Three discoveries of $\gamma$ Cas analogs from dedicated XMM-\textit{Newton} observations of Be stars\textsuperscript{*}

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ABSTRACT

In the last years, a peculiarity of some Be stars - their association with unusually hard and intense X-ray emission - was shown to extend beyond a mere few cases. In this paper, we continue our search for new cases by performing a limited survey of 18 Be stars using XMM-\textit{Newton}. The targets were selected either on the basis of a previous X-ray detection (Exosat, ROSAT, XMM-slew survey) without spectral information available, or because of the presence of a peculiar spectral variability. Only two targets remain undetected in the new observations and three other stars only display faint and soft X-rays. Short-term and/or long-term variations were found in one third of the sample. The spectral characterization of the X-ray brightest 13 stars of the sample led to the discovery of three new $\gamma$ Cas (HD 44458, HD 45995, V558 Lyr), bringing the total to 25 known cases, and another $\gamma$ Cas candidate (HD 120678), bringing the total to 2.

Key words: stars: early-type – stars: Be – stars: massive – stars: variable: general – X-ray: stars

1 INTRODUCTION

Most stars are X-ray emitters, though their X-ray luminosities span a wide range of values. For the cases that display particularly intense emission, the X-rays constitute an important probe of the physical processes occurring in those objects. In massive stars, stellar winds usually play the leading role in generating X-rays. Being intrinsically unstable, these line-driven winds possess shocks distributed through the outflow which generate soft X-rays (typically $kT \sim 0.6$ keV) with an intensity following the “canonical” $\log(L_{X}/L_{BOL}) = -7$ relation in O-stars and very early B-stars (e.g. Berghoefer et al. 1997; Nazé et al. 2011). As the effective temperature decreases, winds become weaker and weaker, hence most B-stars appear X-ray faint. There are several exceptions, however, and the most common ones are: a strong dipolar magnetic field may channel the wind flows towards the equator where they collide, generating bright and moderately hard X-rays (Babel & Montmerle 1997; ud-Doula et al. 2014; Nazé et al. 2014); an otherwise unseen PMS companion generates sufficient X-rays, notably during flares, to lead to a detection of the system (e.g. Sana et al. 2006); the presence of an accreting compact companion leads to the emission of very hard and very intense X-rays, in particular in Be X-ray binaries (Reig 2011). Finally, there is the so-called $\gamma$ Cas category (Smith et al. 2016).

$\gamma$ Cas analogs, named after their prototype, are first of all Be stars, i.e. they possess (or have possessed) a circumstellar Keplerian decretion disk whose signature can be seen through strong emission lines in the optical spectrum (for a review on Be stars, see Rivinius et al. 2003). In the op-
tactical range, up to now, they do not seem to particularly stand out amongst the Be family. The defining criteria of these objects come from the X-ray range (for a review, see Smith et al. 2016). At high energies, Cyg Cas analogs display a thermal spectrum associated to a high plasma temperature (kT ~ 5–20 keV, i.e., much hotter than found in "normal" and magnetic B-stars). Furthermore, their X-ray luminosities are intermediate between those of "normal" massive stars and those of X-ray binaries (log[Lx/Lbol] ~ -5, Lx,Mdot < 0.5–10 keV) = 4 x 10^{31} - 2 x 10^{33} erg cm^{-2} s^{-1}). Finally, they also display short, flaring-like variations of their X-ray emission, as well as long-term changes.

The origin of these peculiarities remains debated. They cannot be due to the presence of strong dipolar magnetic fields, as in confined winds, since the presence of such fields is incompatible with a Keplerian decretion disk, as has been demonstrated both observationally and theoretically (Grunhut et al. 2012; ud-Doula et al. 2018). However, whilst large-scale magnetic fields can be ruled out, localized small-scale fields could exist (Cantiello & Braithwaite 2011) and may interact with instability-generated fields of the disk, leading to flaring X-ray emission (Robinson et al. 2002). Alternative explanations involve accretion under unusual conditions onto a compact companion (white dwarf, Murakami et al. 1986; Hamaguchi et al. 2016; Tsujimoto et al. 2018 or neutron star with a propeller process, Postnov et al. 2017).

