Draft version August 30, 2022
Typeset using LaTeX **RNAAS** style in AASTeX631

Catalog of X-ray Detected Be Stars (XDBS)

Caden Gobat [1,2] Hui Yang [1] Oleg Kargaltsev [1] Jeremy Hare [3,4] and Igor Volkov [1]

[1] *Department of Physics, The George Washington University, 725 21st St NW, Washington, DC 20052*
[2] *Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302*
[3] *NASA Goddard Space Flight Center, Greenbelt, MD, 20771*
[4] *NASA Postdoctoral Program Fellow*

(Received August 2, 2022; Revised August 4, 2022; Accepted August 12, 2022)

Submitted to RNAAS

ABSTRACT

We present a catalog of X-ray Detected Be Stars (XDBS) with 161 Be stars from the Be Star Spectra (BeSS) database having X-ray counterparts in the *Chandra* Source Catalog v2.0, *XMM-Newton* 4XMM-DR11 Catalog, or *Swift* 2SXPS Catalog. The multi-wavelength catalog includes accurate optical positions, X-ray properties (fluxes, photon indices and hardness ratios), optical, near-infrared and infrared photometry, source classifications (when available), and other properties including proper motions, effective temperatures, X-ray to optical flux ratios as well. We also provide a convenient graphical user interface which allows for easy visualization of the catalog content.

Keywords: Catalogs (205) – Be stars (142) – X-ray stars (1823) – X-ray binary stars (1811)

INTRODUCTION

Be stars are hot, luminous B-type stars whose spectra show one or more emission lines. They have high rotational velocities (several hundreds of km s^{-1}, nearing the breakup limit) and possess equatorial decretion disks. Ultraviolet emission from the hot star ionizes the disk, which re-emits photons at longer wavelengths. Be stars are also interesting because they are often found in high-mass X-ray binaries (HMXBs; Walter et al. 2015) and γ-ray binaries (Chernyakova & Malyshev 2020). The end products of Be star (and Be binary) evolution are not fully understood (van den Heuvel 2019) and may include exotic compact objects (e.g., magnetars).

While Be stars have been studied extensively in the optical band, studies of their X-ray properties have been more limited. We present the first catalog of X-ray Detected Be Stars (XDBS), available on GitHub at https://github.com/huiyang-astro/XDBS/blob/main/master.csv. An online interactive plotting tool (described in Yang et al. 2021) has also been built to visualize the multi-wavelength properties of the catalog, and can be accessed at https://home.gwu.edu/~kargaltsev/XDBS/.

CATALOG DESCRIPTION

The catalog compiles multi-wavelength properties of 161 Be stars detected in X-rays as well as source classifications (e.g., HMXBs, γ Cas analogs), when available. Sample of the catalog is shown in Table 1, as well as via GitHub. Below we describe the important details of the catalog construction.

Crossmatches

We crossmatched the Be Star Spectra catalog[1] (BeSS; Neiner et al. 2011) to *Gaia* DR3 (Gaia Collaboration 2022) and *Gaia* eDR3 distance catalogs (Bailer-Jones et al. 2021) using a radius of $2''$ to obtain accurate coordinates to be used in the subsequent crossmatching. If the same BeSS star is matched to multiple *Gaia* sources, only the closest

[1] There were 2264 entries in BeSS when we constructed this catalog. More Be stars are regularly added since BeSS is a living catalog.

match is kept. For BeSS sources that do not have *Gaia* counterparts, the original BeSS coordinates are used for subsequent cross-matching.

We then performed a cross-match with X-ray catalogs using the updated coordinates and error circles of $2''$, $5''$, and $9''$ for the *Chandra* Source Catalog v2 (CSCv2; Evans et al. 2010), the *XMM-Newton* 4XMM-DR11 Catalog (Webb et al. 2020), and the *Swift*-XRT 2SXPS Catalog (Evans et al. 2020), respectively. The error circles correspond to the typical positional uncertainties of the respective X-ray catalogs. If multiple X-ray sources are found near the same BeSS star, only the nearest X-ray counterpart is kept. Eight sources were removed because they had either entirely missing/null flux values or only upper limit detections across all X-ray catalogs in which they were present. We also removed 15 2SXPS detected sources with *Gaia* Gmag<9 due to the large optical loading. We found 161 Be stars that are matched to at least one of the three X-ray catalogs with 74, 124, and 72 sources in CSCv2, 4XMM-DR11, and 2SXPS, respectively. We also applied a backward-matching of X-ray sources to *Gaia* counterparts after we obtained the X-ray counterparts to verify the cross-matching. We also manually investigated all 161 matches and found that some BeSS optical coordinates needed to be updated so that the accurate *Gaia* counterparts can be matched. We set a flag (`match_flag`=1) to mark 20 questionable matches, which include the cases where the initial *Gaia* counterparts of the Be stars do not match the *Gaia* sources that the X-ray sources are backward-matched to, and/or those where we could not independently verify the BeSS coordinates. There are two X-ray sources that do not have *Gaia* counterparts which we flag with `match_flag`=2.

