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
















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The *Swift* Deep Galactic Plane Survey (DGPS) Phase-I Catalog

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ABSTRACT

The *Swift* Deep Galactic Plane Survey is a *Swift* Key Project consisting of 380 tiled pointings covering 40 deg² of the Galactic Plane between longitude $10 < |l| < 30$ deg and latitude $|b| < 0.5$ deg. Each pointing has a 5 ks exposure, yielding a total of 1.9 Ms spread across the entire survey footprint. Phase-I observations were carried out between March 2017 and May 2021. The Survey is complete to depth $L_X > 10^{34}$ erg s^{−1} to the edge of the Galaxy. The main Survey goal is to produce a rich sample of new X-ray sources and transients, while also covering a broad discovery space. Here, we

introduce the Survey strategy and present a catalog of sources detected during Phase-I observations. In total, we identify 928 X-ray sources, of which 348 are unique to our X-ray catalog. We report on the characteristics of sources in our catalog and highlight sources newly classified and published by the DGPS team.

Keywords: X-ray astronomy (1810) — Surveys (1671) — Catalogs (205) — X-ray binary stars (1811)

1. INTRODUCTION

Since the inception and discovery of X-ray astronomy, from the detection of Sco X-1 and the launch of the first X-ray satellite in 1970 (*Uhuru*; [Giacconi et al. 1971](#)), a diverse assortment of X-ray emitting sources have been discovered and sorted into numerous distinct classes. These classes include chromospheric activity from young stars, cataclysmic variables (CVs), symbiotic binaries, young stellar objects (YSOs), magnetars, and X-ray binaries comprising a compact object, either a neutron star (NS) or black hole (BH), and a low-mass (LMXBs) or high-mass (HMXBs) star.

Within our Galaxy, the brightest X-ray sources are known to be X-ray binaries with peak X-ray luminosities in excess of $L_X > 10^{36-39}$ erg s⁻¹. However, our Milky Way (MW) also hosts a significant population of faint X-ray sources ($L_X < 10^{33-35}$ erg s⁻¹) ([Muno et al. 2005a,b](#); [Degenaar & Wijnands 2009, 2010](#)). These sources are likely dominated by magnetic CVs ([Barrett et al. 1999](#); [Wang et al. 2002](#); [Revnivtsev et al. 2009](#); [Pretorius et al. 2013](#)), quiescent LMXBs ([Muno et al. 2005a,b](#)), and quiescent magnetars ([Coti Zelati et al. 2018](#)), among others. Their discovery is crucial to expand our understanding of their source populations and their formation pathways within our Galaxy.

X-ray surveys of the Galactic Plane (GP) present a prime opportunity for discovery of these faint sources. Thus far, sensitive and high-resolution X-ray satellites, such as *XMM-Newton* or *Chandra* ([Wijnands et al. 2006](#); [Jonker et al. 2011](#); [Nebot Gómez-Morán et al. 2013](#)), have been used to search for serendipitous faint X-ray sources within the true target’s field of view. Such procedures, however, are not uniform in depth nor do they cover the full extent of the GP, relying instead on pointings directed at known bright sources. Therefore, dedicated, homogeneous X-ray surveys are required to identify the population and number of faint X-ray sources within the Galaxy.

The *Neil Gehrels Swift Observatory* ([Gehrels et al. 2004](#)) X-ray Telescope (XRT; [Burrows et al. 2005](#)) utilizes a CCD detector with sensitivity to X-ray photons over the range 0.3 – 10 keV. The instrument field of view (FOV) is $23.6' \times 23.6'$ with an effective area of 110 cm² at 1.5 keV and an angular resolution of 18". The low background (10^{-6} cts s⁻¹ pix⁻¹; [Evans et al. 2014](#)),

arcsecond source localization, and fast slew rate, make the *Swift*/XRT optimal for surveys of crowded environments, such as the GP ([Reynolds et al. 2013](#)), Small Magellanic Cloud ([Kennea et al. 2018](#)), and the Galactic Bulge ([Shaw et al. 2020](#); [Bahramian et al. 2021](#)).

Here, we outline our *Swift* Deep Galactic Plane Survey (DGPS) strategy and present the catalog of sources detected in Phase-I observations across the 40 deg² portion of the Plane covered by the DGPS. We present the survey design and strategy in §2. In §3 we discuss our source detection procedures and the process for creating a unique source catalog. The catalog results, discussion of implications, and overall conclusions are presented in §4, §5, and §6, respectively.

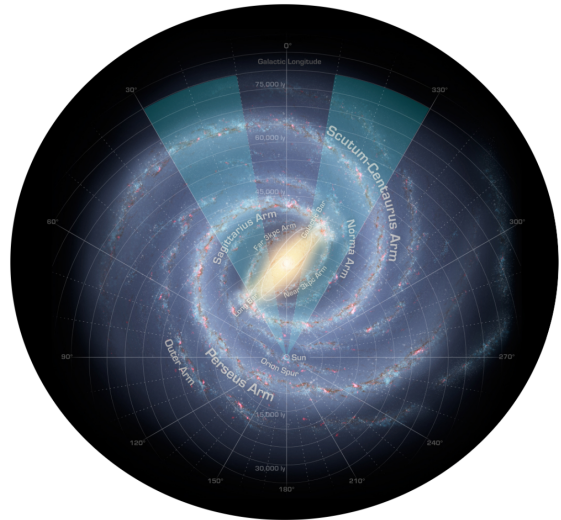


Figure 1. The shaded blue regions show the line of sight of the DGPS survey footprint through the Milky Way’s disk. The background image is an illustration of the Milky Way with credit to NASA/JPLCaltech/ESO/R. Hurt.

2. SURVEY FOOTPRINT AND OBSERVING STRATEGY

The *Swift* Deep Galactic Plane Survey (PI: C. Kouveliotou) is a *Swift* Key Project and *NuSTAR* Legacy Pro-

gram¹ covering 40 deg² of the GP (Figure 1) between Galactic longitude $10 < |l| < 30$ deg and latitude $|b| < 0.5$ deg. The Survey encompasses 380 unique XRT pointings (see Figures 2 and 3), each observed for ~ 5 ks for a total of ~ 1.93 Ms exposure carried out between March 2017 to May 2021. Approximately half of these observations were performed between 2017 and 2019, and the second half between 2020 and 2021. All observations were performed with the *Swift* X-ray Telescope (XRT; Burrows et al. 2005) in Photon Counting (PC) mode.

The design of our survey (latitude and longitude range; Figures 2 and 3) was driven by our primary science goal of thoroughly characterizing the magnetar and HMXB populations in the MW by their persistent emission, while avoiding the crowded Galactic center (Figure 1). We have additionally selected the Survey footprint such that each tile has a 4' overlap with its neighbor, taking into account the 23.6' XRT FOV.

In total, the Survey comprises 769 observations² with *Swift* covering the 380 pointings (Figure 2), including those observed during the DGPS Pilot Survey. This is due to the fact that in most cases ($\sim 70\%$) multiple observations of the same field were required to yield a total of 5 ks exposure. In Figure 4, we display a histogram of exposure times for these 769 single-epoch observations. We note that although a significant fraction (47%) of single-epoch observations consisted of less than 2 ks of exposure, the median cumulative exposure across the Survey footprint is 4.6 ks (Figures 2 and 4). The fact that many tiles were observed multiple times was extremely useful for the identification of variable X-ray sources (see §4.2 and §5.4).

On average, the survey is complete (§5.1) to a depth of $L_X > 1.0 \times 10^{34}$ erg s⁻¹, to the edge of the Galaxy. However, it affords source detection to limits of $L_X \sim 1.0 \times 10^{33}$ erg s⁻¹ out to $\sim 3 - 6$ kpc.

3. SWIFT/XRT DATA ANALYSIS

3.1. Quick-look Analysis

The identification and prompt follow-up of variable or transient sources detected as part of the Survey required a rapid analysis of quick-look data³ as these became available $\sim 2 - 6$ hours after the observations. Quick-look data are not the final fully processed data, and are instead treated as a preliminary first look in order to identify sources displaying variability on a shorter timescale than the fully processed data are available

($\sim 1 - 2$ weeks after the quick-look data⁴). The former data, however, allowed for rapid multi-wavelength follow-up observations.

The single-epoch quick-look data was initially processed within a day of each XRT observation. We note that multiple versions of HEASoft (including v6.20 and up) were utilized to process these quick-look data due to the length of the DGPS Phase-I (2017 to 2021) survey. However, there are only slight variations between these HEASoft versions, and we expect the effect on our analysis to be small. In any case, the fully calibrated data used to determine the final source catalog were reprocessed in a uniform manner using HEASoft v6.29 (see §3.2).

The quick-look pipeline began by retrieving the *Swift* XRT data products from the NASA High Energy Astrophysics Science Archive Research Center (HEASARC) server. We then used the `xselect` task within HEASoft in order to filter the data products to three energy bands: a soft band (0.3 – 3 keV), a hard band (2 – 10 keV) and a full band (0.3 – 10 keV). The `detect` task within `ximage` was utilized to identify sources in these three bands. The `xrtcentroid` task was then used to determine the source position and the statistical error on the position. Source statistics (i.e., count rate and signal-to-noise) were computed using `sosta`. The source count rates were corrected for deadtime, vignetting, and PSF losses using the `xrtmkarf` task. In order to convert from a count rate to unabsorbed flux we computed an energy conversion factor (ECF) for each source using PIMMS⁵. We assumed that the X-ray spectrum of each source was well described by an absorbed power-law with photon index $\Gamma = 1.8$. The hydrogen column density N_H was fixed to the Galactic value in the direction of the source (HI4PI Collaboration et al. 2016), which was determined using the `nH FT00L` (Blackburn et al. 1999). We note that the majority of sources detected as part of the survey likely have smaller hydrogen column densities than this value, and, therefore, our fluxes should serve as upper bounds on the true values.

At this stage, we identified sources at $> 2\sigma$ significance in any band. All observations were subject to manual inspection. Any pointing which was identified to have stray light (Moretti et al. 2009), a very bright source leading to nearby spurious sources (see Table 5 of Evans et al. 2014), or a visibly extended source (e.g., supernova remnant) was checked carefully to exclude any spurious sources mistakenly identified by the automatic source

¹ <https://www.nustar.caltech.edu/page/59#g9>

² An observation is defined as all exposures covering a specific pointing obtained within a single UT day.

³ <https://www.swift.ac.uk/archive/ql.php>

⁴ https://swift.gsfc.nasa.gov/quick-look/swift_process_overview.html

⁵ <https://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html>

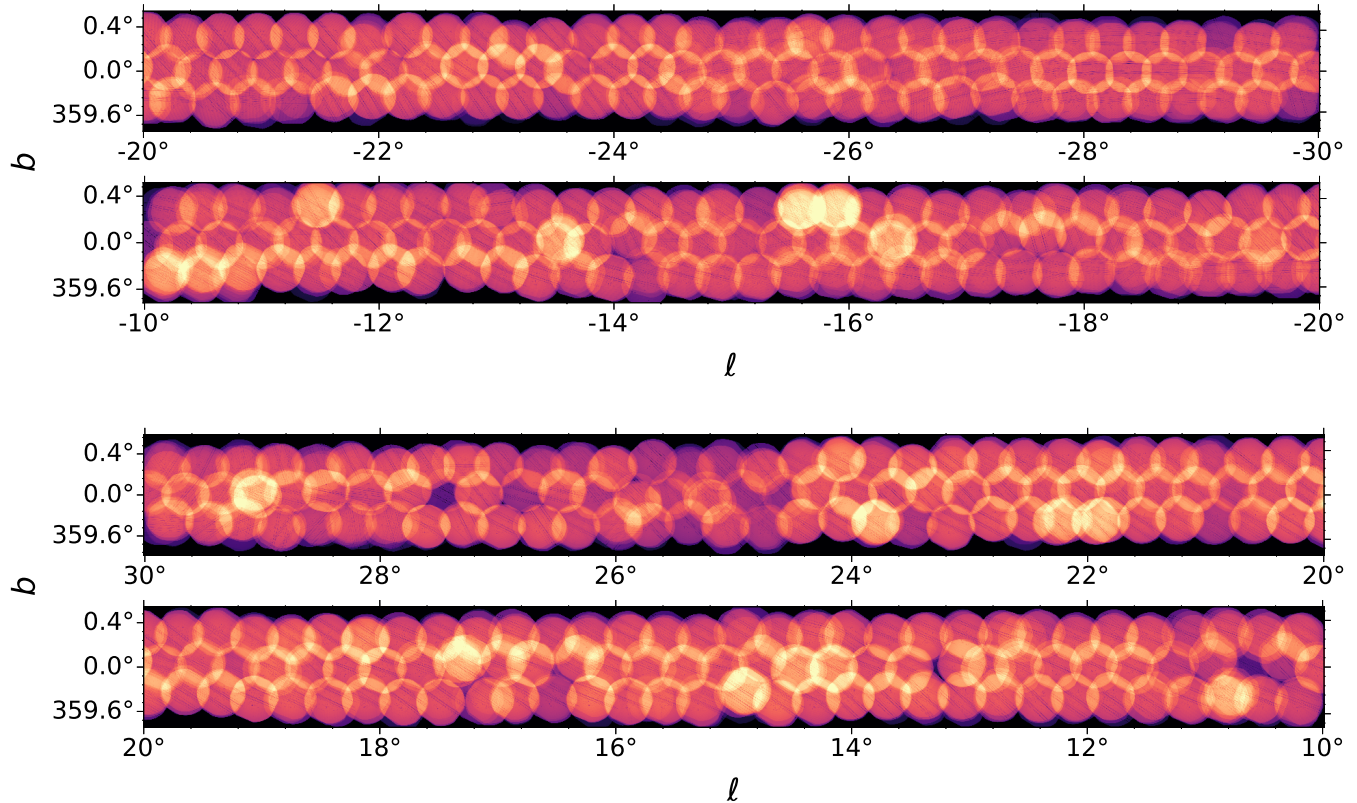


Figure 2. *Swift*/XRT exposure map of the DGPS footprint. The 4' overlap region between adjacent tiles is clearly demonstrated. A few tile positions were serendipitously observed twice, leading to a higher exposure (brighter regions). The median exposure across all pixels is 4.6 ks. The variation in exposure in the two observed regions of the GP is negligible.

finding algorithm. In total, we identified 25 tiles with extended sources, 34 with stray light contamination, and 6 with artificial sources identified in the point spread function (PSF) of a bright source.