Up to now, the data remain scarce as many Cyg Cas stars were discovered by chance. The exact incidence rate of such stars is therefore unclear, with poorly-defined limits (though it is significantly higher than for Be X-ray binaries, see section 6.1 of Smith et al. 2017). Moreover, so far it remains unclear what the physical characteristics and stellar properties that make a Be star display a Cyg Cas behaviour are. Better statistics are thus eagerly needed, which is why specific searches have been undertaken. Nebot Gómez-Morán et al. (2013, 2015) searched for Be counterparts to unidentified X-ray sources while Nazé & Motch (2018) tackled the problem the other way around, searching data archives for serendipitous X-ray observations of Be stars. All these efforts led to the detection of about twenty Cyg Cas analogs.

In this paper, we continue this endeavour and report on an X-ray survey of selected Be stars. The choice of targets was based on two criteria. The first one was a previous detection of the star in the X-ray range. This reveals that the star emits X-rays but it is not a precise characterization of the emission at high energy. Without any available spectrum, the determination of the potential Cyg Cas character cannot be done. In this context, we cross-correlated the Be Star Spectra catalog (BeSS, Neiner et al. 2011) and bright (V < 6 mag) Be stars listed in Simbad with ROSAT OB-stars detections (Berghoefzer et al. 1996). We kept sources displaying log(Lx/Lbol) > -7 and for which no other X-ray observation was available. We added sources detected by EXOSAT-ME in the hard X-ray range but not by ROSAT in the soft band, as was the case of the Cyg Cas analog HD 45314 (Rauw et al. 2013, 2018). Such a situation suggests that these objects display very hard X-ray emissions hence could have a good chance of being Cyg Cas analogs, if the EXOSAT detection was not due to optical/UV loading. A last target, α Ara, was detected as an X-ray source in the XMM-Newton slew survey, as had been the case of the Cyg Cas analog π Aqr (Nazé et al. 2017). The second criterion relies on the presence of an optical peculiarity observed in Cyg Cas and HD 45314 (Rauw et al. 2018): a transition of the Hα line from a classical double-peaked pure emission profile to a so-called shell profile. For steady Be disks, a shell profile is observed when the (equatorial) disk is seen edge-on with respect to our line-of-sight. Yet, a small subset of Be stars have displayed shell episodes during which the Hα line changed from a conventional double-peaked pure emission to a shell morphology (see Sect. 6.1.2 in Rauw et al. 2018, and references therein). This suggests a temporarily more complex geometry of the circumstellar envelope. Since several of the few Be stars displaying these spectacular variations actually belong to the Cyg Cas category, we included in our sample two other stars having undergone an episode of such variations (HD 120678 and 59 Cyg) in the past.

In total, 18 targets were thus selected and observed using XMM-Newton. Section 2 presents the observations and their reduction, Section 3 lists the obtained individual results and compares them with previous observations of Be stars, and Section 4 summarizes our findings and concludes this paper.

2 OBSERVATIONS AND DATA REDUCTION

The limited survey of Be stars was performed with XMM-Newton in 2018 and 2019 for our programs 082031 and 084020. These observations were taken in various modes and filter combinations, chosen to avoid potential X-ray pile-up and optical/UV loading. The list of the exposures is available in Table 1. This table also provides information on the stellar properties, derived as in Nazé & Motch (2018). Spectral types come from the BeSS or Simbad databases, V magnitudes from Simbad, and interstellar color excess E(B-V) from Capitanio et al. (2017) considering the absolute magnitudes of Wegner (2007). The distance intervals were taken from Baile-Jones et al. (2018), except for μ Lup for which the GAIA DR2 parallaxes were used and the optically bright η Ori, α Ara, and Shelık (β Lyr) for which the Hipparcos distances were used as the GAIA distances remain uncertain (Drimmel et al. 2019).

