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Abstract. The well known Be category consists of early-type stars that show or have shown Balmer emission lines, attributed to the presence of a circumstellar decretion disk. Their fast rotation is often considered to be linked to past binary interactions, with the current companion being a compact object (WD, NS) or a stripped He-star. In the X-ray domain, Be stars have been shown to display various properties, with a significant fraction of them emitting hard and bright thermal X-rays. These sources are categorized as “gamma-Cas” analogs. In this contribution, we will present the latest information obtained on these γ Cas stars, assessing their incidence as well as their potential multiplicity.

Key words: X-rays: stars – Stars: Be

1. Introduction

Most types of stars emit X-rays, but the properties of this high-energy emission vary a lot depending on the actual physical processes at work. In massive stars stellar winds often play a key role. Indeed, these line-driven winds are intrinsically unstable, leading to shocks distributed throughout the outflow (see e.g. Feldmeier et al. 1997). Such shocks explain why, in O-type stars and early B-stars, one can observe soft ($kT \sim 0.6$ keV) X-rays following a tight relationship between X-ray and bolometric luminosities ($\log(L_X/L_{BOL}) = -7$, e.g. Berghöfer et al. 1997, Nazé et al. 2011). In addition, if a strong dipolar magnetic field is present, as occurs in about 10% of massive stars, the wind flows are channelled towards the magnetic equator where they collide. This generates additional X-rays (Babel & Montmerle

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1997, ud-Doula et al. 2014, Nazé et al. 2014), rendering the magnetic massive stars somewhat brighter (and often harder) than expected from embedded-wind shocks. In such systems, modulation with the rotational period may exist, as the rotational and magnetic axes differ.

In binaries, additional phenomena may occur. If both objects are massive (O or WR-type) stars, their stellar winds collide and, in some cases, the shocks are strong enough to generate X-ray emissions (for a review, see Rauw & Nazé 2016). Such systems will then appear somewhat brighter and harder than expected from embedded-wind shocks. They also display phase-locked variations of their X-ray emission, due to changes in absorption along the line-of-sight (eclipses, differences in wind densities) or to changes in the intrinsic strength of the collision (in eccentric binaries). On the other hand, if the binary is composed of a massive star and a neutron star or black hole, then accretion onto the compact object occurs and the associated X-ray emission is extremely hard and often exhibits bright outbursts (for a review on some X-ray binaries, see e.g. Reig 2011). A few cases of white dwarf companions to massive stars have also been discovered outside our Galaxy, and these systems appear bright and supersoft in the X-ray range during novae episodes (see e.g. Kennea et al. 2021 and references therein).

Finally, a group of objects display intermediate properties: luminosity between that of OB-stars and that of X-ray binaries, combined to a thermal nature for the X-ray emission with temperatures above 5 keV (while temperatures associated with confined or colliding winds rarely exceed 2 keV). This group has been named after its prototype, γ Cas (for a review, see Smith et al. 2016).

2. The γ Cas phenomenon

γ Cas was the first star for which Balmer emission lines were noticed, more than a century ago. This led to the definition of the “Be” category, for which γ Cas was considered as a prototype. In 1976, however, unusual high-energy emission was discovered for this star thanks to the SAS-3 satellite (Jernigan 1976). For several decades this bright X-ray emission remained an anomaly, but other Be stars with analog X-ray properties were finally found (the first new case being HD 110432, Smith & Balona 2006). Usually, these discoveries were serendipitous (e.g. Lopes de Oliveira et al. 2006, Lopes de Oliveira & Motch 2011, Nazé et al. 2017) or occurred in the context of

limited surveys (e.g. Nazé & Motch 2018). Two dozen cases were found in this way.

Such observations are not devoid of biases, hence the actual incidence of the γ Cas phenomenon just defined remained difficult to constrain. Nazé & Robrade (2023) tried to avoid this problem by performing a specific search with eROSITA. The eROSITA instrument onboard the SRG satellite (Predehl et al. 2021) performed scans of the whole sky over four semesters and a detailed survey catalog has been built for the western half of the sky (galactic longitude $> 180^\circ$). Of the 832 Be stars listed in the BeSS catalog for that half-sky, 170 were detected by eROSITA. As could be expected, more distant detections display larger luminosities (the faint distant sources would not be detected) and late-type Be stars appear fainter than early-type ones. Most detected sources emit soft X-rays, but 34 sources clearly appear bright and hard, i.e. $\log(L_X \text{ in } 0.5 - 5 \text{ keV}) > 31.4$, $\log(L_X/L_{BOL}) > -6.4$, and fraction of the 0.5–5. keV X-rays emitted in the hard (2–5 keV) range > 0.4 . Of these, eleven sources are previously known γ Cas analogs or low-luminosity X-ray binaries (or XRB candidates). Considering only early-type Be stars in the 100–1000 pc range, a distance-limited incidence fraction of 12% is derived. Clearly, being more common than high-mass X-ray binaries, the γ Cas phenomenon is not rare.