Finally, to obtain near-infrared and infrared properties, we cross-matched our best-determined optical coordinates to the 2MASS (Cutri et al. 2003), AllWISE (Cutri et al. 2021), CatWISE2020 (Marocco et al. 2021), and unWISE (Schlafly et al. 2019) using a $1''$ search radius.

X-ray Fluxes

In order to systematically compare the X-ray fluxes and hardness ratios and to compensate for the differing energy band definitions of CSCv2, 4XMM-DR11, and 2SXPS, we converted them to common energy bands, using the CSCv2 definitions of soft (0.5–1.2 keV), medium (1.2–2 keV), and hard (2–7 keV) bands as a standard. The 4XMM-DR11 and 2SXPS fluxes are converted using scaling factors calculated by assuming a power-law spectrum with photon index Γ. We used the best-fitted values of Γ from CSCv2 or 2SXPS where available (without including their uncertainties for the X-ray flux conversion), and otherwise took $\Gamma = 1.7$ (the assumption of the XMM catalog; Watson et al. 2009).

We accounted for asymmetric uncertainties in our determinations of converted fluxes using a custom Python package (`asymmetric_uncertainty`[2]). We also replaced X-ray fluxes with values of zero in a given band with a very small value ($10^{-20}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$) to circumvent divide-by-zero errors during the X-ray flux conversion calculation.

Source Classifications

The known classifications of the X-ray sources in the XDBS catalog include HMXBs based on Liu et al. (2006); Doroshenko et al. (2021); Fortin et al. (2022) and SIMBAD (Wenger et al. 2000), γ Cas analogs (Smith et al. 2016; Nazé & Motch 2018; Nazé et al. 2020), and young stellar objects (YSOs) classified from SIMBAD if `main_type` is `YSO`, `Orion_V*`, or `Ae*`. All other sources are labeled as stars by default, but their true class could still be one of the above. The breakdown of 161 X-ray sources are: 48 HMXBs[3], 19 γ Cas analogs, 12 YSOs and 82 stars.

POTENTIAL APPLICATIONS

The XDBS catalog is a useful tool for many potential applications, which include (but are not limited to) population studies of various types of X-ray sources, classifying unknown X-ray sources and building training datasets for machine-learning classification (e.g., Yang et al. 2022), and searching for rare type X-ray sources (e.g., γ-ray binaries).

ACKNOWLEDGEMENT

This research is partly supported by Chandra X-ray Observatory award AR9-20005A and NASA ADAP award 80NSSC19K0576. This work has made use of the BeSS database (http://basebe.obspm.fr), and the VizieR catalogue access tool (Ochsenbein et al. 2000).

[2] https://github.com/cgobat/asymmetric_uncertainty

[3] These include 3 high-mass γ-ray binaries.

Table 1. A subset of XDBS catalog.

Be_star	Type	RA	DEC	Xcat	Xidentifier	Gamma	Fb	Fs	Fm	Fh	HRms	HRhm
		deg	deg				(10^{-15} erg s^{-1} cm^{-2})					
GSC 02342–00359	B5e	52.29341706	31.36639996	CXO	J032910.3+312159	3.2 ± 0.1	284 ± 11	13 ± 1	77 ± 3	194 ± 10	0.72 ± 0.05	0.43 ± 0.04
BQ Cam	Be	53.74962972	53.17313998	CXO	J033459.9+531023	···	23 ± 7	1 ± 1	10 ± 3	12 ± 7	0.8 ± 0.4	0.1 ± 0.3
MEROPE	B6IVe	56.58167145	23.94814381	CXO	J034619.6+235653	$8.7^{+0.9}_{-0.8}$	202^{+11}_{-10}	180^{+9}_{-10}	22 ± 3	$0.00001^{+4.36435}_{-0.00001}$	-0.78 ± 0.06	-1.0 ± 0.3
Menkhib	O7.5IIIe	59.74126439	35.79104207	XMM	J035857.8+354728	···	2494 ± 5	2053 ± 5	394 ± 2	47 ± 1	-0.678 ± 0.002	-0.786 ± 0.006
lam Eri	B2IVne	77.28660799	-8.75409389	XMM	J050908.8–084514	···	78 ± 6	56 ± 4	15 ± 2	7 ± 4	-0.58 ± 0.07	-0.4 ± 0.2

DR3Name	Plx	RPlx	PM	epsi	sepsi	RUWE	G	BP	RP	Teff	Gflux	dist
	mas		mas yr^{-1}	mas			mag	mag	mag	K	(10^{-12} erg s^{-1} cm^{-2})	kpc
Gaia DR3 121406360248113920	3.3957	6.21	20.1 ± 0.5	2.901	1861.0	2.889	14.608 ± 0.004	15.45 ± 0.01	12.491 ± 0.008	···	14.53 ± 0.05	$0.31^{+0.06}_{-0.04}$
Gaia DR3 444752973131169664	0.1343	6.67	0.52 ± 0.02	0.0	0.0	1.07	14.2 ± 0.003	15.475 ± 0.005	13.087 ± 0.006	···	21.17 ± 0.07	$5.6^{+0.7}_{-0.5}$
Gaia DR3 65205373152172032	7.067	24.69	50.1 ± 0.2	1.505	3081.0	2.33	4.173 ± 0.004	4.148 ± 0.003	4.159 ± 0.005	···	217078 ± 730	$0.143^{+0.006}_{-0.005}$
Gaia DR3 219375904303684224	2.4457	9.35	2.7 ± 0.2	1.328	3186.0	2.236	3.975 ± 0.003	3.97 ± 0.003	3.889 ± 0.004	21760	260471 ± 810	$0.42^{+0.06}_{-0.04}$
Gaia DR3 3182891931108590336	3.6256	15.63	2.9 ± 0.2	1.547	4507.0	2.283	4.243 ± 0.003	4.117 ± 0.003	4.386 ± 0.005	···	203391 ± 639	0.27 ± 0.02