The XMM-Newton data were processed with the Science Analysis Software (SAS) v18.0.0 using calibration files available in Oct. 2019 and following the recommendations of the XMM-Newton team. After the initial pipeline processing, the European Photon Imaging Camera (EPIC) observations were filtered to keep only the best-quality data (pattern 0–12 for MOS and 0–4 for pn). To assess the crowding near the targets in order to choose the best extraction region, a source detection was performed on each EPIC dataset using the task edetectchain, which uses first sliding box algorithms and then performs a PSF fitting, on the 0.3–10.0 keV energy band and for a log-likelihood of 10. We obtained a 1 In a few observation files, the filter was incorrectly set to “CalThick” but we corrected files manually, setting it to the actual “Thick” filter identification.

2 SAS threads, see http://xmm.esac.esa.int/sas/current/documentation/threads/
formal detection for all our targets but two, µ Lup and κ Dra. The EPIC count rates of the others are provided in Table 1. The detected X-ray sources lie in 2′′ or less for all stars (average separation is 1.2′′) but three: d Lup is at 3.4′′ of its X-ray counterpart, I Hyα at 3.7′′, and HD 43285 at 4.2′′. Contrary to catalogs like the XMM, no further astrometric correction has been applied hence small shifts remain possible. Unfortunately, the lack of X-ray sources in the I Hyα and HD 43285 fields prevents us to check source alignment for other targets and therefore the accuracy of the astrometry calculation of the X-ray counterparts which are associated with our targets. Near d Lup, however, star 2MASS J15555876–4456355 is detected and it appears at 1.4′′ only of the X-ray source. We therefore consider these three detections as tentative, awaiting independent confirmation. For three targets with low count rates (QY Car, d Lup, α Ara), it was not possible to extract a spectrum hence we estimated the source hardness by performing a second detection run, this time using the 0.5–2.0 keV and 2.0–10.0 keV energy bands. Finally, it should be noted that the observation of HD 120678 was affected by straylight from a nearby bright source (probably the RSCVn HD 119285).

Light curves for events beyond 10 keV were built for the full fields. Using them, background flares were detected in about half of the exposures and the time intervals corresponding to flaring events were further processing. For the brighter detections (i.e. EPIC-pn count rate larger than 0.01 cts s⁻¹), we then extracted EPIC light curves (in the 0.3–10.0 keV energy band) and spectra of the source using circular regions centered on the Simbad positions of the targets with radii between 12.5 and 30′′, depending on the crowding and position of CCD gaps. Background was derived in nearby circular regions of 30′′ radius devoid of sources, except for HD 120678 where nearby boxes were rather used for MOS as they better allow to avoid straylight contamination. Light Curves were corrected using the task epiclccorr to provide full-PSF, equivalent on-axis count rates. Time bins between 100s and 2000s were used, depending on source brightness, and bins with fractional exposure times smaller than 50% were discarded. Spectra and their dedicated calibration matrices (ancillary response file and redistribution matrix file response matrices, which are used to calibrate the flux and energy axes, respectively) were derived using the task especcet. EPIC spectra were grouped with specgroup to obtain an oversampling factor of five and to ensure that a minimum signal-to-noise ratio of 3 (i.e., a minimum of ten counts) was reached in each spectral bin of the background-corrected spectra.

### 3 RESULTS

Our sample consisted of 18 Be stars. Two of these, µ Lup and κ Dra, are not detected in the new observations. The previous claimed ROSAT detection of µ Lup can however be easily explained by confusion as an X-ray source actually appears at 22′′ southeast of the target. It corresponds to the A-star HD 135748. The previous Exosat detection of κ Dra, on the other hand, is most probably due to optical/UV loading from this bright hot star.

