Survey of nearby Be binary candidates.

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1. Description of the proposed programme

A) Scientific Rationale: Massive stars have winds that are radiatively driven and susceptible to instabilities and shocks that can heat plasma to temperatures of few hundreds of eV, enough to produce soft X-rays. The winds become slower and less energetic for cooler (dimmer) stars, hence the X-ray emission, if associated with the wind itself, is expected to become weaker from O to B and A for main sequence stars. Therefore, ordinary solitary B stars, with luminosity classes IV-V, are expected to be very weak sources of X-ray emission. However, there have been a number of cases when observations of such stars revealed a significantly enhanced and relatively hard X-ray emission. Possible explanations of these X-ray excesses include:

- presence of a companion star which can be (1) a pre-main sequence star (PMS) producing X-rays due to strong chromospheric activity and flares, (2) a neutron star (NS) which can be accreting from the massive star wind (X-ray pulsar) or can have its own (pulsar) wind which collides with the massive star wind driving an intra-binary shock, (3) another massive star with strong wind (colliding wind binary), and (4) a accreting black hole (BH);
- presence of the strong large-scale (dipolar) magnetic field (anchored in the B star) which can channel the wind to generate additional heating of the wind's plasma;
- more exotic processes, e.g., accretion onto a NS in the "propeller" regime (where the inflowing matter is stopped at magnetospheric radius and propelled away by the centrifugal force; Illarionov & Sunyaev 1975) or magnetic reconnection activity associated with the decretion disc of Be star (see below);

Of the above-mentioned phenomena the relatively well studied one is the wind-fed accreting X-ray pulsars (~ 100 are known in our Galaxy; Walter et al. 2015; Liu et al. 2006) which are bright X-ray sources even in quiescence (blue circles in Fig. 1, left). Others are less understood due to the small population statistics and because the corresponding objects are not expected to be as bright as accreting X-ray pulsars.

Long considered as the oddity among B stars, the γCas (B0.5e IV) binary ($P = 203.5$ days), now serves as the prototype of a class of X-ray bright B stars that are not accreting X-ray pulsars or systems with colliding winds (e.g., pulsar-Be or two massive stars). γCas and its analogs are Be stars (i.e. B stars with circum-stellar decretion disk seen via strong emission lines in the optical spectrum; Porter & Rivinius 2003) with hard X-ray spectra described by optically thin, hot ($kT \approx 5 - 15$ keV), multi-temperature thermal plasma components or, possibly, by a mixture of thermal and nonthermal components (Smith et al. 2016). γCas is a factor of $10 - 100$ brighter than a typical B star but still significantly fainter than most accreting X-ray pulsars in a low state (Fig. 1, left).

Be stars are rapidly rotating, at a speed close to break-up. The spin-up can be explained by a mass-transfer from a more rapidly evolving (more massive) companion star. The very fast rotation causes Be stars to eject matter via transient (or variable) decretion disc wind in addition to the radiatively driven isotropic wind. If a NS (or BH) forms in a supernova explosion of a more evolved star, it can accrete from the wind of the Be star (accretion rate would strongly correlate the state of decretion disk and the NS orbit[1]) and appear as a luminous (at least during part of the orbit) X-ray source. These X-ray binaries (XRBs) consist of at least two distinct populations: accreting X-ray pulsars (HMXBs) and systems where the young pulsar wind collides with Be star wind (γ-ray binaries or HMGBs; Dubus et al. 2017). Only one BH-Be binary is known (MWC 656; $L_X \approx 3 \times 10^{30}$ erg s^{-1}; Ribó et al. 2017).

γCas analogs, however, are not considered to belong to either of the above BeXRBs because the existence of a compact object has not been proven in these systems and their X-ray spectra are different from those of HMXBs/HMGBs. One possible explanation of the γCas phenomenon could be the accretion onto a NS (or WD, or even BH in some cases) *in the propeller regime* but other options (an interaction with a WD or a "naked core" companion, or reconnection in the decretion disk) are possible (Rauw et al. 2018 and references therein). Despite recent findings of a few more γCas analogs (Nazé et al. 2020; Nazé & Motch 2018), the total number of γCas stars identified in X-rays is small (~ 20), and understanding their nature requires a substantially larger sample. The recently released Gaia DR2 survey offers an opportunity to find more

[1]NS receives a kick during the SN explosion which strongly perturbs the original orbit

massive Be binaries via astrometric excess noise (Lindegren et al. 2012), ϵ, caused by the binary motion (Belokurov et al. 2020) which correlates with X-ray detectability for Gaia DR2 stars (Gandhi et al. 2020).