J	H	K	W1	W2	W3	W4	Vsini	Vtran	LX	fX2O	match_flag	Class	ref
mag	mag	mag	mag	mag	mag	mag	km s^{-1}	km s^{-1}	(10^{31} erg s^{-1})	(10^{-5})			
9.37 ± 0.03	7.99 ± 0.03	7.17 ± 0.02	6.37 ± 0.01	5.761 ± 0.008	···	···	···	30^{+6}_{-4}	$0.33^{+0.13}_{-0.08}$	1955^{+73}_{-77}	1	YSO	1
11.82 ± 0.02	11.21 ± 0.03	10.74 ± 0.03	9.97 ± 0.02	9.71 ± 0.02	9.08 ± 0.03	8.5 ± 0.3	···	14^{+2}_{-1}	9^{+4}_{-3}	108 ± 35	0	HMXB	3
4.2 ± 0.2	4.3 ± 0.2	4.22 ± 0.02	4.3 ± 0.2	4.0 ± 0.1	4.16 ± 0.01	2.99 ± 0.04	240	34 ± 1	0.049 ± 0.005	0.093 ± 0.005	0	star	···
4.0 ± 0.3	4.1 ± 0.2	3.95 ± 0.04	4.0 ± 0.3	3.7 ± 0.2	3.95 ± 0.01	3.76 ± 0.03	213	$5.4^{+0.9}_{-0.7}$	$5.2^{+1.4}_{-1.0}$	0.957 ± 0.004	0	star	···
4.9 ± 0.2	4.83 ± 0.08	4.71 ± 0.02	4.7 ± 0.2	4.3 ± 0.1	4.07 ± 0.01	3.65 ± 0.02	318	$3.7^{+0.4}_{-0.3}$	$0.071^{+0.012}_{-0.01}$	0.038 ± 0.003	0	star	···

Note—See the entire table electronically. Column descriptions are provided at https://github.com/huiyang-astro/XDBS/blob/main/XDBS_column_descriptions.pdf.

REFERENCES

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., et al. 2021, AJ, 161, 147.

Chernyakova, M. & Malyshev, D. 2020, Multifrequency Behaviour of High Energy Cosmic Sources - XIII. 3–8 June 2019. Palermo, 45

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, II/246

Cutri, R. M., Wright, E. L., Conrow, T., et al. 2021, VizieR Online Data Catalog, II/328

Doroshenko, V., Santangelo, A., Tsygankov, S. S., et al. 2021, A&A, 647, A165.

Evans, I. N., Primini, F. A., Glotfelty, K. J., et al. 2010, ApJS, 189, 37.

Evans, P. A., Page, K. L., Osborne, J. P., et al. 2020, ApJS, 247, 54.

Fortin, F., Garcia, F., & Chaty, S. 2022, arXiv:2207.02114

Gaia Collaboration 2022, VizieR Online Data Catalog, I/355

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2006, A&A, 455, 1165.

Marocco, F., Eisenhardt, P. R. M., Fowler, J. W., et al. 2021, ApJS, 253, 8.

Nazé, Y. & Motch, C. 2018, A&A, 619, A148.

Nazé, Y., Rauw, G., & Pigulski, A. 2020, MNRAS, 498, 3171.

Neiner, C., de Batz, B., Cochard, F., et al. 2011, AJ, 142, 149.

Ochsenbein, F., Bauer, P., & Marcout, J. 2000, A&AS, 143, 23.

Schlafly, E. F., Meisner, A. M., & Green, G. M. 2019, ApJS, 240, 30.

Smith, M. A., Lopes de Oliveira, R., & Motch, C. 2016, Advances in Space Research, 58, 782.

van den Heuvel, E. P. J. 2019, IAU Symposium, 346, 1.

Walter, R., Lutovinov, A. A., Bozzo, E., et al. 2015, A&A Rv, 23, 2.

Watson, M. G., Schröder, A. C., Fyfe, D., et al. 2009, A&A, 493, 339.

Webb, N. A., Coriat, M., Traulsen, I., et al. 2020, A&A, 641, A136.

Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, A&AS, 143, 9.

Yang, H., Hare, J., Kargaltsev, O., et al. 2022, arXiv:2206.13656

Yang, H., Hare, J., Volkov, I., et al. 2021, RNAAS, 5, 102.