Three further targets, QY Car, d Lup, and α Ara, are detected but remain faint in XMM-Newton data. A detection run in two energy bands (soft, 0.5–2.0 keV, and hard, 2.0–10.0 keV) reveals that the soft count rate is at least three times larger than the hard one, clearly indicating that these stars are emitting mostly at low energies. To estimate their X-ray luminosities, we converted their count rates within WebPIMMs³ using temperatures of 0.3 or 1 keV (since we know their softness but without a precise temperature constraint) and the interstellar absorption derived from the color excess (Table 1) using the relation of Guennouvar et al. (2012). The resulting luminosities are 0.7–40.0, 1.3–2.7, 0.6–2.3×10²⁸ erg cm⁻² s⁻¹ for QY Car, d Lup, and α Ara, respectively. This corresponds to log(Lx/Lbol) or -9.6–7.8, -8.6–

³ https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
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and V558 Lyr (Fig. 1) red symbols correspond to the background light curves; x-axes are MOS1 on the left, MOS2 in the middle, and pn on the right. Open

Figure 1. Background-corrected EPIC light curves in 0.3–10 keV for HD 44458 (top), I Hya (middle), and V558 Lyr (bottom), with MOS1 on the left, MOS2 in the middle, and pn on the right. Open red symbols correspond to the background light curves; x-axes are the same for HD 44458 and I Hya and, for each star, y-axes are the same for both MOS.

8.3, and −9.2…8.6 for QY Car, d Lup, and α Ara, respectively. Clearly, those three stars do not display the typical γ Cas characteristics.

The light curves and spectra of the 13 remaining targets can be analyzed in some detail. Using $\chi^2$ tests, significant (SL < 1%) variability is detected for the background-corrected EPIC light curves of HD 44458, I Hya, and V558 Lyr (Fig. 1). Moreover, since most of the targets had been previously detected in the X-ray range, we also investigated the longer-term variability. By folding the best-fit XMM-Newton spectral model (see text below and Table 2) through the ROSAT response matrices, we predicted an equivalent ROSAT count rate (Table 3), which we compared to the one reported by Berghoefer et al. (1996). The differences between predicted and observed count rates are always below 3σ; in fact, they are even below 2σ for all but one source (HD 44458, 2.4σ) which may hint at long-term changes for that star. For d Lup, XMM-Newton spectra could not be extracted hence the XMM-Newton count rate was transformed into its ROSAT equivalent within WebPIMMS, with the same hypotheses as above. The predicted count rate is significantly (3.3σ) below the observed ROSAT value, implying a decrease of the X-ray emission. For Exoas-MT, similarly converting the XMM-Newton count rates of QY Car leads to very small values (< 2 x 10$^{-5}$ ct s$^{-1}$), strongly suggesting that the previous detection could have been spurious, i.e. due to optical/UV loading (as for α Dra). In parallel, α Ara is reported in the XMM slew survey catalog v2.0 as XMMSSL J173150.8−495233 with an EPIC-pn count rate of 2.1±0.9 ct s$^{-1}$ in the 0.2–12 keV energy band. This is fully compatible with its value in the 0.3–10 keV band (Table 1) but the slew survey error is very large and only permits to detect drastic changes of brightness. α Ara was however observed twice by XMM-Newton in pointed observations and these two exposures display differences larger than 3σ for the EPIC-pn count rate (for the less sensitive MOS cameras, the rate differences amount to 1–2σ). This implies that this star undergoes variations of its X-ray flux on timescales of months. Finally, the two XMM-Newton observations of Shelik provide similar count rates, suggesting a rather constant X-ray emission from that star.