It now seems clear that (1) all γ Cas analogs are Be stars, hence a natural question about the exact link between the X-ray sources and the Be disks arises; (2) not all Be stars present the γ Cas peculiarities, hence one may ask what makes them so special. Over the last years, various authors have tried to tackle those questions and we present the recent results of our researches in the following sections.

3. Multiplicity of γ Cas analogs

Be stars are now generally considered to be the products of binary interactions (e.g. Pols et al. 1991, Van Bever & Vanbeveren 1997). In such interactions, the initially lower mass star of the system gained mass and angular momentum and became a fast-rotating Be star. The initially higher mass star has lost so much mass that it now has only $\sim 1 M_\odot$. Theoretical simulations indicate that it can be a neutron star, a white dwarf, or a stripped helium star, with the last two possibilities much more common than the first one (Shao & Li 2014 - a black hole is also a possibility, but with ex-

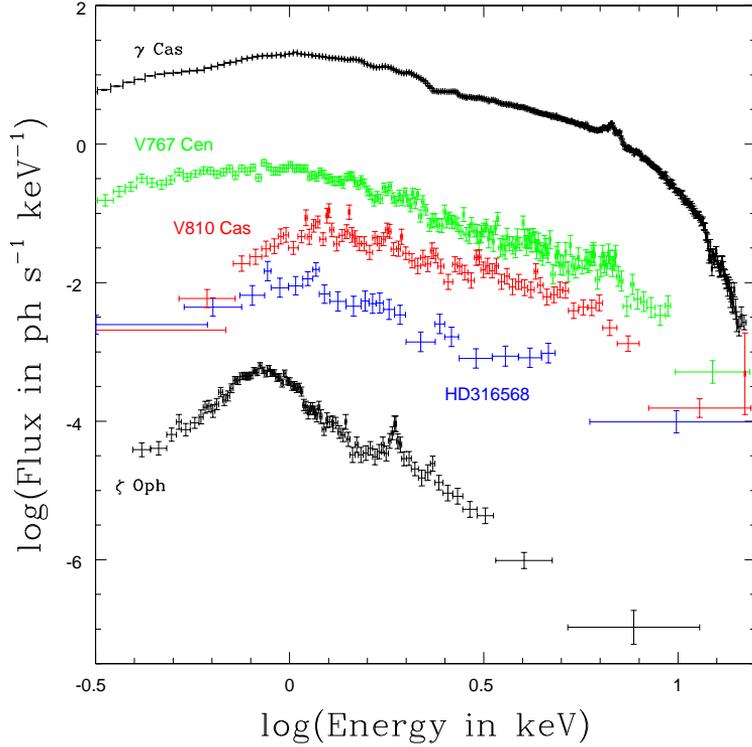


Figure 1: Spectra of γ Cas and three analogs, compared to that of ζ Oph, a normal O star. For γ Cas analogs the spectral slopes at high energies clearly are much flatter. Note also the strong iron complex near 6.7 keV. (From Nazé & Motch 2018, reproduced with permission ©ESO)

treme rarity, so it won't be considered further). It may be noted that all three types of objects have been detected as companions of Be stars, thanks to UV or X-ray observations. Not all Be stars have identified companions, however, due to the difficulties in detecting these low-mass objects.

Amongst γ Cas analogs, three cases have been known to be binaries for a long time: γ Cas, π Aqr, and ζ Tau, but the multiplicity status of other analogs remained unknown. Nazé et al. (2022a) performed a spectroscopic monitoring of 16 other γ Cas analogs. A few cases harboured large H α profile variations impairing the derivation of reliable radial velocities (RVs). Five other objects display RV shifts, but no orbital solution could be derived in

view of the few number of available spectra. For six cases, however, recurrent RV variations led to the determination of an orbital solution. All display a long period and small RV amplitude, suggesting low-mass companions. This is similar to what was found in other Be binaries. Therefore, the γ Cas analogs do not seem peculiar regarding their multiplicity properties.