After these quality checks, we automatically cross-matched these sources against other X-ray catalogs to determine whether each source is *i*) classified, *ii*) unclassified, and/or *iii*) previously unknown. These catalogs include the HEASARC Master XRAY catalog⁶, the *Chandra* Source Catalog (CSC; Evans et al. 2010) Release 2.0, the *XMM-Newton* Serendipitous Source Catalog (4XMM-DR9; Webb et al. 2020; Traulsen et al. 2020), 1SXPS (Evans et al. 2014), 2SXPS (Evans et al. 2020), 1SWXRT (D’Elia et al. 2013), the *INTEGRAL* 14-year Galactic hard X-ray survey (Krivonos et al. 2017), the ASCA Galactic Plane Survey (Sugizaki et al. 2001), and the Second ROSAT all-sky survey (2RXS) source catalogue (Boller et al. 2016). In case of an archival X-ray detection of the source, we compared the observed *Swift*/XRT flux to the archival flux to

determine whether the source displayed any significant change in brightness that could be classified as variable behavior.

In many cases ($\sim 70\%$), *Swift* did not perform the full ~ 5 ks exposure in a single epoch (see Figure 4). Therefore, in order to reach the full exposure for each tile, *Swift* carried out multiple observations⁷, sometimes taken months apart. We utilized this to better identify variability by comparing the source flux between each observation. This method was the most successful at determining sources for multi-wavelength follow-up. We additionally checked archival flux values from available catalogs to compare to our more current observations. We selected previously unknown or unclassified variable sources with an unabsorbed X-ray flux brighter than $F_X > 1.0 \times 10^{-12}$ erg cm⁻² s⁻¹ (0.3 – 10 keV) for Target of Opportunity (ToO) follow-up with a variety of X-ray satellites, such as *XMM-Newton*, *Chandra*, *NuSTAR*, and *NICER*, through our approved programs.

⁶ <https://heasarc.gsfc.nasa.gov/W3Browse/all/xray.html>

⁷ In most cases, it took *Swift* three observations of varying length for an individual tile to reach 5 ks exposure.

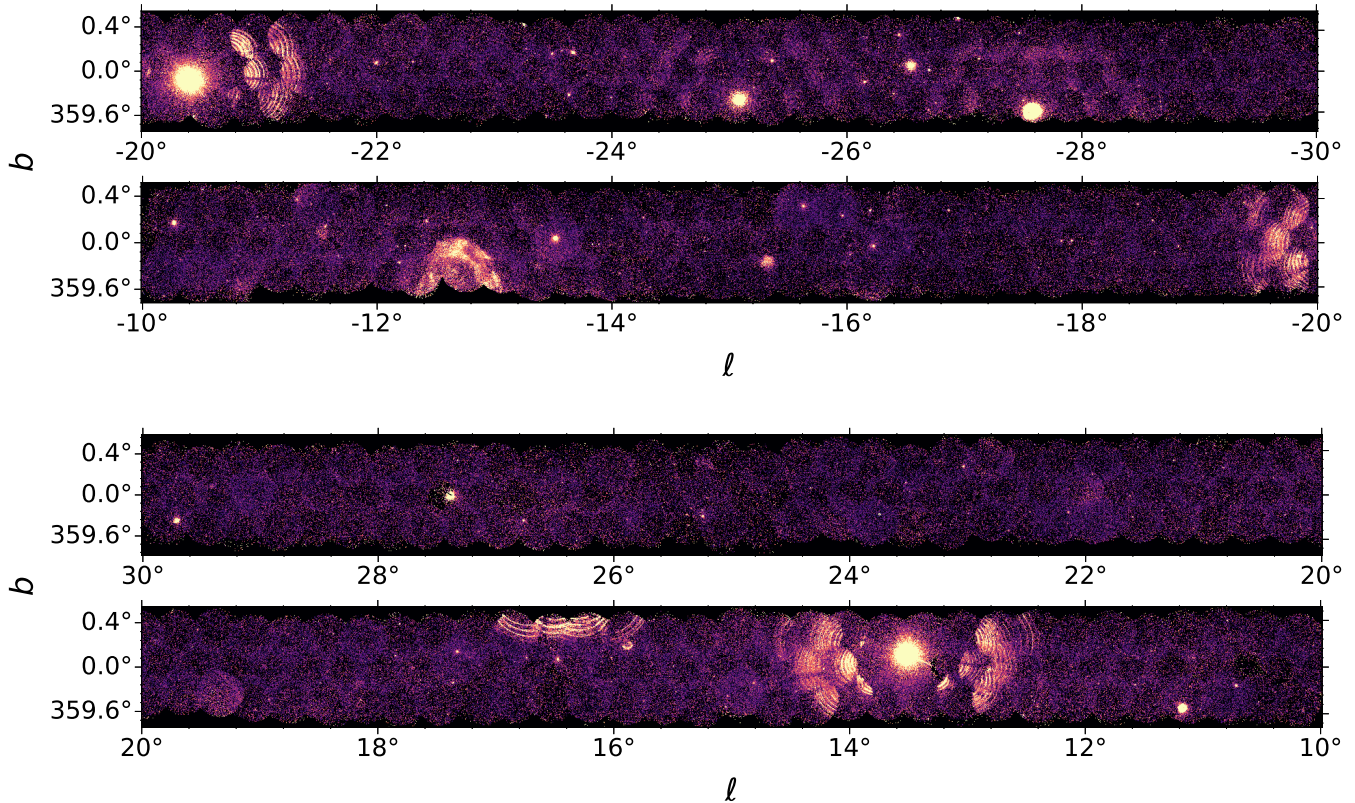


Figure 3. Full XRT band (0.3 – 10 keV) mosaic of the Galactic plane using an Aitoff projection in Galactic coordinates. The image covers the full 40 deg² of the DGPS Phase-I. The pixel size is 4.7''/pix, and images have been smoothed to improve visual clarity. The image has been divided by the exposure map (Figure 2) in order to smooth out exposure related background in the overlapping regions. The dominant sources of stray light at $l \approx -25^\circ$, -20.5° , and 13.5° are the LMXBs 4U 1624-49, 4U 1642-45, and GX 13+01.

The final number of unique sources detected with our quick-look pipeline is 290, of which 90 sources satisfied $F_X > 1.0 \times 10^{-12}$ erg cm⁻² s⁻¹. The majority of these sources were previously known, but those which were unclassified and displaying variable behavior were followed up through our ToO programs. This rapid multi-wavelength follow-up of variable or transient sources identified through our quick-look analysis has led to multiple publications (§5.4), including the source classification of a LMXB (Gorgone et al. 2019), a Be/X-ray Binary (O’Connor et al. 2022), an intermediate polar (IP) CV (Gorgone et al. 2021), and a polar magnetic CV (O’Connor et al. 2023). The classification of additional sources targeted through our follow-up campaign is ongoing.

3.2. Final Image Processing and Source Detection

The rapid quick-look analysis of DGPS observations does not reach the full depth of the Survey. In order to produce a complete source catalog, we turned towards a more robust, yet computationally intensive, data analysis pipeline used to generate previous *Swift* X-ray cat-

alogs (Evans et al. 2014, 2020). This pipeline allows for the mosaicing of all observations within the DGPS. However, the *Swift* DGPS covers 40 deg² of the Galactic Plane and performing source detection on regions of this size is not feasible due to the computational cost (time-wise) and intensity. Therefore, in order to reduce the computation time, while still achieving the maximum exposure across every part of the Survey, we defined 124 small mosaics covering the entire Phase-I Survey area. The mosaics were created such that there is an overlap for every mosaic, which means that some pointings were part of multiple mosaics. This ensures that every possible overlap of tiles was accounted for and allowed us to obtain the maximum exposure at every location within the DGPS footprint. An example mosaic is displayed in Figure 5.

The image processing, mosaic creation, and source detection algorithm are described in detail in Evans et al. (2014, 2020). The pipeline made use of HEASoft 6.29. The iterative source detection procedure classifies each source using numerous quality flags, such as ‘good’, ‘rea-

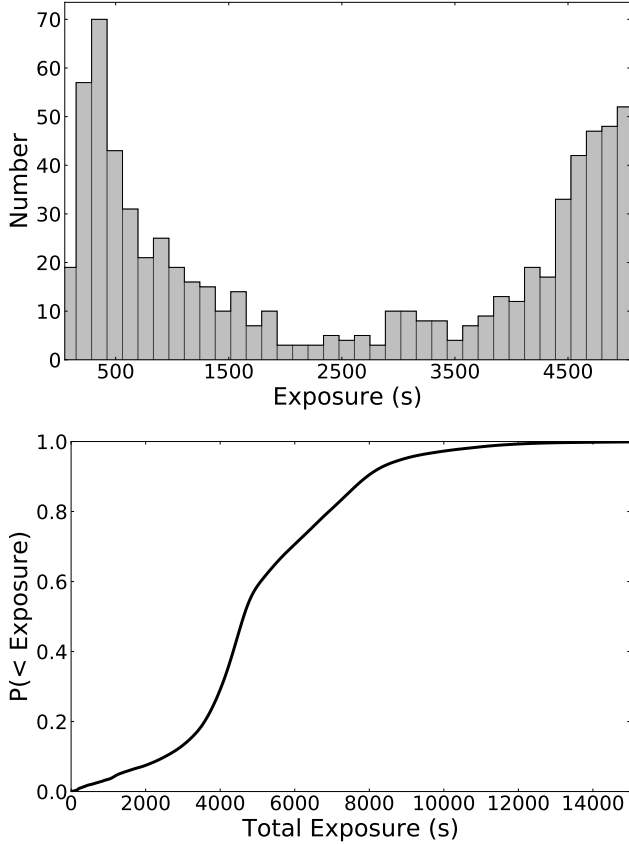


Figure 4. Top: Histogram of single-epoch *Swift*/XRT exposure time for all DGPS observations. **Bottom:** Cumulative distribution of the exposure time across the entire DGPS Survey footprint after mosaicing all observations. The median exposure is 4.6 ks. The overlap regions between tiles lead to a higher exposure of up to 15 ks.

sonable’, or ‘poor’ (see Evans et al. (2014, 2020) for details⁸.) These flags indicate the level of significance of the detection and were calibrated using simulations of point sources. The false positive rate for *good* sources is 0.3%, and increases to 1% when also including *reasonable* sources, whereas including *poor* sources yields a rate of spurious sources on the order of 10% (Evans et al. 2020). These false positive rates are considered cumulative, and we note that the true rate for *reasonable* and *poor* sources is $\sim 7\%$ and $\sim 35\%$, respectively. Therefore, we remove sources with a *poor* quality flag.

The Evans et al. (2020) pipeline also includes quality flags to prevent spurious sources in regions contaminated by stray light or extended sources (e.g., supernova remnants) as well as sources which are possible aliases of bright sources (see Table 5 of Evans et al. 2014). We

have excluded all sources occurring in the PSF of extremely bright sources, in regions of stray light or known extended objects, as well as those due to optical loading⁹. The field flags were set manually by Evans et al. (2020).

After removing all sources with quality flags, we began by merging all blindly-detected sources in the same mosaic across the different energy bands. Source detection is run independently in four energy bands¹⁰: the soft band (SB; 0.3 – 1 keV), medium band (MB; 1 – 2 keV), hard band (HB; 2 – 10 keV), and the full band (FB; 0.3 – 10 keV). We merged sources that were identified as the same source, but in different energy bands, by defining a match as either being within 10 pixels (1 pixel = 2.36”) or consistent at the 99.7% level using Rayleigh statistics. At this stage, we include only the statistical position errors as each source within a single mosaic has the same astrometric solution. This process yields a list of unique sources identified in each mosaic.

As there is a one tile overlap between each mosaic, there are some duplicate sources that must be removed. We therefore cross-matched the source lists between every mosaic in order to remove duplicate sources which were consistent at the 99.7% confidence level (including both the statistical and systematic error on the source positions). We are then left with a unique list of sources detected across the entire DGPS footprint.

The source count rates and fluxes in each energy band were then pulled from the Living Swift-XRT Point-source catalog¹¹ (LSXPS; Evans et al. 2022) using the API tool¹². We determined the LSXPS counterpart to each DGPS source using a radius of 20” or the 99.7% combined error radius. As the LSXPS is a low-latency, continuously updated catalog, we note that our cross-match was performed on the LSXPS catalog of 2022 August 31.

The count rates were converted to a 0.3 – 10 keV flux assuming a power-law spectrum with photon index $\Gamma = 1.7$ and the Galactic hydrogen column density in the source direction from Willingale et al. (2013)¹³. We further took from the LSXPS catalog the hard-

⁹ https://www.swift.ac.uk/analysis/xrt/optical_loading.php

¹⁰ These energy bands differ from those used in the original quick-look analysis. For the full catalog we adopted the same energy bands as previously used in the 1SXPS and 2SXPS catalogs (Evans et al. 2014, 2020), whereas the quick-look energy bands agreed with 1SWXRT (D’Elia et al. 2013).

¹¹ <https://www.swift.ac.uk/LSXPS/docs.php>

¹² <https://www.swift.ac.uk/API/>

¹³ We clarify here that these methods for correcting the source flux are in contrast to our quick-look analysis. Instead, the main survey methods were chosen to agree with 1SXPS and 2SXPS.

⁸ <https://www.swift.ac.uk/2SXPS/docs.php>

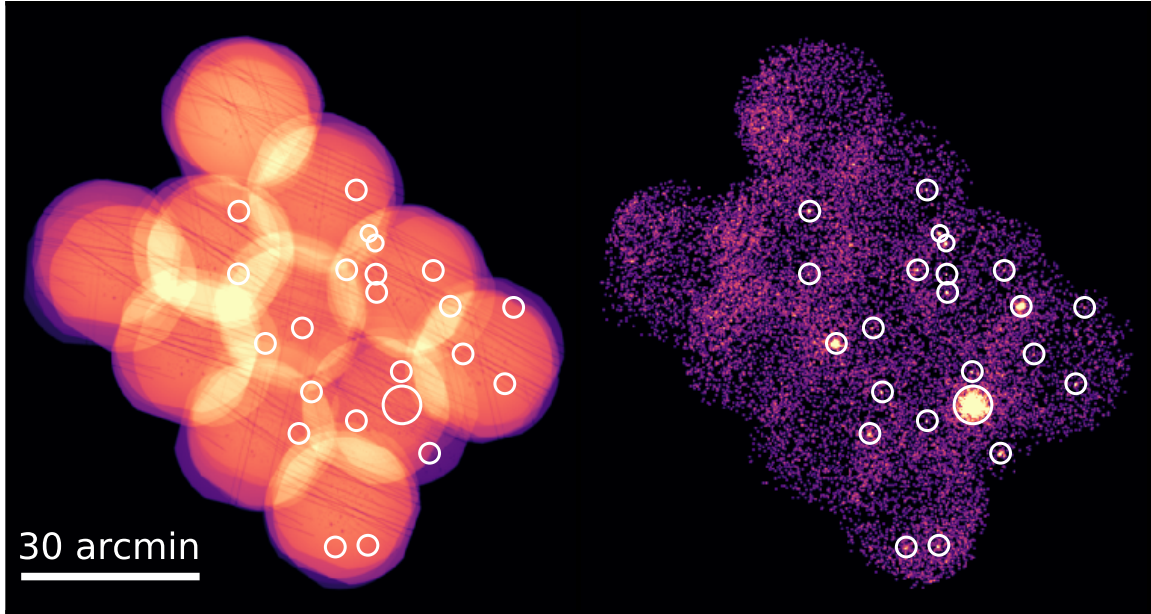


Figure 5. Example exposure map and science image (0.3–10 keV) of a DGPS mosaic. The mosaic is centered at $l, b = 333.87^\circ, 0.026^\circ$. The bright source to the right of the image is MAXI J1651-501, a Type-I X-ray Burster uncovered through DGPS observations (Gorgone et al. 2019). A weak stray light pattern (concentric bands) is visible on the left end of the mosaic. The images have been re-binned ($7.07''/\text{pix}$) and smoothed for display purposes.

ness ratios $HR_1 = M - S / M + S$, $HR_2 = H - M / H + M$, and the Pearson’s χ^2 probability that each source is variable based on their LSXPS lightcurves binned by observation.