All available EPIC spectra were fitted simultaneously within Xspec v12.9.1p, as in Nazé & Motch (2018). As is

Table 2. Results of the spectral fitting (see text for details).

| Name   | MOS1 | MOS2 | pn |
|--------|------|------|----|
|        | $N_{\text{H}}$ | $N_{\text{L}}$ | $kT_1$ | $\text{norm}_1$ | $kT_2$ | $\text{norm}_2$ | $kT_3$ | $\text{norm}_3$ | $\chi^2/\nu$ | $F_{\text{ROSAT}}^{\text{source}}$ | $F_{\text{ROSAT}}^{\text{background}}$ |
|--------|------|------|------|-------|------|-------|------|-------|------|-----------------|-----------------|
| HD 18552 | 0.024 | 0.023 | 0.031 | 0.230 | 0.240 | 0.033 | 857.5 | 6.24 | 0.37 | 5.14 | 1.20 (136) |
| q Ori  | 0.004 | 0.032 | 0.008 | 1.874 | 0.003 | 4.55 | 36 | 4 | 5.38 | 1.66 (73) |
| II 847 | 0.094 | 0.030 | 0.004 | 8.945 | 0.007 | 1.22 | 16 | 5 | 4.07 | 2.44 (18) |
| HD 43855 | 0.010 | 0.083 | 0.015 | 5.247 | 0.018 | 3.65 | 4.5 | 0.28 | 1.40 | 1.10 (18) |
| HD 44588 | 0.005 | 0.069 | 0.010 | 9.140 | 0.055 | 2.73 | 7.2 | 0.09 | 1.90 | 1.00 (94) |
| HD 59959 | 0.063 | 0.027 | 0.151 | 5.45 | 0.19 | 7.3 | 34.1 | 0.73 | 0.98 | 1.30 (156) |
| II 848 | 0.009 | 0.060 | 0.002 | 2.354 | 0.008 | 4.17 | 0.07 | 0.08 | 1.02 | 1.91 (223) |
| HD 120678 | 0.26 | 0.51 | 0.64 | 0.140 | 0.115 | 0.34 | 13.0 | 0.02 | 0.16 | 1.16 (71) |
| V886 Oph | 0.11 | 0.084 | 0.014 | 0.184 | 0.02 | 0.72 | 2.40 | 0.08 | 2.38 | 1.40 (79) |
| Shellak $^a$ | 0.021 | 0.064 | 0.007 | 0.254 | 0.07 | 0.240 | 0.08 | 0.13 | 0.21 | 1.49 (197) |
| 59 Cyg $^b$ | 0.025 | 0.018 | 0.022 | 0.240 | 0.04 | 0.32 | 0.05 | 0.01 | 0.16 | 1.07 (25) |
| Aqr $^c$ | 0.002 | 0.042 | 0.014 | 0.234 | 0.017 | 4.240 | 0.75 | 0.09 | 0.97 | 1.07 (133) |

$^a$ The total band (tot) corresponds to the 0.3–10 keV energy band.
$^b$ HR is defined, as in Nazé & Motch (2018), as the ratio between the ISM-corrected fluxes in the hard (2.0–10.0 keV) and soft (0.2–5.0 keV) energy bands.
$^c$ This fit refers to ObsID 0840201501, the other exposure being too short for more than a simple detection.

Table 3. ROSAT observed count rates (Berghoefer et al. 1996) and expected values assuming the XMM fluxes or count rates (see text for details).

| Name   | Obs $(\text{ct s}^{-1})$ | Pred $(\text{ct s}^{-1})$ |
|--------|-----------------|-----------------|
| HD 18552 | 0.017±0.008 | 0.031 |
| q Ori  | 0.053±0.016 | 0.054 |
| II 847 | 0.090±0.006 | 0.092 |
| HD 43855 | 0.017±0.007 | 0.010 |
| HD 44588 | 0.030±0.009 | 0.052 |
| HD 45995 | 0.024±0.010 | 0.032 |
| II 848 | 0.035±0.011 | 0.043 |
| d Lup | 0.054±0.016 | 0.001 |
| V886 Oph | 0.020±0.010 | 0.016 |
| Shellak | 0.073±0.011 | 0.068 |
| V558 Lyr | 0.042±0.010 | 0.053 |
| Aqr $^e$ | 0.021±0.010 | 0.014 |