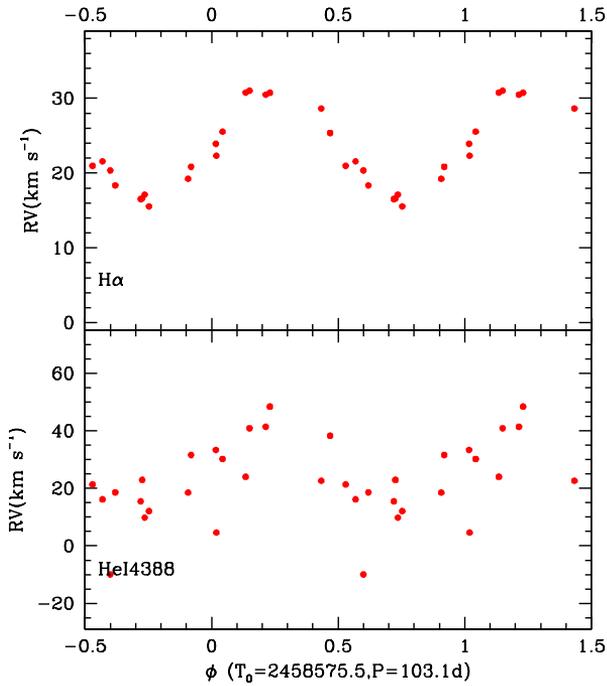


Figure 2: RVs of the γ Cas analog HD 45995 measured on the HeI4388Å (bottom) and H α (top) lines, folded with the best-fitting ephemeris. (From Nazé et al. 2022a)

4. Test of the disk-wind scenario

An important question regarding this γ Cas phenomenon is its origin. Several scenarios have been proposed and they can be split into two classes. The first class considers the X-rays to arise because of the presence of a companion to the Be star. cAs there are typically three types of possible

companions, there are three distinct mechanisms for X-ray production. The strong and hard X-ray emission could come from accretion onto a white dwarf (e.g. Hamaguchi et al. 2016), accretion onto a neutron star in the propeller stage (Postnov et al. 2017), or a collision between the Be disk and the wind of a subdwarf helium star (e.g. Langer et al. 2020). In contrast, the second class of scenarios instead considers the X-rays to arise from small-scale magnetic interactions between the star and its disk (Smith et al. 1998, Robinson & Smith 2000, Robinson et al. 2002). In this case, a companion, whatever its nature, can be present but plays no active role in the generation of X-rays.

To test the disk-wind scenario, Nazé et al. (2022c) examined X-ray data of 18 cases of Be stars known to be paired with stripped stars (thanks to UV observations, see Wang et al. 2018, 2021) as well as seven Be binaries whose low-mass companion is suspected to be a sdOB star. In that sample, one system had previously been found to display γ Cas properties, while another was known to not have them. By enlarging the view, the new X-ray data clarified the situation. Most systems were found to be X-ray faint, with either a non-detection (with stringent limits) or a faint detection in the soft X-ray range. Only two systems display γ Cas properties, a number which agrees with expectations, in view of the incidence rate of the γ Cas phenomenon. Furthermore, no link could be found between the level of X-ray emission and the orbital period or the companion’s properties (temperature, mass, luminosity). This is atypical of colliding winds phenomenology and directly contradicts the scenario of Langer et al. (2020), who predicted a higher X-ray luminosity for systems with more massive companions. Finally, one may note that the collision scenario required extreme sdOB properties (which are not found in observed sdOB companions). Also, a typical collision feature, phase-locked variability of the X-ray emission, is not detected in γ Cas analogs while a typical γ Cas feature (the short-term “flaring”) is not detected in the observed cases of high-energy emission from colliding winds. It is thus highly unlikely that a disk-wind collision is responsible for the bright and hard X-rays of γ Cas stars.