The source positions in LSXPS are based on either standard or astrometric positions. We therefore used the API tool to build XRT enhanced positions (Goad et al. 2007; Evans et al. 2009) for all DGPS sources. We successfully built enhanced positions for 290 sources, and for these positions we accepted the position with the smallest error. We used the final source positions to name DGPS sources in the format “DGPS JHHMMSS.S \pm DDMMSS”.

All sources and their properties (along with LSXPS ID; Evans et al. 2022) are displayed in Table 2. We detected a total of 802 sources of which 784 are detected in the FB, 724 in the HB, 668 in the MB, and 564 in the SB. This is a factor of ~ 3 more sources than identified through the quick-look analysis of single-epoch observations (see §3.1).

3.2.1. Sources with no LSXPS Counterpart

In addition to those sources described above (the “main” catalog), we detect ~ 200 sources in the DGPS mosaics which do not have LSXPS counterparts within $60''$ (Evans et al. 2022). We refer to these as non-LSXPS sources throughout the manuscript. There are a number of plausible reasons as to why these sources would not have been detected in the LSXPS mosaics, including a

different combination of observations used to build the mosaics in LSXPS, hot pixels, which are harder to detect in stacked observations, or a lower background to variable or transient sources in the DGPS mosaics as they include less overall observations. Therefore, there is no obvious reason to exclude these sources from our catalog.

After removing sources with field flags or those lying in the PSF of a bright source, we are left with 126 sources, 83 classified as *good* and 43 as *reasonable*. Based on simulations of *Swift*/XRT point sources (Evans et al. 2014, 2020), these sources are detected at the 99% confidence level.

We utilized the Python API tool to call the Swift-XRT LSXPS Upper limit server¹⁴ (Evans et al. 2022), which allows for the calculation of 3σ upper limits for any position within the LSXPS footprint. We specifically called only the DGPS observations covering the position of each source. Aperture photometry using a circular region with a radius of 12 pixels ($28''$) was then performed on the images to determine the source and background counts in each energy band. We then applied the Bayesian procedure of Kraft et al. (1991) to determine whether the source is detected at the 3σ level, and, if detected, the mean number of counts and 1σ errors. The Upper Limit Server also computes a PSF

¹⁴ <https://www.swift.ac.uk/LSXPS/ulserv.php>

correction to account for vignetting and the encircled energy fraction of the circular aperture. After multiplying the number of counts by this correction factor and dividing by the exposure time, we obtain a count rate in each energy band. This is all done through the `mergeUpperLimits` tool. These methods are identical to those utilized to compute count rates for LSXPS sources.

However, we only find a 3σ detection for 35 out of 126 sources with 22 detections in the FB, 17 in the HB, 9 in the MB, and 6 in the SB. Of the 35 sources, 16 were detected in multiple bands using this method. This serves to confirm that at least some of these sources, likely more than 35, are not spurious in nature. We note that the [Evans et al. \(2020\)](#) source detection algorithm does not necessarily require a 3σ statistical significance for detection, and, in fact, the signal-to-noise ratio for many of these sources is ~ 2 . Instead, the algorithm computes a likelihood that the source is real, which was calibrated using simulations ([Evans et al. 2014, 2020](#)). This could explain why only 35 of 126 sources are above the 3σ threshold according to [Kraft et al. \(1991\)](#).

We convert the count rate to an unabsorbed flux (0.3–10 keV) for each source assuming the median ECF for all sources in the main catalog. This is dependent on the energy band, and we find median values of $\text{ECF}_{\text{FB}} = 2.7 \times 10^{-11} \text{ erg cm}^{-2} \text{ cts}^{-1}$ for the full band, and $\text{ECF}_{\text{SB}} = 5.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ cts}^{-1}$, $\text{ECF}_{\text{MB}} = 6.6 \times 10^{-11} \text{ erg cm}^{-2} \text{ cts}^{-1}$, and $\text{ECF}_{\text{HB}} = 4.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ cts}^{-1}$. These ECFs were all determined assuming a power-law X-ray spectrum with photon index $\Gamma = 1.7$ and Galactic hydrogen column density ([Willingale et al. 2013](#)). For these non-LSXPS sources we record only the standard position derived by the source detection algorithm as performed on the DGPS mosaics. We report the results for these 126 sources separately from the main catalog in Table 3.

4. RESULTS

4.1. Cross-matching with External Catalogs

We cross-matched the 802 sources in the main DGPS catalog (Table 2) with a variety of radio, optical, infrared, and X-ray catalogs in order to identify their multi-wavelength counterparts. We defined a match as when the catalog and DGPS positions were consistent at the 99.7% confidence level¹⁵ when adding both catalog and DGPS errors in quadrature. The distribution of 90% position errors are shown in Figure 6 (top panel).

¹⁵ In order to convert between the 90% and 99.7% position error, we have assumed that our source position errors follow Rayleigh statistics ([Evans et al. 2014, 2020](#)).

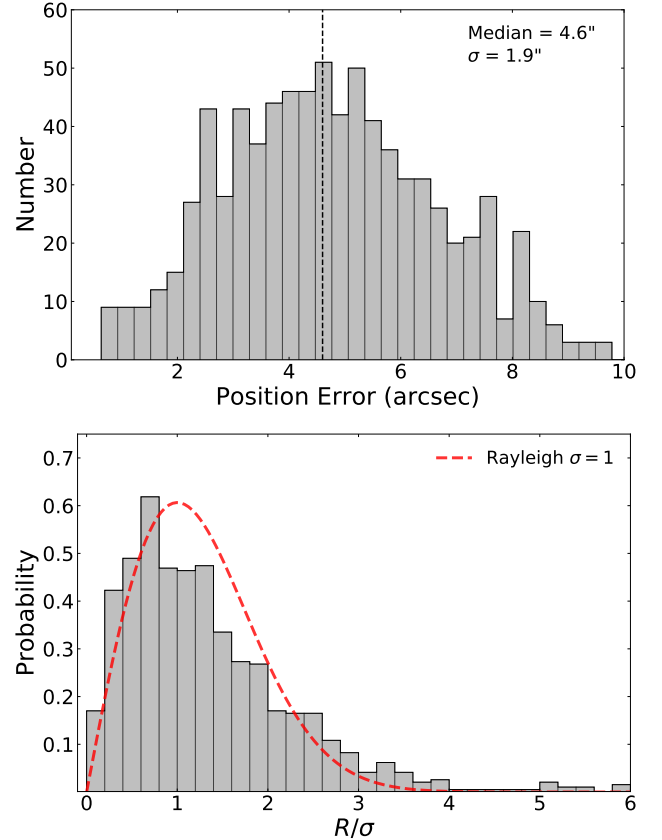


Figure 6. **Top:** Histogram of the 90% X-ray position error for sources in the DGPS catalog. **Bottom:** Radial separation R divided by the 68% error of the DGPS sources and the 68% error of other X-ray source error added in quadrature. The radial separation is from the DGPS source to the X-ray counterpart centroid from 4XMM, 2CSC, and 1SWXRT. The dashed red line shows the expected Rayleigh distribution with $\sigma = 1$.

The median 90% position error is $4.6''$, leading to a 99.7% error of $\sim 7''$.

We began by searching the SIMBAD Astronomical Database ([Wenger et al. 2000](#)) in order to identify any previous source classifications. As the SIMBAD database does not include positional errors uniformly it is possible some real associations were missed. For all other catalogs, we include the catalog's positional error added to the DGPS position error in quadrature.

We used `astroquery` ([Ginsburg et al. 2019](#)) to search the VizieR Database ([Ochsenbein et al. 2000](#)) for the following X-ray catalogs: the *Chandra* Source Catalog (CSC; [Evans et al. 2010](#)) Release 2.0, the *XMM-Newton* Serendipitous Source Catalog (4XMM-DR9; [Webb et al. 2020; Traulsen et al. 2020](#)), 1SXPS ([Evans et al. 2014](#)), and 2SXPS ([Evans et al. 2020](#)), 1SWXRT ([D'Elia et al. 2013](#)). In addition to the number of matches in each X-ray catalog we report the number of unique, previously

unknown, X-ray sources. We additionally searched the following optical, infrared, and radio catalogs: USNO-B1 (Monet et al. 2003), *Gaia* EDR3 (Gaia Collaboration et al. 2021), the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), and the Very Large Array Sky Survey (VLASS; Lacy et al. 2020). The results of our cross-matching analysis are displayed in Table 1.

We find that 249 (31%) of DGPS sources were previously unknown to other X-ray surveys (with the exception of LSXPS). In Table 2 we record whether a source has a known X-ray counterpart. Figure 6 (bottom panel) shows the distribution of offsets between X-ray source matches normalized by the 68% position uncertainty of both sources added in quadrature. The distribution of position-error-normalized offsets approximately follows a Rayleigh distribution with scale parameter $\sigma = 1$. However, there is some excess at $R/\sigma > 3$ that may hint at an additional systematic position error that was not included. We note that counterparts in 2SXPS are not included in this calculation as their separations are likely tighter than a Rayleigh distribution due to the use of a similar source detection algorithm on similar data.

We determined the number of false associations by shifting all DGPS sources randomly by $1-2'$ and repeating the cross-match. All matches found after shifting are considered false positives. We repeated this procedure multiple times. Due to the high density of optical and infrared sources in the crowded GP, generally there are multiple counterparts within a typical X-ray localization (e.g., between 2–4 *Gaia* counterparts are found on average for DGPS sources). This is reflected in the high false positive fraction ($> 77\%$). Therefore, the determination of the true counterpart is difficult using XRT positions alone. Through our follow-up campaigns, we found that *Chandra* observations were pivotal to the identification of the true multi-wavelength counterpart (see §5.4).

4.1.1. Source Classification Breakdown

Our cross-match with the SIMBAD database (Wenger et al. 2000) resulted in a total of 248 (31%) previously classified sources. However, we found that in some cases the classification was incorrect or incomplete. Thus, while the SIMBAD database provides a useful check as to whether a source is already known (and cross-listings between the same source in other catalogs), it does not provide a robust measure of the number of confidently classified sources in our catalog.

Therefore, we performed an additional search of other external catalogs containing classified source types, including the McGill Online Magnetar Catalog¹⁶ (Olausen

Table 1. Results of multi-wavelength cross-matching with external catalogs using the combined 3σ source localization. The expected fraction of spurious matches was determined by shifting our source catalog by $1-2'$ and re-running our cross-matching algorithm.

External Catalog	Matches	Spurious Matches
X-ray Catalogs		
2CSC	186	2 (1.0%)
4XMM-DR9	264	3 (1.1%)
2SXPS	463	3 (0.6%)
1SWXRT	63	1 (1.6%)
Unique	249	–
Radio Catalogs		
VLASS	17	1 (5.9%)
Unique	745	–
Optical/nIR Catalogs		
2MASS	689	618 (90.0%)
GAIA	699	635 (90.8%)
USNO-B1	562	431 (76.7%)
Unique	58	–

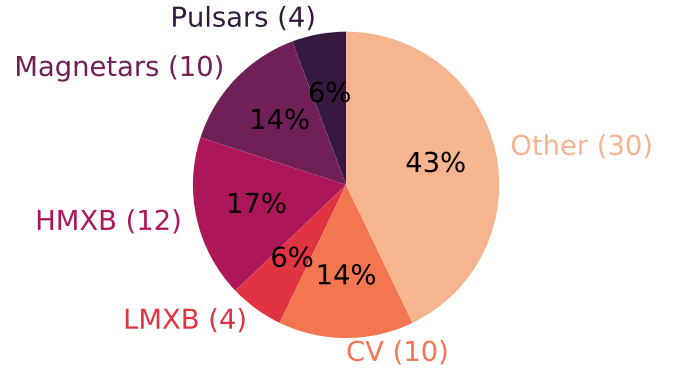


Figure 7. Breakdown of the source type for the 70 classified sources in the main DGPS catalog.

& Kaspi 2014), HMXBCAT¹⁷ (Liu et al. 2006), LMXB-CAT¹⁸ (Liu et al. 2007), Australia Telescope National Facility (ATNF) Pulsar Catalogue (Manchester et al. 2005), The Million Quasars (Milliquas) v7.2 Catalogue (Flesch 2021), Symbiotic stars catalogue¹⁹ (Belczyński et al. 2000), X-ray catalog of Galactic O stars (Nebot Gómez-Morán & Oskinova 2018), Catalog of X-Ray Detected Be Stars²⁰ (XDBS; Gobat et al. 2022), a cat-

¹⁶ <https://www.physics.mcgill.ca/~pulsar/magnetar/main.html>

¹⁷ <https://heasarc.gsfc.nasa.gov/W3Browse/all/hmxbcat.html>

¹⁸ <https://heasarc.gsfc.nasa.gov/W3Browse/all/lmxbcat.html>

¹⁹ <https://heasarc.gsfc.nasa.gov/W3Browse/all/symbiotics.html>

²⁰ <https://home.gwu.edu/~kargaltsev/XDBS/>

atalogue of chromospherically active binary stars (Eker et al. 2008), the Open Cataclysmic Variable Catalog²¹ (Guillochon et al. 2017; Jackim et al. 2020), and IP CVs from Koji Mukai’s catalog²². This ensures we probe the majority of known sources within these classes.

In total we find 70 classified sources across the following categories:

- i) 4 pulsars,
- ii) 10 magnetars,
- iii) 12 HMXBs,
- iv) 4 LMXBs,
- v) 10 CVs (6 being IPs),
- vi) 5 Wolf Rayet (WR) stars,
- vii) 18 young stellar objects (YSO),
- viii) 5 quasars (QSO),
- ix) and 2 X-ray detected O stars.