$^e$ The fit refers to ObsID 0840201501, the other exposure being too short for more than a simple detection.
usual for massive stars, we used absorbed optically thin thermal plasma models (i.e., \textit{tbabs} $\times$ \textit{phabs} $\times$ \textit{apec}) with solar abundances of Asplund et al. (2009). The first absorption component was fixed to the interstellar column, derived from the known color excess (Table 1) using the formula of Gudennavar et al. (2012), $N_{\text{H}} = 6.12 \times 10^{21} \times E(B-V) \text{cm}^{-2}$, whereas the second absorbing component accounts for possible local absorption and was allowed to vary. In one case, however, the additional absorption converged to $-0$ and yielded erratic results with unrealistic errors, hence we fixed it to zero. For the emission components, we used up to three temperatures, depending on the goodness of fit. Final fitting results are provided in Table 2. Errors correspond to 1σ uncertainties; whenever they were asymmetric, the largest value is reported in Table 2. For the X-ray luminosities (in total band 0.5–10 keV), errors combine the distance errors (see Table 1) with errors on X-ray fluxes (derived from the “flux err” command in Xspec), but do not integrate the impact of model choices; errors on $\log(L_X/L_{\text{bol}})$, however, do not depend on distance and reflect only X-ray flux uncertainties. Hardness ratios $HR$ were calculated as the ratios between the fluxes, corrected for interstellar absorption, in the hard (2.0–10.0 keV) and soft (0.5–2.0 keV) energy bands.

Figure 2 compares the X-ray luminosities, bolometric luminosities, and hardness of the X-ray emission of our 13 brightest targets to the sample of Nazé & Motch (2018). It is immediately obvious that the new X-ray sources lie amongst the previous sample of Be stars. To assess whether new γ Cas analogs are amongst them, we recall the criteria for such a classification: presence of the Kα fluorescence line from relatively low-ionization iron near the high-ionization iron lines at 6.7–7.0 keV (only visible in well exposed spectra), presence of variability (on short and/or long-term), large but not extreme X-ray brightness ($\log(L_X/\text{bol}) \sim 31.6–33.2$ or $\log(L_X/L_{\text{bol}})$ between $-6.2$ and $-4$), unusual hardness ($kT > 5$ keV, $HR > 1.6$, $L_X^{\text{SM cor}}(2. - 10$ keV) $> 10^{31}$ erg cm$^{-2}$ s$^{-1}$).

Amongst the 13 targets, four display an intense X-ray emission at high energies ($L_X^{\text{SM cor}}(2. - 10$ keV) $> 3 \times 10^{31}$ erg cm$^{-2}$ s$^{-1}$): HD 44458, HD 45995, V558 Lyr, and HD 120678. The first three stars also display large hardness ratios ($HR = 1.9 – 2.3$, $kT = 7 – 13$ keV) and rather intense overall X-ray emission ($L_X^{\text{SM cor}}(0.5 – 10$ keV) $= 6 – 9 \times 10^{31}$ erg cm$^{-2}$ s$^{-1}$, $\log(L_X/L_{\text{bol}})$ $= -6.0$ to $-5.4$). Those values are well beyond what could be expected from a PMS companion. Furthermore, HD 44458 and V558 Lyr were found to be significantly variable and the spectra of HD 44458 and HD 45995 clearly show the presence of the iron complex (Fig. 3). As a complement, the BeSS database was searched for optical spectra taken close to the XMM-Newton observation dates of those three stars. High-resolution TIGRE spectra of HD 44458 and HD 45995 were also taken in the framework of a stellar survey of B-stars to be observed with eROSITA (P. J. Robrade). While not strictly simultaneous, as they were obtained some months before or after the XMM-Newton observations, these spectra provide an idea of the disk emission strength, which is usually quite high in γ Cas stars. These spectra were corrected within IRAF from telluric absorptions using the template of Hinkle et al. (2000) and then normalized using low-order polynomials. The equivalent width (EW) of the Hα line was estimated from $-540$ km s$^{-1}$ to $+540$ km s$^{-1}$ and its values are reported in Table 4. In all three cases, a dense disk seems to be present. As a last information, we may add that the three stars display quite early spectral types, again a typical feature of γ Cas stars. Therefore, HD 44458, HD 45995, and V558 Lyr clearly display γ Cas characteristics and can be added to the list of such objects.