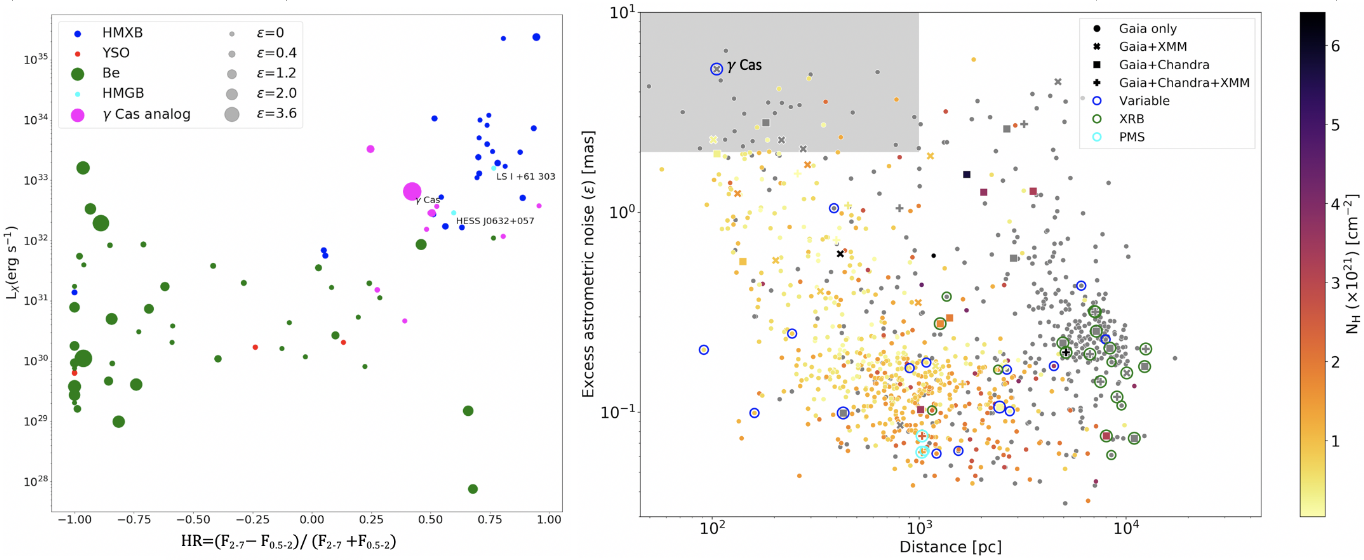

Figure 1: *Left panel*: Properties (1-10 keV luminosity vs. hardness ratio) of X-ray counterparts of BeSS catalog stars found in 4XMM-DR9 and CSCv.2 catalogs. *Right panel*: Astrometric noise excess, ϵ, and distances for BeSS stars. The proposed sample is shown by shaded area. Color shows $N_{\rm H}$ column estimated from A_G for those stars where it is available in Gaia DR2.

B) Immediate Objective:

We will investigate the dependence of X-ray properties of nearby Be stars on Gaia's astrometric noise excess, which, if high enough ($\epsilon > 2$ mas), can be a good signature of binarity (proxy for astrometric wobble) and is found to correlate with X-ray detectability for Gaia DR2 stars (Gandhi et al. 2020). We expect to find X-ray excesses in selected Be stars that can be attributed to the γCas phenomenon, HMGBs, unusual decretion disk activity, etc. We may also uncover Be-BH systems, which are expected to be relatively faint due to the low radiative efficiency of BH accreting from wind but have distinct variability and orbital parameters. We will study X-ray spectra and variability together with the optical/NIR properties to understand the fractions different types of sources in our sample and reliability of using ϵ as a proxy for binarity and X-ray flux prediction. We will also study overall X-ray luminosity function of Be stars and their stacked spectra. We will supplement our program with radial velocity measurements and *TESS*/ZTF data analysis for those stars from our sample that exhibit interesting X-ray properties and propose them for longer X-ray observations. This program will be a pathfinder for future studies of Be stars in the *eROSITA* all-sky survey.

References: • Walter, R., et al. 2015, A&ARv, 23, 2 • Liu, Q., et al. 2006A&A, 455, 1165L • Porter, J. M. & Rivinius, T. 2003, PASP, 115, 1153 • Dubus, G., et al., 2017, A&A, 608, 59 • Ribó, M. et al. 2017, ApJ, 835, 33 • Illarionov, A. & Sunyaev, R. 1975, A&A, 39, 185 • Smith, M., et al. 2016, AdSR, 58, 782 • Rauw, G., et al. 2018, A&A, 615, 44 • Nazé, Y., et al. 2020, MNRAS, 493, 2511 • Nazé, Y., & Motch, C. 2018, A&A, 619, 148 • Belokurov, V., ett al. 2020, MNRAS, 496, 1922B • Gandh, P., et al. 2020, arXiv:2009.07277

2. Justification of requested observing time, feasibility and visibility

Our targets come from BeSS catalog of spectroscopically confirmed Be stars (http://basebe.obspm.fr). We require $d < 1$ kpc, $\epsilon > 2$, and absence of X-ray observations with *XMM-Newton*, *CXO* or *Swift* for > 100s (shaded area in Fig.1, right). For all targets the significance of excess astrometric noise is very high (GaiaDR2's `sepsi`> 1000; Lindegren et al. 2012). All targets are expected to have $N_{\rm H} \lesssim 4 \times 10^{21}$ cm^{-2}.

Since some fraction of proposed sources are expected to be of γCas type we take their $L_X = 10^{32} - 10^{33}$ erg s^{-1} (Rauw et al. 2018) as a benchmark. HMGBs have similar luminosities (Dubus 2017). For ϵ, d and $N_{\rm H}$ within the shaded area in Fig. 1 (right) the absorbed fluxes can be as low as few $\times 10^{-13}$ cgs in 0.5-10 keV. Therefore, many targets are too faint even for low-resolution spectroscopy with *Swift* XRT while a 8-ks exposures with EPIC will provide ~ 800 photons (in pn+2MOS) for the faintest γCas/HMGB analogues in our sample. We will even be able to detect X-rays from solitary B stars with $L_X \approx 10^{30}$ erg s^{-1} up to 1 kpc.

3. Report on the last use of XMM-Newton data: ID: 080303 (15×10 ks); PI: Kargaltsev – Snap-shot survey of INTEGRAL sources in the Galactic plane (last data obtained in 2018, paper submitted).