The classification breakdown is demonstrated in Figure 7. We find no known associations with X-ray detected Be stars (Gobat et al. 2022), Symbiotic stars (Belczyński et al. 2000), or chromospherically activate binaries (Eker et al. 2008). The sources with a classification are labeled in Table 3.

Thus, we find only $\sim 9\%$ of DGPS sources are confidently classified. This is likely a lower limit to the true number of classified sources in the Survey given that many of the catalogs searched are over a decade old and may be lacking in completeness. This further emphasizes the need for up-to-date catalogs of source classifications and for machine learning techniques to determine preliminary source classifications for large datasets (Yang et al. 2021, 2022; Tranin et al. 2022), see §5.5.

In Figure 8 we display the X-ray flux distribution of DGPS sources compared to known IP CVs, HMXBs, LMXBs, and magnetars. The large majority of DGPS sources lie below the distribution of classified sources, emphasizing the difficulty in classifying faint sources. This may suggest that the DGPS population of sources lies at further distances and are possibly more absorbed.

4.1.2. Cross-match of non-LSXPS Sources

We performed the same cross-matching analysis outlined in §4.1 on the 126 non-LSXPS sources (Figure 9 and Table 3). We find 17 matches in the X-ray catalogs searched, implying that these sources largely comprise a faint, previously undiscovered population of X-ray sources. Of these 17 matches, 12 were in 4XMM-DR9, 7 in 2SXPS, and 7 in CSC 2.0. The sources with matches in these catalogs are marked in Table 3

²¹ <https://depts.washington.edu/catvar/index.html>

²² <https://asd.gsfc.nasa.gov/Koji.Mukai/iphone/catalog/alpha.html> (cross-matched as of 2022 August 31)

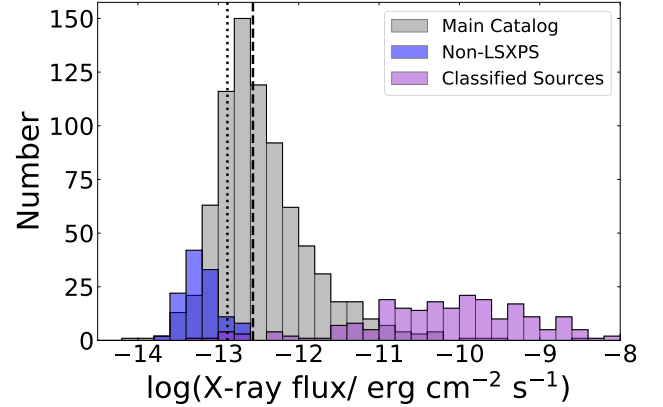


Figure 8. Histogram of average flux values for sources in the main DGPS catalog (gray), the non-LSXPS sources (blue), and known classified sources (purple), including IP CVs, LMXBs, HMXBs, and Magnetars. The dotted and dashed lines correspond to the 50% and 90% completeness flux of the DGPS, respectively (see §5.1).

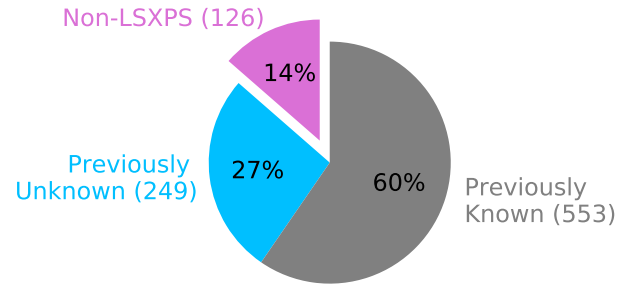


Figure 9. Breakdown of the 928 X-ray sources (802 LSXPS + 126 non-LSXPS) in the DGPS source catalog.

We further note that a cross-match of the non-LSXPS sources with SIMBAD results in only 3 classified source matches, and 123 sources without a SIMBAD counterpart. Therefore, a significantly larger fraction of those sources not in LSXPS are previously unknown and unclassified, likely due to their faintness and lower number of counterparts in other X-ray catalogs.

While only 17 (13%) of these sources have a known X-ray counterpart, compared to 69% in the main catalog, this further implies (see also §3.2.1) that at least some of these non-LSXPS sources are real. Moreover, the 7 sources detected in 2SXPS (Evans et al. 2020), but not in the re-analysis for LSXPS (Evans et al. 2022), emphasizes that the combination of specific observations used to create the mosaic is an important factor in the source detection process.

4.2. Variable X-ray Sources

The DGPS was aimed at uncovering new or variable X-ray sources within the GP. This was done through the

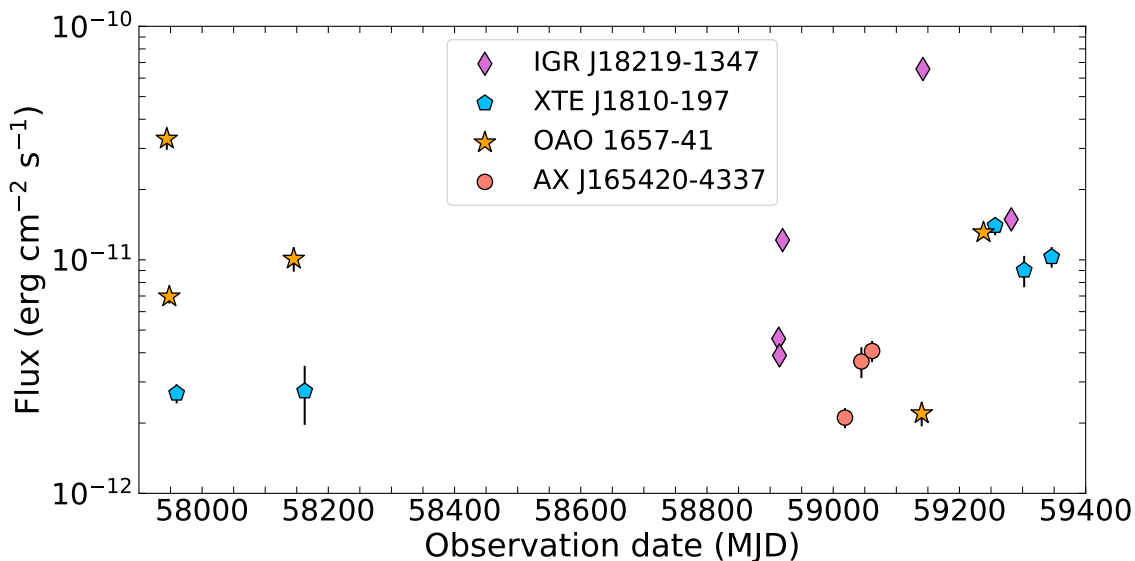


Figure 10. Examples of variable sources identified in DGPS observations: IGR J18219-1347 is a BeXRB (O’Connor et al. 2022), XTE J1810-197 is a magnetar candidate (Markwardt et al. 2003; Israel et al. 2004), OAO 1657-41 is a HMXB (Polidan et al. 1978; Chakrabarty et al. 1993), and AX J165420-4337 (also known as 1RXS J165424.6-433758) is a polar CV (O’Connor et al. 2023).

rapid analysis of quick-look data (§3.1) and the comparison of source flux levels with archival observations. An example of variable sources uncovered in DGPS observations is displayed in Figure 10. The majority of sources displaying obvious variable behavior were already classified (typically HMXBs, LMXBs, or magnetars; Figure 10), but we were also able to classify a number of variable sources (e.g., Gorgone et al. 2019, 2021; O’Connor et al. 2022, 2023) through our follow-up programs, with more classifications in progress.

For the purposes of the DGPS catalog, we make use of the Pearson’s χ^2 variability test (see also Evans et al. 2014, 2020). This test computes the probability that the source count rate is constant across all *Swift* observations of the source. We consider a source variable if the probability is $P_{\chi, \text{const}} < 0.05$. Approximately half of DGPS sources satisfy this criterion and are classified as variable (Figure 11).

In addition, following Eyles-Ferris et al. (2022), we compute the ratio of the peak-to-mean X-ray flux, denoted by R_{flux} , as an indicator of flaring sources. We display R_{flux} for each source in Figure 12. We find that only 50 sources in the Survey are consistent with $R_{\text{flux}} > 10$ and 138 with $R_{\text{flux}} > 5$. Out of the 50 sources with $R_{\text{flux}} > 10$, only 31 satisfy $F_X/\sigma_{F_X} > 3$ (Figure 12). Thus only 31 of these sources have accurate enough flux determinations that the increase in flux by an order of magnitude is statistically significant.

If we further sort these to sources with $F_X > 10^{-12}$ erg cm $^{-2}$ s $^{-1}$, our threshold for source follow-up (§3.1),

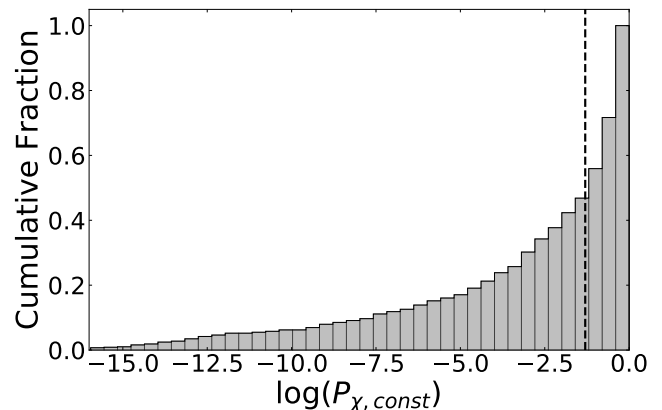


Figure 11. Cumulative distribution of the Pearson’s χ^2 variability test for all DGPS sources. The dashed line represents a threshold of $P_{\chi, \text{const}} = 0.05$, below which a source is considered variable. Approximately 50% of sources lie below this threshold.

we find that only 11 sources satisfy these criterion, all of which are classified and have a known X-ray counterpart: 1 LMXB, 4 HMXBs, 3 magnetars, 1 pulsar, a pulsar wind nebula (Ng et al. 2008), and the young star cluster Westerlund 1. This is in contrast to a total of 151 sources with $F_X > 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ in the DGPS main catalog (115 of which have a known X-ray counterpart).

5. DISCUSSION

5.1. Completeness

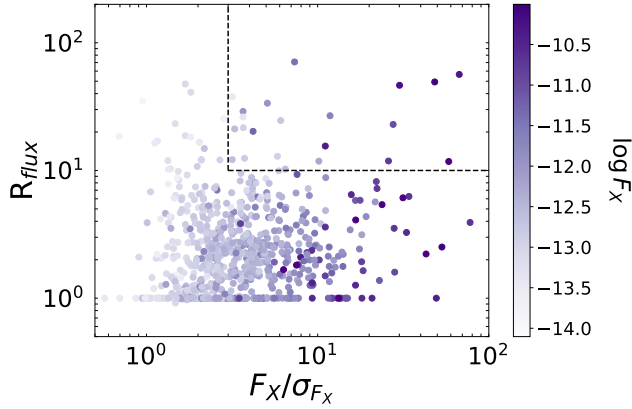


Figure 12. The ratio of the peak-to-mean X-ray flux R_{flux} versus the ratio of the mean X-ray flux F_X and the X-ray flux error σ_{F_X} . The points are colored by the log of the 0.3–10 keV X-ray flux in $\text{erg cm}^{-2} \text{s}^{-1}$. The black dashed line indicates a region of parameter space where sources are likely flaring or highly variable.

We estimated the completeness of the DGPS catalog using the simulations performed by Evans et al. (2014, 2020). Evans et al. (2014, 2020) performed detailed simulations of source detection likelihood with *Swift*/XRT as a function of flux and exposure time. The source detection algorithm utilized in this work is most similar to Evans et al. (2020), which displayed a factor of $3.5\times$ improvement in sensitivity compared to Evans et al. (2014) due to differences in the detection procedure and a more accurate modeling of the XRT PSF. Therefore, we estimate our completeness using Figure 6 of Evans et al. (2020). We used the simulations corresponding to the inclusion of sources classified as both ‘good’ and ‘reasonable’.

The median exposure time of DGPS tiles is ~ 4.6 ks. Using the calculations performed by Evans et al. (2020), this corresponds to a 50% completeness flux of $1.3 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$ and a 90% completeness of $2.7 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$. However, as shown in Figure 2, the exposure varies over the GP due to regions of overlap between tiles. Therefore, these completeness values may underestimate the true fraction of faint sources expected in the overlap regions (see Figure 2).

In order to account for this, we performed a Monte Carlo simulation to sample exposure times from random locations within the Survey footprint (Figure 2). We then estimated the 50% and 90% completeness using the same method outlined above. We repeated this procedure for 20,000 locations in order to find a distribution of completeness flux levels across the Survey. We find a 50% completeness flux of $(1.3^{+0.3}_{-0.4}) \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$ and a 90% completeness of $(2.7^{+0.4}_{-0.7}) \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$.

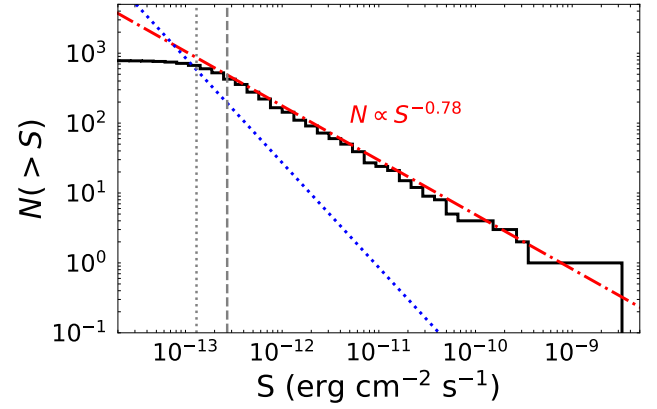


Figure 13. $\log N - \log S$ plot for the *Swift* DGPS (0.3–10 keV). The best fit line is displayed in red corresponding to $N(> S) \propto S^{-0.78}$. The dotted and dashed lines correspond to the 50% and 90% completeness flux of the DGPS, respectively. The blue dotted line is an estimate of the extragalactic source population (Ueda et al. 1999).

$\text{erg cm}^{-2} \text{s}^{-1}$. As expected, these values are consistent with our initial estimate.

5.2. Luminosity Function

Using the DGPS source catalog, we derive the slope and normalization of the $\log N - \log S$ curve at Galactic latitudes $|b| < 0.5$ (Figure 3). We adopt a power-law form of this curve as $N(> S) = KS^\alpha$, where K is a normalization factor. The slope of this curve yields insight into the spatial distribution of X-ray source populations within our Galaxy.

In Figure 13, we display the $\log N - \log S$ derived from the mean fluxes of DGPS sources in the 0.3–10 keV energy range in units of $\text{erg cm}^{-2} \text{s}^{-1}$. The best fit power-law distribution has a slope $\alpha = -0.78 \pm 0.03$. We have only fitted the distribution for fluxes above the 50% completeness value (dotted line in Figure 13), where the curve rapidly flattens. We note that including the non-LSXPS sources (§3.2.1) has no impact on the value of the slope as they all lie below the completeness flux value.