HD 120678, which had undergone a shell-event in mid-2008 (Gamen et al. 2012), appears slightly less bright (its $\log(L_X/L_{\text{bol}})$ only amounts to $-6.8$) and less hard considering its $HR$ of 1.3, though its spectrum still requires a $\sim 9$ keV component to be fitted and its hard X-ray emission is well above $10^{31}$ erg cm$^{-2}$ s$^{-1}$. However, its X-ray observation was strongly affected by straylight, even if that contamination remains minimal at the source position. An independent confirmation of its X-ray properties would thus be welcome and, until then, we will consider it as a γ Cas candidate.
Finally, Sheliak (β Lyr) does seem slightly hard ($HR = 0.25$) and quite bright compared to its bolometric luminosity ($\log(L_X/L_{BOL}) = -6.5$). Its high-energy tail requires three thermal components for achieving a good fit, and the third temperature is $kT ∼ 24$ keV. Those are very unusual features for a B7 star and their possible relationship with the companion’s presence remains to be explored, hence we consider it as an interesting target deserving further study. A few other stars appear to display a slightly hard spectrum, though not with the extreme characteristics of γ Cas stars: HD 18552 has $HR = 0.1$ and $\log(L_X/L_{BOL}) = -6.6$; I Hya is variable and has $HR = 0.75$ with $\log(L_X/L_{BOL}) = -6.3$. We however recall that HD 43285 and I Hya appeared somewhat distant from their XMM-Newton counterpart, casting some doubt on their association (see Section 2). Figure 3 compares the spectra of these sources to those of γ Cas and of a “normal” massive star: a hard tail, though steeper than for γ Cas stars, is clearly present. All other stars are much less bright, with $L_{X}^{\text{ISM cor}}(0.5–10\text{ keV}) < 4 \times 10^{31} \text{ erg cm}^{-2} \text{ s}^{-1}$, and less hard ($HR < 0.1$).

### 4 SUMMARY AND CONCLUSIONS

In this paper, we continue our search for γ Cas analogs thanks to a small dedicated X-ray survey. XMM-Newton was pointed at 18 Be stars with previous reports of X-ray detections (ROSAT, Exosat, XMM-slew survey) or which underwent a “shell” event as did the γ Cas star HD 45314. Two of these stars (µ Lup and κ Dra) remain undetected and three others (QY Car, d Lup, α Ara) display only a faint and soft X-ray emission leading to a simple detection. The remaining 13 targets could be studied spectroscopically. Amongst the detections, three X-ray sources appear at distances of 3–4″.

### Table 4. EW of the Hα line measured on optical spectra (see text for details). The labels “b, t” indicate the source of the data (BeSS or TIGRE, respectively).

| Name    | Date      | EW (Å) |
|---------|-----------|--------|
| HD 44458| 2017-10-18| –37.6  |
|         | 2018-11-25| –38.4  |
|         | 2018-12-11| –37.4  |
|         | 2019-02-05| –35.6  |
|         | 2019-02-09| –37.0  |
|         | 2019-02-15| –35.8  |
|         | 2019-03-05| –30.2  |
| HD 45995| 2018-03-22| –16.8  |
|         | 2018-11-24| –21.3  |
|         | 2018-12-10| –21.4  |
|         | 2019-01-19| –12.9  |
|         | 2019-02-05| –22.0  |
|         | 2019-03-03| –22.6  |
| V558 Lyr| 2019-08-01| –23.9  |