5. The role of the disk

If accretion by a compact companion is the source of the γ Cas X-rays, then the accreted material would preferentially come from the Be disk (the wind

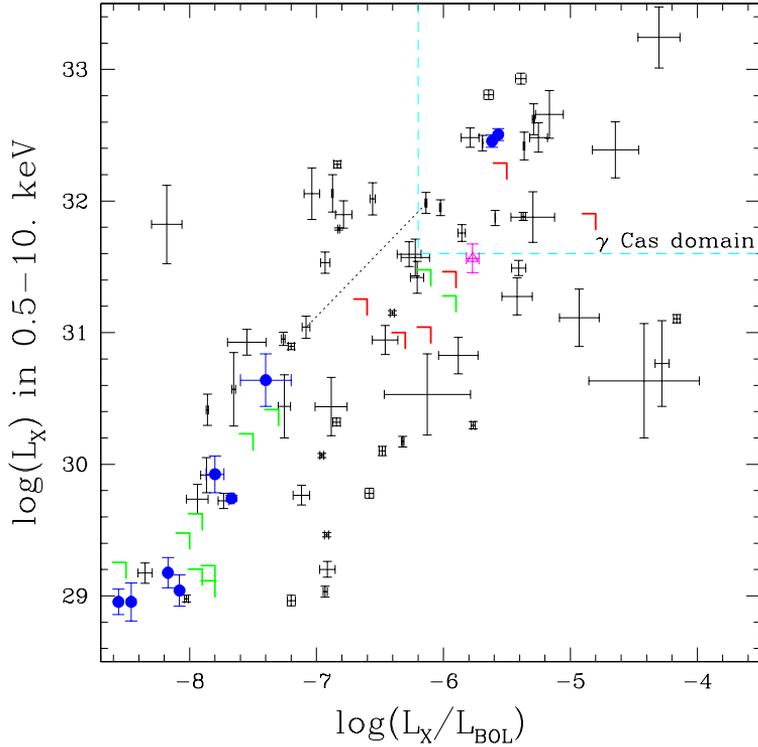


Figure 3: X-ray luminosities in the sample of Be+sdO binaries, compared to objects analyzed in Nazé & Motch (2018) and Nazé et al. (2020). Blue circles are used for Be+sdO systems with detected X-ray emissions, green symbols for the 95% upper limits of undetected Be+sdO systems, a magenta triangle for the Be binary with detected X-rays, red symbols for the 95% upper limits of the undetected Be binaries, and black symbols for objects reported in previous studies. Note that HD 157832 is represented twice as two XMM-Newton observations are available. (From Nazé et al. 2022c)

being tenuous). If instead a star-disk interaction occurs, its characteristics will also depend on the disk properties. In both cases it is highly relevant to study the link between the X-ray emission and the Be disk. This is achieved by multiwavelength monitoring, combining optical and X-ray observations. In this context, several γ Cas analogs have been surveyed in the last years to complement the earlier works on γ Cas itself and HD 110432 (see details in the review by Smith et al. 2016).

HD 45314, the most massive γ Cas analog, has been the target of sev-

eral X-ray exposures (Rauw et al. 2018). The first two were performed with a well-grown disk, but the third one was taken as the disk was dissipating (small emission in $H\alpha$, change in broad-band magnitudes). This near-disappearance of the disk led to a large decrease of the hard X-rays, i.e. to a near-disappearance of γ Cas characteristics. Recent observations confirm that the low state continues, both in optical and X-rays (Nazé & Robrade 2023).

π Aqr suffered from a near-disappearance of its disk in early 2014. While the dissipation was not as complete as seen a decade before, the equivalent width (EW) became positive, i.e. absorption-dominated. Comparing an XMM exposure taken at that time with a more recent Swift dataset obtained when the disk was fully re-built (and growing) revealed only a slightly fainter and softer emission at the time of $H\alpha$ minimum (Nazé et al. 2019, 2022b). At all times, π Aqr clearly maintained its γ Cas-like X-ray emission. In addition, the long Swift campaign was used to search for changes tied to the orbital phase but none were found.

HD 119682 recently underwent a decrease of $H\alpha$ line strength, with a positive EW in the second half of 2019. However, while there were some (limited) X-ray flux changes, this near-disappearance of the Be disk did not coincide with a change in hardness of the X-ray emission (Nazé et al. 2022b). In the same vein, the $H\alpha$ line of V767 Cen decreased in recent years. Then its strength oscillated, though always keeping small EW values. The broad-band g magnitude remained stable, though, and the X-ray monitoring did not reveal any significant change in hardness or flux either (Nazé et al. 2022b). In both cases, the two stars clearly kept their γ Cas character at all times.