Our value is similar to the slope derived with the ASCA GP Survey (Sugizaki et al. 2001) of -0.79 ± 0.07 , and consistent with the -0.64 ± 0.15 slope derived for HMXBs (Grimm et al. 2002). Both values are flatter than the -1 expected for a uniform infinite-plane source distribution. However, past X-ray surveys using different instruments have found values in agreement with $\alpha \approx -1$ (Hertz & Grindlay 1984; Dean et al. 2005). These differences may be due to the survey area covered, with different populations of X-ray sources probed, as well as instrument sensitivity. The DGPS covers regions of the plane dominated by spiral arms (Figure 1) at low Galactic latitudes, and therefore we would expect

a shallow slope for the $\log N - \log S$ relation (Sugizaki et al. 2001; Grimm et al. 2002), whereas past Galactic X-ray surveys also covered larger scale heights, leading to a steeper slope. We note that the $\log N - \log S$ curve for extragalactic X-ray sources is considerably steeper ($\alpha \approx -1.5$; Gioia et al. 1990; Hasinger et al. 1993; Ueda et al. 1999; Luo et al. 2017), and in agreement with the expectations for a 3D Euclidean Universe ($N \propto S^{-3/2}$).

In order to determine whether extragalactic sources visible through the plane were contaminating our sample, we estimated their contribution following the methods of Sugizaki et al. (2001) and by converting the $\log N - \log S$ fit (2–10 keV) from Ueda et al. (1999) to the 0.3–10 keV flux, assuming an extragalactic source spectrum with power-law photon index $\Gamma = 2$ absorbed by $N_H = 5 \times 10^{22} \text{ cm}^{-2}$. These values were chosen under the assumption that the extragalactic source population comprises only active galactic nuclei (AGN). The extragalactic population begins to significantly contribute at fluxes less than $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, and has a negligible impact on the population of brighter sources.

5.3. Catalog Characteristics

In the main DGPS catalog (Table 2), we detected a total of 802 sources of which 784 are detected in the FB, 724 in the HB, 668 in the MB, and 564 in the SB. In Figure 14 we display the cumulative distribution of count rates in these energy bands, while Figure 15 compares the count rate between the HB and SB for sources detected in both bands. The SB and MB rate are typically lower than the HB and FB, which may be due to either absorption by the interstellar medium (ISM) or the smaller energy range covered by those bands.

Figure 16 shows the 0.3–10 keV X-ray flux versus HR_1 and HR_2 for all sources in the main catalog. For comparison we display the known population of IP CVs, LMXBs (Liu et al. 2007), HMXBs (Liu et al. 2006), and magnetars (Olausen & Kaspi 2014) from the 2SXPS catalog (see Appendix C for details). We see that the majority of our sources lie both below the completeness values (vertical lines) and below the flux of classified sources (Figure 8), underscoring a very large population of faint, unclassified sources. However, it is difficult to classify these sources based on the hardness ratios alone, as demonstrated by Figure 17 (for details see Appendix C). There is significant overlap in the population of classified sources, emphasizing the need for machine learning to disentangle source properties in higher dimensional space (Yang et al. 2022; Tranin et al. 2022).

The DGPS sources are distributed relatively uniformly across Galactic longitude (Figures 18 and 19) within the Survey footprint (§2). For example, the num-

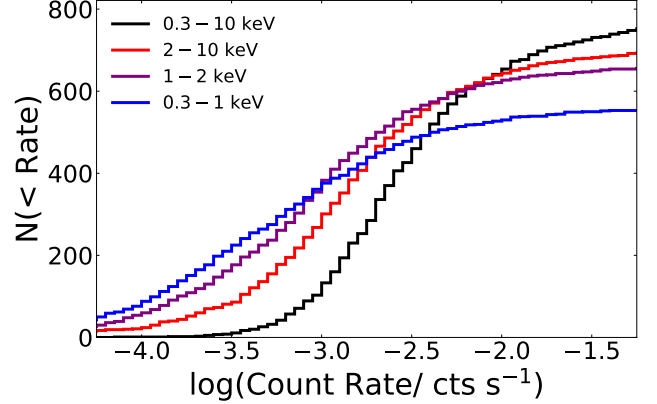


Figure 14. Cumulative distribution of XRT count rates for sources detected in each of the four energy bands.

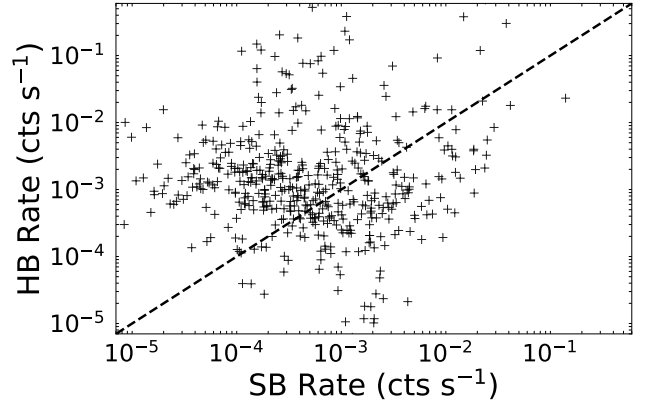


Figure 15. Source count rates in the HB (2–10 keV) versus the SB (0.3–1 keV). Only sources detected in both bands are shown. Error bars are not displayed. The dashed line shows sources where the count rate is the same in both bands.

ber of sources between $10 < l < 30 \text{ deg}$ and $330 < l < 350 \text{ deg}$ is 413 and 389, respectively. However, pockets of longitude with less sources exist. We find that this is due, at least in part, to sources of intense stray light (Figure 3) at $l \approx 338 - 342 \text{ deg}$ and $l \approx 12 - 14 \text{ deg}$ (see the black star in Figure 19; bottom panel). This is caused by the fact that we excluded sources with an LSXPS field flag indicating that they reside in regions of stray light, and, therefore, may be the result of unreliable detections (§3.2). In Galactic latitude we see a marked decrease in sources as we move away from the GP, as expected. In Appendix B, we display additional characteristics of sources across the GP (e.g., hardness ratios and variability).

5.4. New or Newly Classified Sources

We followed up unclassified, variable sources using our approved ToOs on *Chandra*, *NuSTAR*, *NICER*, and

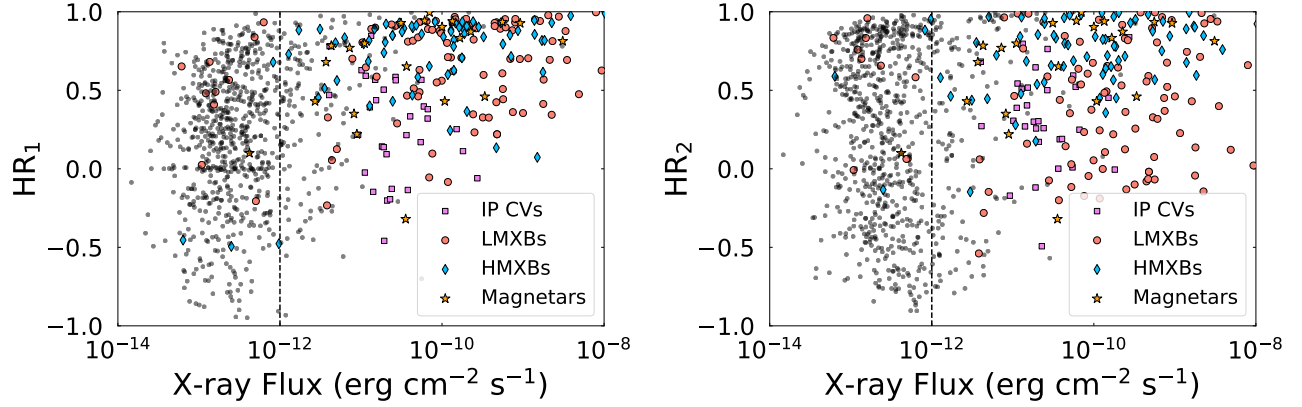


Figure 16. Distribution of DGPS sources (gray circles) in terms of hardness ratio and X-ray flux. For reference, we display LMXBs, IP CVs, HMXBs, and magnetars from the 2SXPS catalog.

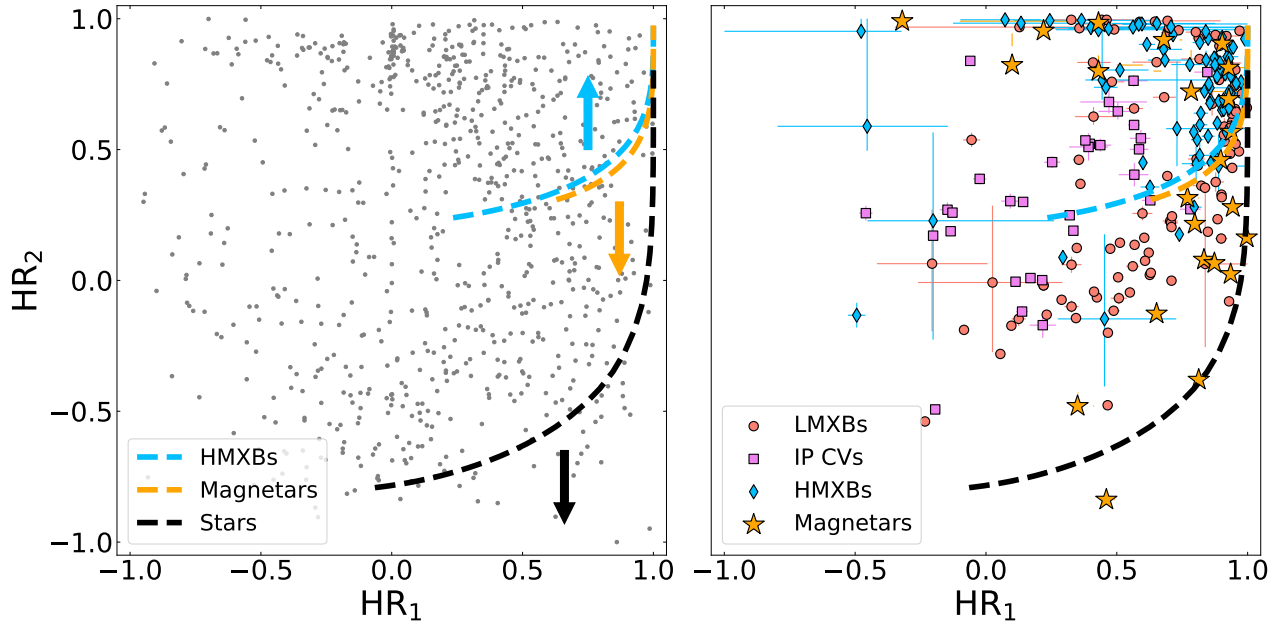


Figure 17. Left: Location of DGPS sources (gray circles) in the $HR_1 - HR_2$ plane. The dashed lines represent typical spectra for HMXBs, Magnetars, and stars as outlined in Appendix C. The arrows mark the general location of these sources with respect to the lines. **Right:** The mean hardness ratios of LMXBs, IP CVs, HMXBs, and magnetars from 2SXPS are shown for comparison.

XMM-Newton, including *XMM-Newton* AO17 (Proposal ID: 082186; PI: Kouveliotou), *Chandra* Cycles 19, 20, and 23 (Proposal IDs: 19500723, 20500298, and 23500070; PI: Kouveliotou), and *NICER* Cycle 3 and 4 (Proposal IDs: 4050 and 5097; PI: Kouveliotou). The DGPS was a *NuSTAR* Legacy Survey until 2019, although since this time we have utilized Director’s Discretionary Time (DDT) observations. In total, we carried out 3 *XMM-Newton* ToOs, 9 *NuSTAR* ToOs, 9 *Chandra* ToOs, 6 *NICER* ToOs, and 20 *Swift* ToOs to follow DGPS sources. In addition, we made use of multi-wavelength observations from the Lowell Discov-

ery Telescope (LDT), the South African Astronomical Observatory (SAAO) 1-m telescope, and the Southern African Large Telescope (SALT).

A summary of the published results is presented below (Gorgone et al. 2019, 2021; O’Connor et al. 2022, 2023). Additional papers are in preparation, including the classification of another magnetic CV (O’Connor et al., in preparation) and a solar analog (Kouveliotou et al., in preparation).

5.4.1. *MAXI J1621-501*

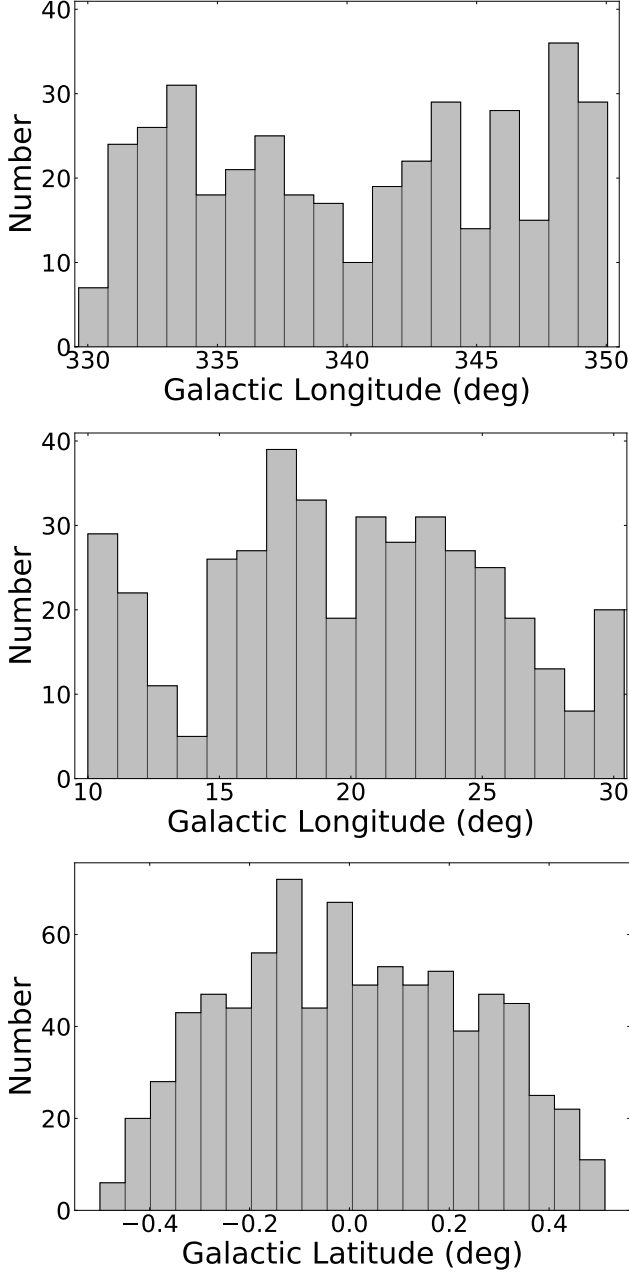


Figure 18. Histograms of the number of sources detected per Galactic longitude on both sides of the plane and in Galactic latitude (combining both sides of the plane). We note that the dip in sources at $l \approx 14$ deg and 340 deg are due to stray light contaminating those fields.