### Table 5. List of all γ Cas analogs known to date (Smith et al. 2016 and references therein, Nazé & Motch 2018, and this paper).

| γ Cas stars | γ Cas | TYC 3681-695-1 | V782 Cas |
|-------------|-------|----------------|---------|
| HD 44458    | HD    | HD 45314       | HD 45995|
| HD 90563    | HD    | HD 110452      | HD 119682|
| V767 Cen    | CQ Cir| HD 157832      |         |
| HD 161103   | V771 Sgr| HD 316568     |         |
| 2XMMJ 180816.6-191939 | GSC2 8300302371 | SS397     |
| CI* NGC 6649 WL 9 | 3XMMJ 190144.5+045914 | V558 Lyr |
| SAO 49725   | V2156 Cyg | π Aqr     |         |
| V810 Cas    |       |               |         |

| γ Cas candidates | HD 42054 | HD 120678 |
|------------------|-----------|-----------|

shows $HR = 0.1$ and $\log(L_X/L_{BOL}) = -6.6$; I Hya is variable and has $HR = 0.75$ with $\log(L_X/L_{BOL}) = -6.3$. We however recall that HD 43285 and I Hya appeared somewhat distant from their XMM-Newton counterpart, casting some doubt on their association (see Section 2). Figure 3 compares the spectra of these sources to those of γ Cas and of a “normal” massive star: a hard tail, though steeper than for γ Cas stars, is clearly present. All other stars are much less bright, with $L_{X}^{\text{ISM cor}}(0.5–10\text{ keV}) < 4 \times 10^{31} \text{ erg cm}^{-2} \text{ s}^{-1}$, and less hard ($HR < 0.1$).
from the locations of their Be counterparts (d Lup, I Hya, and HD 43285), hence their associations are only considered as tentative.

Both the short-term and long-term variability of the sources were examined. The EPIC light curves of the 13 X-ray brightest targets were extracted and tested against constancy using \(x^2\) tests: only HD 44458, I Hya, and V558 Lyr appear significantly variable over an exposure. Turning to the long-term behaviour, we find that the previous ROSAT detections and XMM-Newton observations generally agree well, except for a 2.4\(\sigma\) change in HD 44458 and a 3.3\(\sigma\) difference in d Lup. The analysis of pairs of XMM-Newton observations further indicates a significant (3\(\sigma\)) change on a five-months timescale in \(\alpha\) Ara. Finally, because the X-ray brightnesses found by XMM-Newton are very low, the previous Erossal detections of \(\alpha\) Dra and QY Car were probably due to UV contamination.

The X-ray properties of the 13 X-ray brightest targets appear in line with those found in a general survey of Be stars. With their hard and moderately bright X-ray emission, three stars clearly belong to the \(\gamma\) Cas category: HD 44458, HD 45995, and V558 Lyr. An additional one, HD 120678, can be considered as a \(\gamma\) Cas candidate as it is only slightly softer. It may be noted that the new detections occurred at the low-luminosity end amongst the \(\gamma\) Cas cases, while the hardness of their spectra clearly sets them apart from the typical massive stars. Furthermore, the studied Be stars seem to show a continuum of behaviours in luminosity/hardness plots, suggesting that, perhaps, low-level \(\gamma\) Cas activity is possible.

This study brings the total of known \(\gamma\) Cas objects to 25, with two \(\gamma\) Cas candidates (Table 5). In just two years, the number of such objects has doubled. This shows that the \(\gamma\) Cas phenomenon is not a rare peculiarity but that such stars constitute a true new class of astronomical objects, whose exact nature remains to be determined, however. Future surveys, such as that performed by e-ROSITA will certainly find additional cases and constrain their actual incidence rate in distance-limited samples.

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