Finally, the recent behaviour of γ Cas itself was examined by Rauw et al. (2022). This bright X-ray source has been a regular target of many X-ray facilities, which facilitates multi-wavelength monitoring. There was a “bump” in 2021 in $H\alpha$ line strength, but without any significant change in V magnitude. During the event the average X-ray flux varied by a factor of 2 but the change mostly came from an absorbing event affecting the soft band: the hard X-ray emission underwent little variation. Considering the whole dataset, one finds that there was no obvious link between X-ray luminosity and $H\alpha$ line strength or orbital phase. However, the annual luminosity averages measured in V magnitude and in X-rays with RXTE/MAXI appeared correlated (confirming previous results by Henry & Smith 2012, Motch et

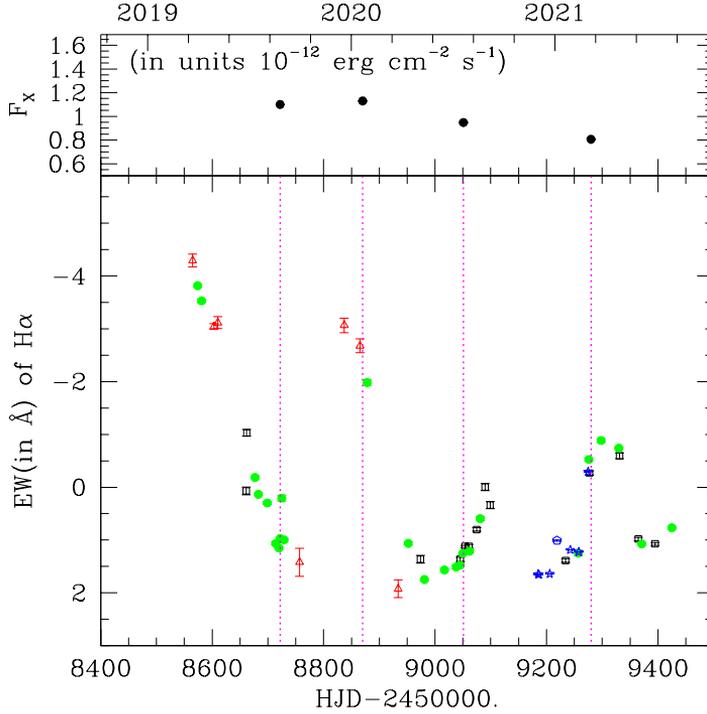


Figure 4: Evolution with time of the EWs of the H α line and of X-ray fluxes in HD 119682. The top axis provides the date in years, while the bottom axis uses Julian dates. Different symbols are used for optical data of different sources and/or of various signal-to-noise ratios. The vertical magenta dotted lines indicate the times of the XMM-Newton observations. (From Nazé *et al.* 2022b)

al. 2015). This correlation suggests that the hard X-rays arise from the inner disk. An origin at the inner disk would also account for the enhanced absorption that would then be due to an expanded flaring disk as diagnosed by the increased H α emission strength in 2020 - 2021.

6. Conclusion

Amongst Be stars, a subcategory consisting of about 10% of the objects, the γ Cas analogs, displays a bright, hard, and flaring X-ray emission atypical of

what is observed for OB stars at high energies. Apart from the X-ray range, these objects do not present peculiar characteristics. For example, when investigated in detail, several of these objects are found to have low-mass companions in long-period orbits, just as detected for other Be stars.

Multiwavelength monitoring of several γ Cas analogs was performed. These observations revealed the existence of long-term changes in the X-ray emission, but no clear link could be established between the X-ray properties and the orbital period or the strength of the H α line (a usual disk diagnostics). In fact, the γ Cas character may remain even if the H α emission is weak.

One scenario proposed to explain this peculiar X-ray emission through collisions between the Be disk and the wind of its hot sdOB companion. A thorough investigation of the known and candidate Be+sdOB systems showed that their X-ray properties disagree with predictions of this scenario, hence it can most probably be discarded. While this is a step forward, much remains to be done, however, to pinpoint the origin of the hard X-rays. In this context, further monitoring is needed as well as a detailed investigation of the iron fluorescence line at 6.4 keV which is a sensitive indicator of the configuration of both X-ray source and reflection site. New X-ray facilities (such as XRISM, LEM, Athena) will thus provide critical diagnostics which may finally shed light on this γ Cas mystery.

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