MAXI J1621–501 is the first transient observed through the DGPS (Gorgone et al. 2019). Following the source’s discovery by *MAXI* on 2017 October 19, Gorgone et al. (2019) began an extensive multi-wavelength follow-up campaign using *NuSTAR*, *Swift*, *Chandra*, *NICER*, *INTEGRAL*, and *MAXI* as well as a variety of ground-based observatories including Gemini,

the Infra-Red Survey Facility (IRSF), and the Australia Telescope Compact Array (ATCA). *NuSTAR* observations revealed 2 Type-I X-ray bursts, which identified MAXI J1621–501 as a LMXB with a NS primary. Overall, 24 Type-I bursts were reported by Gorgone et al. (2019) over a 15 month period. Gorgone et al. (2019) further identified a possible super-orbital period at 78 d, agreeing well with the theoretical prediction of ~ 82 d.

5.4.2. *Swift* J183920.1–045350

The second source for which an extensive multi-wavelength campaign was initiated was *Swift* J183920.1–045350 (Gorgone et al. 2021). The source was initially observed with *Swift*, *Chandra*, *NuSTAR* and *XMM-Newton*. Observations were also obtained by the Karl G. Jansky Very Large Array (VLA), APO, SALT, and SAAO. In the *NuSTAR* and *XMM-Newton* data, Gorgone et al. (2021) identified a 449.7 s spin period. High-speed photometry from SAAO yielded a 459.9 s optical period that was interpreted as the beat period produced by a 5.6 hr orbital period. Paired with a candidate X-ray emission line near 6.4 keV, hard X-ray spectrum, and $H\alpha$ emission line in the optical spectra, *Swift* J183920.1–045350 was identified as an IP CV.

5.4.3. *IGR* J18219–1347

The DGPS observed Type-I outbursts from the HMXB candidate *IGR* J18219–1347 in 2020 March and June (O’Connor et al. 2022). We followed up this source with *NuSTAR* and *NICER*, allowing for the identification of a NS spin period of 52.46 s. This periodicity, combined with the known orbital period of 72.4 d (La Parola et al. 2013), indicated that the system was a BeXRB. We confirmed the BeXRB classification through the identification of an infrared counterpart in the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). Our X-ray observations further revealed that the source’s broadband X-ray spectrum (1.5 – 50 keV) is described by an absorbed power-law with photon index $\Gamma \sim 0.5$ and cutoff energy at ~ 13 keV. These properties are typical of BeXRBs.

5.4.4. *1RXS* J165424.6–433758

We put forth a number of unclassified, variable X-ray sources with bright optical counterparts in *Gaia* for spectroscopy with SALT (PI: D. Buckley). Spectroscopy of the brightest optical source 1RXS J165424.6–433758 ($G \sim 17.6$ AB mag) revealed a flat continuum peppered by emission features of Hydrogen and Helium, including an inverse Balmer decrement, the $\lambda 4640$ Bowen blend, and HeII $\lambda 4686$. We carried out high speed optical photometry over 8 epochs with the 1m SAAO, yielding an

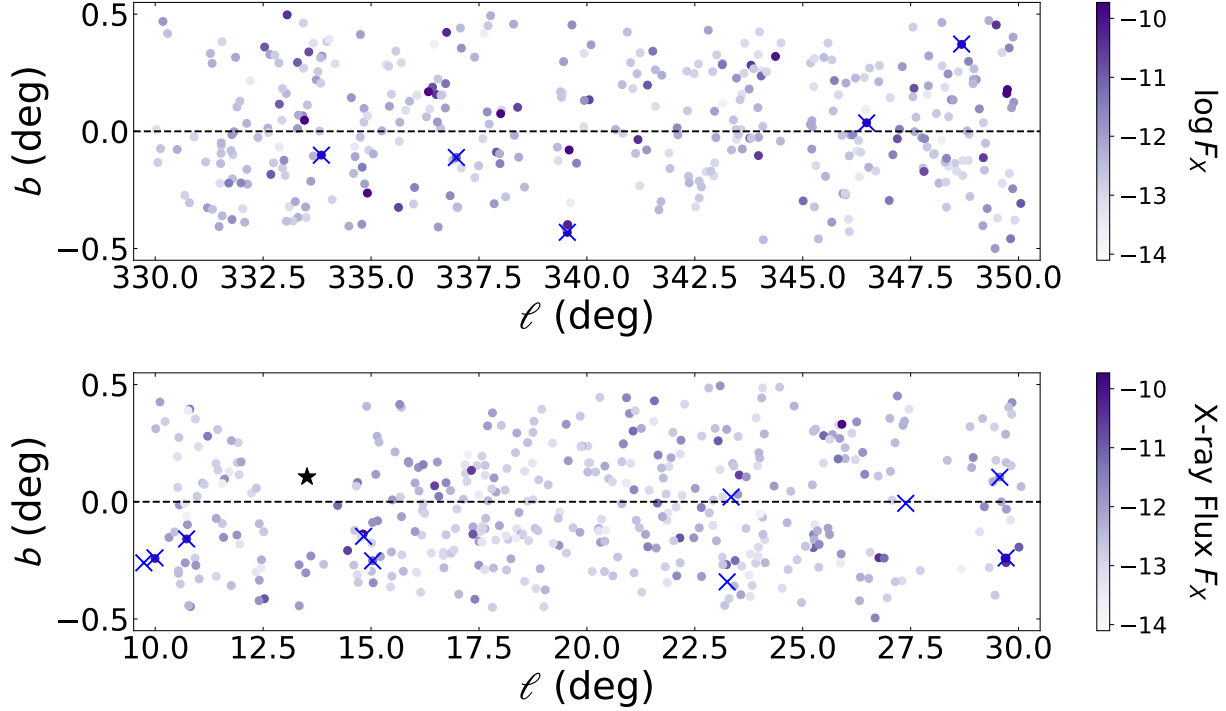


Figure 19. The location of DGPS sources in Galactic coordinates. The sources are colored based on their X-ray flux. The blue crosses show the locations of known magnetars. The black star (bottom panel) marks a dominant source of stray light, leading to an obvious lack of sources at that region of the Survey.

orbital period of $P_{\text{orb}} = 2.87$ hr. Based on these characteristics, we classified 1RXS J165424.6-433758 as a nearby ($d = 460 - 550$ pc) polar magnetic CV (O’Connor et al. 2023).

5.5. Machine Learning Classification of DGPS Sources

As shown in §4.1.1, the DGPS has detected a large number of unclassified X-ray sources. The classification of hundreds of X-ray sources based on manual compilation and analyses of multi-wavelength datasets is difficult and time consuming. Instead, it is more efficient to turn to supervised machine learning methods to perform the classification of a large number of sources based on the properties of a training dataset comprising sources with already known classes. Yang et al. (2022) performed such analysis for a subset of the *Chandra* Source Catalog version 2.0 (CSCv2) using a publicly available²³ Python framework and a training dataset of $\sim 3,000$ sources with verified classifications²⁴. They first applied a selection criterion to CSCv2 to remove *Chandra* sources with low signal-to-noise, poor localization errors, or those that were either extended or confused (see Yang et al. 2022 for details). The sources

satisfying their criteria are referred to as “good” CSCv2 sources (GCS). In total, they are able to provide classifications to 66,359 CSCv2 sources, approximately 21% of the CSCv2 catalog.

While Yang et al. (2022) have not yet extended their analysis to other X-ray missions (see, however, Tranin et al. 2022), their results can provide useful insight into the classification of a subset of DGPS sources. We note that one of the main obstacles for extending these analyses to *Swift* is the significantly larger localization uncertainties of X-ray sources precluding accurate multi-wavelength cross-matching. Therefore, below we only review the classifications of DGPS sources that have counterparts in CSCv2, which provide much more accurate positions.

After performing a cross-match between DGPS sources and the CSCv2 catalog we find 186 matches (Table 1). We then matched these sources to the results of Yang et al. (2022), finding 45 classified GCSs in addition to 19 sources in their training dataset. These sources have a classification confidence threshold (CT) indicating the confidence level, with $\text{CT} \geq 2$ adopted for confidently classified GCSs (CCGCSs). Out of the 45 GCS sources, only 8 are CCGCSs. In Figure 20 we display the classification stacked histogram of all 45 sources. The

²³ https://github.com/huiyang-astro/MUWCLASS_CSCv2

²⁴ <https://home.gwu.edu/~kargaltsev/XCLASS/>

largest number of CCGCSs are 4 YSOs, followed by 3 NSs, and 1 CV.

Although 3 NS candidates (2CXO J171428.6–383601, 2CXO J182524.7–114524 and 2CXO J181210.3–184208), which each lack any optical or infrared counterpart, have been confidently classified, this may be due to a bias in the training dataset against faint sources without multi-wavelength counterparts. A large fraction of faint sources do not have multi-wavelength counterparts simply because of the insufficient sensitivity of optical and infrared surveys combined with the significant extinction in the GP. The classification algorithm of Yang et al. (2022) may instead interpret the lack of multi-wavelength counterparts as a sign of the NS class (which includes both magnetars and isolated NSs). Indeed, upon further investigation, 2 out of 3 of these NS candidates (2CXO J182524.7–114524 and 2CXO J181210.3–184208) have infrared counterparts in UKIDSS, which is significantly more sensitive than the 2MASS catalog used in Yang et al. (2022). The third source (2CXO J171428.6–383601) may have an infrared counterpart in VVV, but the source lies outside of the 95% localization region ($0.9''$) from CSCv2 at an offset of $1.2''$. Based on the VVV sky density in this region of the GP, we compute a probability of chance coincidence of between 25 – 37%, depending on whether or not we account for the brightness of the counterpart.

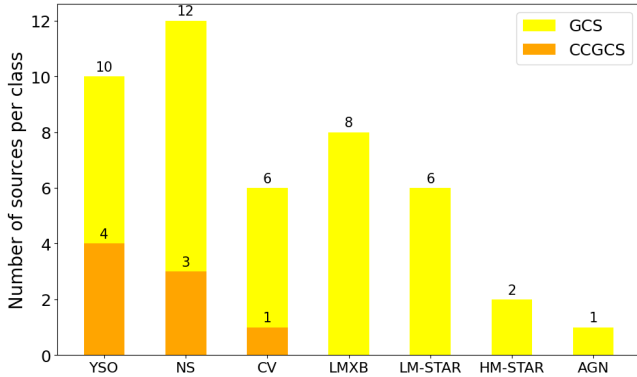


Figure 20. Histogram of source classification breakdown for 45 GCSs and 8 CCGCSs based on results from Yang et al. (2022).

5.6. Constraints on the population of magnetars

The main targets of the *Swift* DGPS were magnetars and HMXBs. However, although several of the already known sources from both populations were observed (Figure 7), we did not concretely identify any new transient events associated with magnetars, and classified only a single new HMXB (O’Connor et al. 2022).

Magnetars are generally identified during their bright X-ray outbursts. As such, the quiescent magnetar population is poorly constrained. Using the Magnetar Outburst Online Catalog²⁵ (Coti Zelati et al. 2018), we compiled the distance and quiescent X-ray (0.3 – 10 keV) luminosity for 15 magnetars. Their observed quiescent luminosities lie between 10^{30-35} erg s⁻¹ (Coti Zelati et al. 2018). Using the best available distance for each event, we find quiescent X-ray fluxes in the range 10^{-15} to 10^{-12} erg cm⁻² s⁻¹. Therefore, only 7 out of 15 magnetars would be detectable based on the DGPS 50% completeness flux.

For example, we note here that the DGPS observed the field of the magnetar *Swift* J1818.0 – 1607 (Blumer & Safi-Harb 2020; Champion et al. 2020; Hu et al. 2020) approximately 2.7 yr before its discovery. Unfortunately the source was not active and we were only able to obtain an upper limit (3σ) of $\lesssim 2 \times 10^{-13}$ erg cm⁻² s⁻¹. This demonstrates that quiescent magnetars exist in the region covered by the DGPS, but their identification is difficult, possibly due to faintness. A significant benefit of this survey is to constrain the quiescent luminosity of future magnetars, or other transients, discovered in these regions.

In fact, Beniamini et al. (2019) found that based on the observed persistent luminosity and $\log N - \log S$ distribution, the number of hidden magnetars could outweigh the known population by a factor of up to ~ 10 . They found that the missing magnetars should have unabsorbed fluxes $< 10^{-13}$ erg cm⁻² s⁻¹, which is below the DGPS completeness values.

In the general spin-down model for magnetars the magnetic field evolution is parameterized by $\dot{B} \propto B^{1+\alpha}$ (Colpi et al. 2000). Beniamini et al. (2019) used the observed $\log N - \log S$ for magnetars to show that both $\alpha = 0$ and -1 can explain the observed population of absorbed and unabsorbed magnetar fluxes. We perform a similar calculation using the constraints of our Survey. Based on the DGPS $\log N - \log S$ (Figure 13) we have detected 144 sources at $> 1.0 \times 10^{-12}$ erg cm⁻² s⁻¹ of which 10 are known magnetars (Figure 7) and 400 sources at $> 2.7 \times 10^{-13}$ erg cm⁻² s⁻¹ (including the 144 mentioned above). Under the assumption that none of these new sources are magnetars we constrain $\alpha < -0.65$ at the 90% confidence level (CL). We note that the assumption that none of the $\sim 1,000$ sources in our Survey are magnetars is likely too restrictive as there could be unidentified quiescent magnetars hiding in this population. If instead we assume there are 10 (20) unidentified

²⁵ <http://magnetars.ice.csic.es/#/welcome>

magnetars with a flux between 2.7×10^{-13} to 1.0×10^{-12} erg cm $^{-2}$ s $^{-1}$ the constraint is $\alpha < 0.86$ (2.15). These results are consistent with Beniamini et al. (2019).

The upper limit to α is therefore strongly dependent on the unknown population of unidentified quiescent magnetars hiding in our sample. Nevertheless, the identification of their quiescent population is extremely difficult. This issue was explored in detail by Munro et al. (2008) using constraints from *XMM-Newton* and *Chandra*. They searched for periodic variability in deep X-ray observations of the GP region ($|b| < 5$ deg), but did not identify any new periods between 5 and 20 s. Based on their analysis, Munro et al. (2008) found that < 540 magnetars (90% CL) should exist in the Milky Way. Due to the lower exposure times and photon counts of our Survey compared to the deep *XMM-Newton* and *Chandra* data used by Munro et al. (2008), a timing analysis of our sources is not as fruitful.

