Catalog of X-ray Detected Be Stars (XDBS)

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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 catalog1 (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 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

1 There were 2264 entries in BeSS when we constructed this catalog. More Be stars are regularly added since BeSS is a living 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 $\Gamma$. We used the best-fitted values of $\Gamma$ 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\_uncertainty²). We also replaced X-ray fluxes with values of zero in a given band with a very small value ($10^{-20}$ 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), $\gamma$ 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 $\gamma$ 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., $\gamma$-ray binaries).

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² https://github.com/cgobat/asymmetric\_uncertainty

³ These include 3 high-mass $\gamma$-ray binaries.
### Table 1. A subset of XDBS catalog.

| Be star     | Type | RA     | DEC    | Xcat  | Xidentifier | Gamma | Fb   | Fs   | Fm   | Fh   | HRms  | HRhm  |
|-------------|------|--------|--------|-------|-------------|-------|------|------|------|------|-------|-------|
| GSC 02342-00359 | B5e  | 52.29341706 | 31.36369996 | 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 | 180±10 | 22±3 | 0.0001±0.0001 | −0.78 ± 0.06 | −1.0 ± 0.3 |
| Menkhib     | O7.5IIe| 59.74126439 | 35.79104207 | XMM   | J035857.8+354728 | ··· | 249 ± 5 | 2053 ± 5 | 394 ± 2 | 47 ± 1 | −0.678 ± 0.002 | −0.786 ± 0.006 |
| lam Eri     | B2IVne| 77.28666799 | −8.75409389 | XMM   | J050908.8−084514 | ··· | 78 ± 6 | 56 ± 4 | 15 ± 2 | 7 ± 4 | −0.58 ± 0.07 | −0.4 ± 0.2 |

### Additional Table

| DR3Name    | Plx  | RPix | PM  | epsi | sepsi | RUWE | G    | BP   | RP   | Teff | Gflux | dist |
|------------|------|------|-----|------|-------|------|------|------|------|------|-------|------|
| 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 ± 0.04 |
| 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 | 5.4 ± 0.7 |
| 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 | 4.150 ± 0.005 | ··· | 217078 ± 730 | 0.145 ± 0.006 |
| Gaia DR3   | 219375904306384224 | 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 ± 0.04 |
| Gaia DR3   | 318289193110859336 | 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 |

### Additional Table

| J   | H   | K   | W1  | W2  | W3  | W4  | Vsini | Vtrans | LX  | fX2O | matchflag | Class | ref |
|-----|-----|-----|-----|-----|-----|-----|-------|--------|-----|-----|------------|-------|-----|
| 9.37 ± 0.03 | 7.99 ± 0.03 | 7.17 ± 0.02 | 6.37 ± 0.01 | 6.371 ± 0.008 | ··· | ··· | ··· | 30 ± 4 | 0.33 ± 0.08 | 1955 ± 77 | I | 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 | 9 ± 4 | 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 | 0.939 ± 0.005 | 0 | star | ··· |
| 4.0 ± 0.2 | 4.3 ± 0.2 | 4.35 ± 0.04 | 4.0 ± 0.3 | 3.7 ± 0.2 | 3.95 ± 0.01 | 3.76 ± 0.03 | 213 | 5.4 ± 0.7 | 5.2 ± 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 | 3.8 ± 0.4 | 0.073 ± 0.012 | 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.
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