6. CONCLUSIONS

We have presented the results of the DGPS Phase-I observations, covering Galactic longitude $10 < |l| < 30$ deg and latitude $|b| < 0.5$ deg. These observations led to the identification of 928 unique X-ray sources (Tables 2 and 3) of which 358 (40%) were previously unknown to other X-ray surveys. Our results indicate a significant population of very faint X-ray sources below $F_X < 10^{-13}$ erg cm $^{-2}$ s $^{-1}$, emphasizing the necessity for sensitive, next generation, wide-field X-ray telescopes (e.g., *Athena*, Nandra et al. 2013; *AXIS*, Mushotzky et al. 2019; *Lynx*, Gaskin et al. 2019) to characterize the missing faint X-ray population in our Galaxy.

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This work made use of data supplied by the UK *Swift* Science Data Centre at the University of Leicester. This research has made use of the XRT Data Analysis Software (XRTDAS) developed under the responsibility of the ASI Science Data Center (ASDC), Italy. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France (DOI: 10.26093/cds/vizier). The original description of the VizieR service was published in A&AS 143, 23. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of data obtained from the Chandra Source Catalog, provided by the Chandra X-ray Center (CXC) as part of the Chandra Data Archive. This research has made use of data obtained from the 4XMM XMM-Newton serendipitous source catalogue compiled by the 10 institutes of the XMM-Newton Survey Science Centre selected by ESA. This research has made use of data and/or software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC), which is a service of the Astrophysics Science Division at NASA/GSFC.

Facilities: *Swift*/XRT

Software: HEASoft, XRTDAS, swifttools (Evans et al. 2022), PIMMS, Astropy (Astropy Collaboration et al. 2013)

APPENDIX

A. ADDITIONAL GP MOSAICS

Here we present additional mosaics of the DGPS observations in the SB, MB, and HB (Figures 21 and 22). These mosaics complement the FB image of the plane displayed in Figure 3.

B. COMPARISON OF SOURCE PROPERTIES IN GALACTIC COORDINATES

Here we present additional figures demonstrating how source properties vary with location in the Galactic

Plane. Figure 23 shows the hardness ratio for each source versus their location in Galactic coordinates. There appears to be a clustering of sources in HR_2 , but less so in HR_1 . We note that the hardness ratios are uncorrected for Galactic hydrogen column density, and that a line of sight absorption effect may be at play here.

In Figure 24 (left) we show a histogram of Galactic latitude for variable and constant sources. There is no discernible difference and a Kolmogorov-Smirnov test

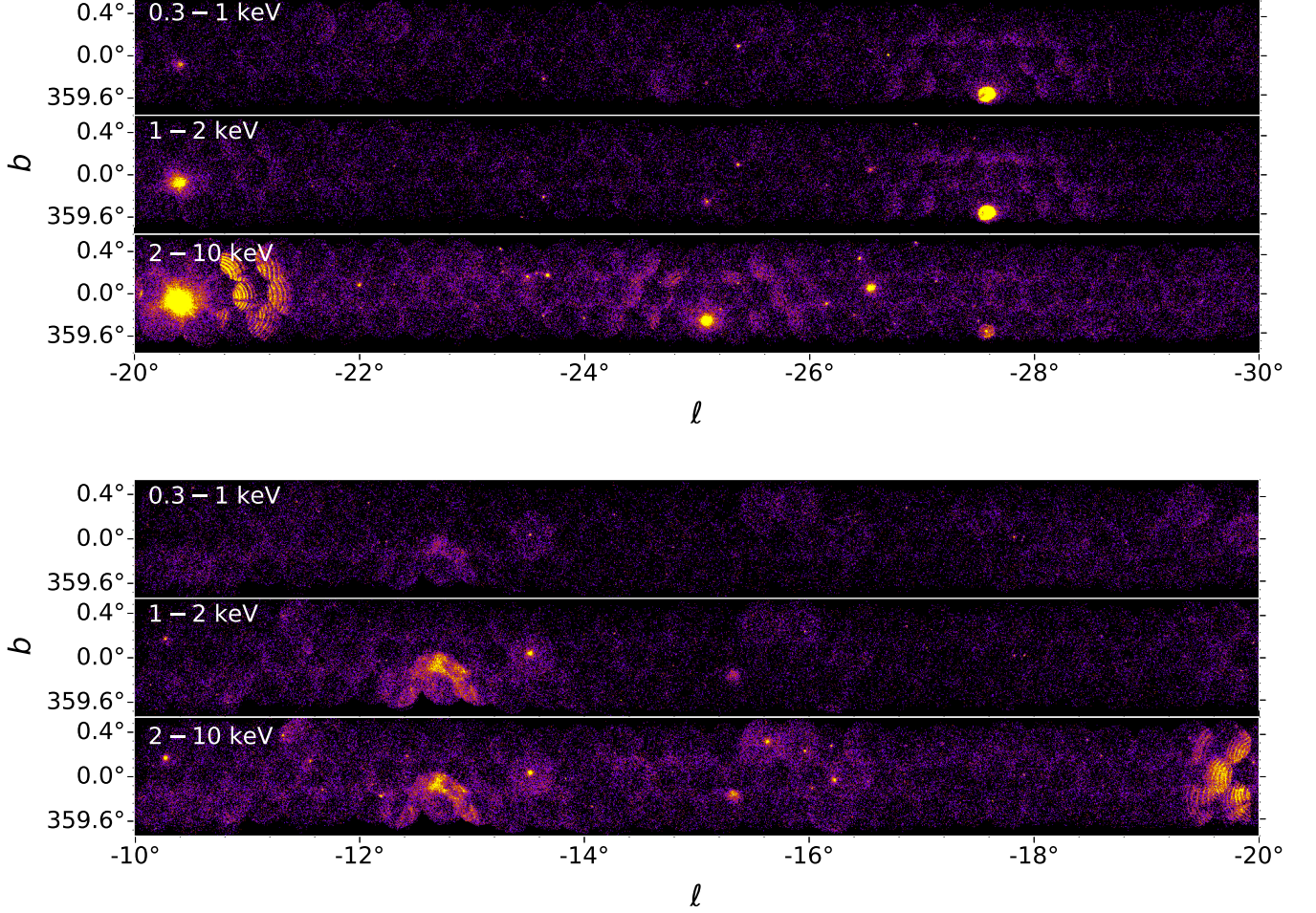


Figure 21. Mosaic of the GP at negative galactic longitudes in the SB (0.3 – 1 keV), MB (1 – 2 keV), and HB (2 – 10 keV). The background variation across the plane is due to higher exposure in regions with overlapping tiles and is not due to an intrinsic structure in the emission.

supports the null hypothesis (p -value = 0.7) that they are drawn from the same distribution.

We also show the source distribution in the hardness ratio plane separated between $|b| < 0.1$ deg and $|b| > 0.1$ deg (Figure 24; right). There is no obvious clustering of sources based on this separation criterion.

C. DERIVATION OF HARDNESS RATIOS FOR X-RAY SOURCE POPULATIONS

The majority of sources detected with the DGPS are faint, with a low number of source counts (i.e., < 30 cts), and, therefore, an analysis of their X-ray spectra does not provide strong constraints on the intrinsic source properties. Therefore, we utilized the X-ray hardness ratios, comparing the count rate between different energy bands, as a way to characterize source spectra despite the small number of counts. The hardness ratios HR_1

and HR_2 are defined as in Evans et al. (2014, 2020):

$$HR_1 = \frac{MB - SB}{MB + SB} \text{ and } HR_2 = \frac{HB - MB}{HB + MB}, \quad (C1)$$

where $SB = 0.3 - 1$ keV, $MB = 1 - 2$ keV, and $HB = 2 - 10$ keV count rate. The use of two hardness ratios is ideal for characterizing soft sources, and distinguishing between different source classifications.

In order to characterize the expected location of different source classes in the $HR_1 - HR_2$ plane we assumed spectral properties belonging to each class and varied the hydrogen column density (see also Rigoselli et al. 2022). We did this for HMXBs assuming a power-law spectrum with photon index $\Gamma = 1$, for stars assuming an APEC spectrum with temperature $kT = 1.085$ keV and 0.6 solar abundance, and for magnetars assuming a blackbody with $kT = 1$ keV. We varied the hydrogen column density uniformly between $\log(N_H/\text{cm}^{-2}) = 18 - 23$. We performed this calcula-

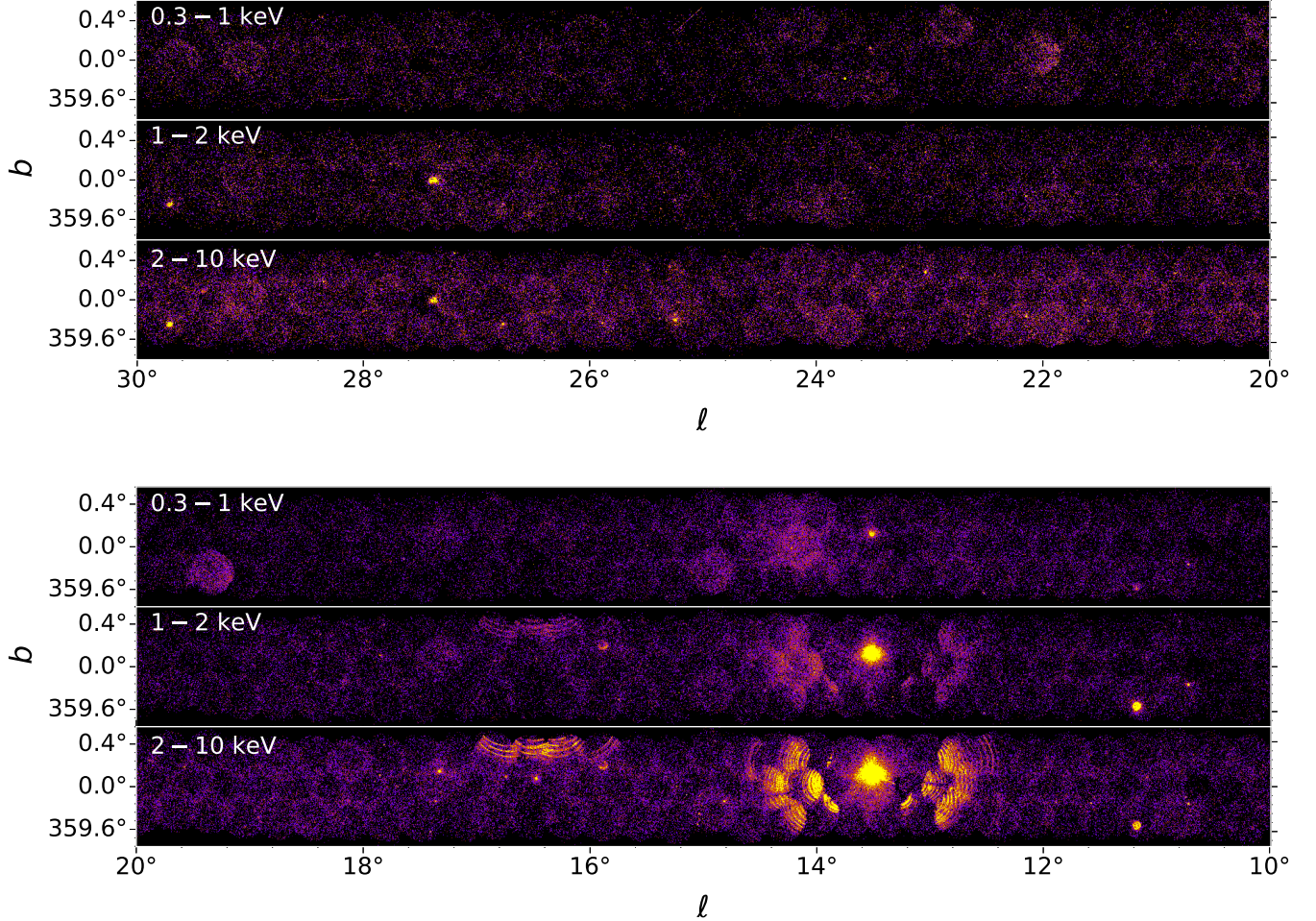


Figure 22. Mosaic of the GP at positive galactic longitudes in the SB (0.3 – 1 keV), MB (1 – 2 keV), and HB (2 – 10 keV).

tion using PIMMS to compute the *Swift*/XRT count rate in the SB, MB, and HB at each step in the grid. We then determined both hardness ratios based on these values. We show the tracks of each source type in Figure 17. The majority of stars have thermal plasma temperatures less than $kT < 1$ keV, such that they lie below the line in $HR_1 - HR_2$ space. Similarly, many HMXBs display harder spectra than $\Gamma = 1$, and for that reason lie above the line in $HR_1 - HR_2$ space. In the case of magnetars, their quiescent spectra are generally described by a softer blackbody with $kT \approx 0.4$ keV (Coti Zelati et al. 2017), suggesting that quiescent magnetars will lie below the line drawn.

We further checked the observed location of different source classes in the $HR_1 - HR_2$ plane by obtaining the observed mean flux and mean hardness ratios from the 2SXPS catalog. In Figure 17 (right) we show the observed locations for magnetars from the McGill Online Magnetar Catalog (Olausen & Kaspi 2014), HMXBs from Liu et al. (2006), LMXBs from Liu et al. (2007),

and IP CVs from Koji Mukai’s online catalog. As expected, many HMXBs lie above our computed line for $\Gamma = 1$. Of further note is the broad diversity observed for magnetars, possibly due to the observed outbursts by *Swift* and the spectral cooling of the sources during outburst (Coti Zelati et al. 2018).

D. TABLES OF CATALOG CONTENTS

Here we provide a description of the contents available through Vizier for the two DGPS catalog:

1. Main catalog (Table 2)
2. Sources not in LSXPS (Table 3)

In these tables, the energy bands are coordinated such that they agree with the Evans et al. (2022) definitions:

- band0 is the full band (FB; 0.3 – 1 keV)
- band1 is the soft band (SB; 0.3 – 10 keV)
- band2 is the medium band (MB; 1 – 2 keV)

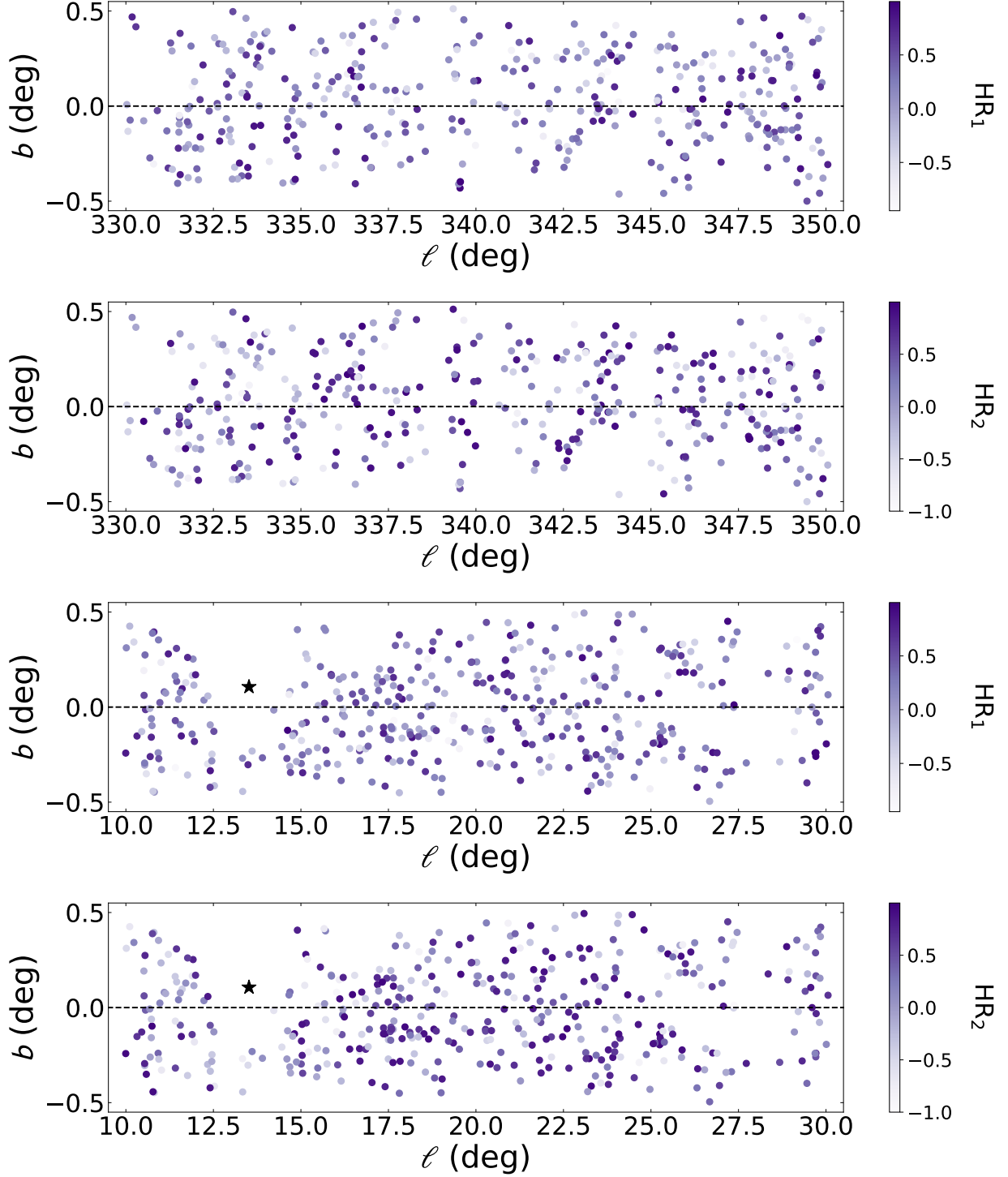


Figure 23. The location of DGPS sources in Galactic coordinates. The sources are colored based on their hardness ratio (either HR_1 or HR_2). The black star (bottom panels) marks a dominant source of stray light, leading to an obvious lack of sources in that region of the Survey.

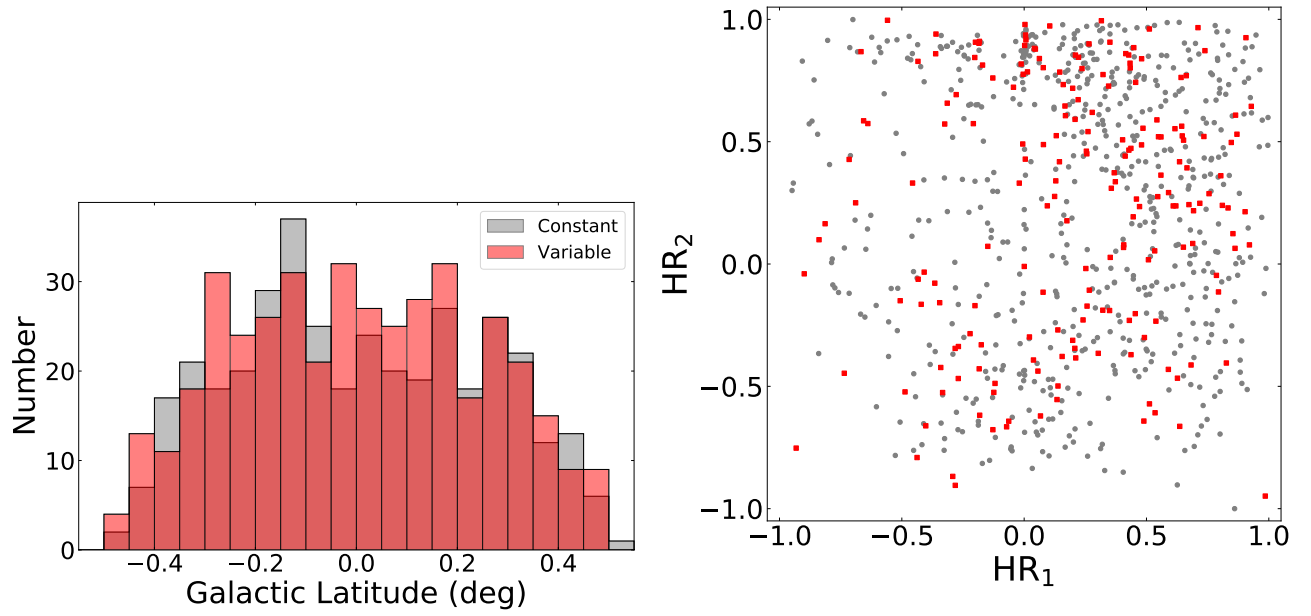


Figure 24. Left: Histogram of source location in Galactic latitude for constant (gray) and variable (red) sources (see §4.2). **Right:** Distribution of sources in the hardness ratio plane. Red squares are sources on the GP with $|b| < 0.1$ deg and gray circles are off-plane sources with $|b| > 0.1$ deg

- band3 is the HB (HB; 2 – 10 keV).

REFERENCES

- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Bahramian, A., Heinke, C. O., Kennea, J. A., et al. 2021, *MNRAS*, 501, 2790, doi: [10.1093/mnras/staa3868](https://doi.org/10.1093/mnras/staa3868)
- Barrett, P., Singh, K. P., & Mitchell, S. 1999, in *Astronomical Society of the Pacific Conference Series*, Vol. 157, Annapolis Workshop on Magnetic Cataclysmic Variables, ed. C. Hellier & K. Mukai, 180
- Belczyński, K., Mikołajewska, J., Munari, U., Ivison, R. J., & Friedjung, M. 2000, *A&AS*, 146, 407, doi: [10.1051/aas:2000280](https://doi.org/10.1051/aas:2000280)
- Beniamini, P., Hotokezaka, K., van der Horst, A., & Kouveliotou, C. 2019, *MNRAS*, 487, 1426, doi: [10.1093/mnras/stz1391](https://doi.org/10.1093/mnras/stz1391)
- Blackburn, J. K., Shaw, R. A., Payne, H. E., Hayes, J. J. E., & Heasarc. 1999, *FTOOLS: A general package of software to manipulate FITS files*. <http://ascl.net/9912.002>
- Blumer, H., & Safi-Harb, S. 2020, *ApJL*, 904, L19, doi: [10.3847/2041-8213/abc6a2](https://doi.org/10.3847/2041-8213/abc6a2)
- Boller, T., Freyberg, M. J., Trümper, J., et al. 2016, *A&A*, 588, A103, doi: [10.1051/0004-6361/201525648](https://doi.org/10.1051/0004-6361/201525648)
- Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, *SSRv*, 120, 165, doi: [10.1007/s11214-005-5097-2](https://doi.org/10.1007/s11214-005-5097-2)
- Chakrabarty, D., Grunsfeld, J. M., Prince, T. A., et al. 1993, *ApJL*, 403, L33, doi: [10.1086/186715](https://doi.org/10.1086/186715)
- Champion, D., Cognard, I., Cruces, M., et al. 2020, *MNRAS*, 498, 6044, doi: [10.1093/mnras/staa2764](https://doi.org/10.1093/mnras/staa2764)
- Colpi, M., Geppert, U., & Page, D. 2000, *ApJL*, 529, L29, doi: [10.1086/312448](https://doi.org/10.1086/312448)
- Coti Zelati, F., Rea, N., Pons, J. A., Campana, S., & Esposito, P. 2018, *MNRAS*, 474, 961, doi: [10.1093/mnras/stx2679](https://doi.org/10.1093/mnras/stx2679)
- Coti Zelati, F., Rea, N., Turolla, R., et al. 2017, *MNRAS*, 471, 1819, doi: [10.1093/mnras/stx1700](https://doi.org/10.1093/mnras/stx1700)
- Dean, A. J., Bazzano, A., Hill, A. B., et al. 2005, *A&A*, 443, 485, doi: [10.1051/0004-6361:20053513](https://doi.org/10.1051/0004-6361:20053513)
- Degenaar, N., & Wijnands, R. 2009, *A&A*, 495, 547, doi: [10.1051/0004-6361:200810654](https://doi.org/10.1051/0004-6361:200810654)
- . 2010, *A&A*, 524, A69, doi: [10.1051/0004-6361/201015322](https://doi.org/10.1051/0004-6361/201015322)
- D’Elia, V., Perri, M., Puccetti, S., et al. 2013, *A&A*, 551, A142, doi: [10.1051/0004-6361/201220863](https://doi.org/10.1051/0004-6361/201220863)
- Eker, Z., Ak, N. F., Bilir, S., et al. 2008, *MNRAS*, 389, 1722, doi: [10.1111/j.1365-2966.2008.13670.x](https://doi.org/10.1111/j.1365-2966.2008.13670.x)
- Evans, I. N., Primini, F. A., Glotfelty, K. J., et al. 2010, *ApJS*, 189, 37, doi: [10.1088/0067-0049/189/1/37](https://doi.org/10.1088/0067-0049/189/1/37)
- Evans, P. A., Page, K. L., Beardmore, A. P., et al. 2022, *arXiv e-prints*, arXiv:2208.14478. <https://arxiv.org/abs/2208.14478>
- Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, *MNRAS*, 397, 1177, doi: [10.1111/j.1365-2966.2009.14913.x](https://doi.org/10.1111/j.1365-2966.2009.14913.x)
- Evans, P. A., Osborne, J. P., Beardmore, A. P., et al. 2014, *ApJS*, 210, 8, doi: [10.1088/0067-0049/210/1/8](https://doi.org/10.1088/0067-0049/210/1/8)
- Evans, P. A., Page, K. L., Osborne, J. P., et al. 2020, *ApJS*, 247, 54, doi: [10.3847/1538-4365/ab7db9](https://doi.org/10.3847/1538-4365/ab7db9)
- Eyles-Ferris, R. A. J., Starling, R. L. C., O’Brien, P. T., & Evans, P. A. 2022, *arXiv e-prints*, arXiv:2207.04067. <https://arxiv.org/abs/2207.04067>
- Flesch, E. W. 2021, *arXiv e-prints*, arXiv:2105.12985. <https://arxiv.org/abs/2105.12985>
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, *A&A*, 649, A1, doi: [10.1051/0004-6361/202039657](https://doi.org/10.1051/0004-6361/202039657)
- Gaskin, J. A., Swartz, D. A., Vikhlinin, A., et al. 2019, *Journal of Astronomical Telescopes, Instruments, and Systems*, 5, 021001, doi: [10.1117/1.JATIS.5.2.021001](https://doi.org/10.1117/1.JATIS.5.2.021001)
- Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, *ApJ*, 611, 1005, doi: [10.1086/422091](https://doi.org/10.1086/422091)
- Giacconi, R., Kellogg, E., Gorenstein, P., Gursky, H., & Tananbaum, H. 1971, *ApJL*, 165, L27, doi: [10.1086/180711](https://doi.org/10.1086/180711)
- Ginsburg, A., Sipőcz, B. M., Brasseur, C. E., et al. 2019, *AJ*, 157, 98, doi: [10.3847/1538-3881/aafc33](https://doi.org/10.3847/1538-3881/aafc33)
- Gioia, I. M., Maccaro, T., Schild, R. E., et al. 1990, *ApJS*, 72, 567, doi: [10.1086/191426](https://doi.org/10.1086/191426)
- Goad, M. R., Tyler, L. G., Beardmore, A. P., et al. 2007, *A&A*, 476, 1401, doi: [10.1051/0004-6361:20078436](https://doi.org/10.1051/0004-6361:20078436)
- Gobat, C., Yang, H., Kargaltsev, O., Hare, J., & Volkov, I. 2022, *Research Notes of the American Astronomical Society*, 6, 163, doi: [10.3847/2515-5172/ac8937](https://doi.org/10.3847/2515-5172/ac8937)
- Gorgone, N. M., Kouveliotou, C., Negoro, H., et al. 2019, *ApJ*, 884, 168, doi: [10.3847/1538-4357/ab3e43](https://doi.org/10.3847/1538-4357/ab3e43)
- Gorgone, N. M., Woudt, P. A., Buckley, D., et al. 2021, *arXiv e-prints*, arXiv:2103.14800. <https://arxiv.org/abs/2103.14800>
- Grimm, H. J., Gilfanov, M., & Sunyaev, R. 2002, *A&A*, 391, 923, doi: [10.1051/0004-6361:20020826](https://doi.org/10.1051/0004-6361:20020826)

Table 2. Contents of the main DGPS catalog (see also [Evans et al. 2022](#)). The catalog is accessible through VizieR ([Ochsenbein et al. 2000](#)).

Column	Units	Description
IAU Name		IAU name in format “DGPS JHHMMSS.S \pm DDMMSS”
LSXPS_ID		Numerical unique source identifier within LSXPS
RA	deg	Right Ascension (J2000)
DEC	deg	Declination (J2000)
Err90	arcsec	90% source position uncertainty
l	deg	Galactic longitude
b	deg	Galactic latitude
Rate_band0	cts s ⁻¹	FB (0.3 – 10 keV) count rate
Rate_band0_pos	cts s ⁻¹	Positive count rate error
Rate_band0_neg	cts s ⁻¹	Negative count rate error
Rate_band1	cts s ⁻¹	SB (0.3 – 1 keV) count rate
Rate_band1_pos	cts s ⁻¹	Positive count rate error
Rate_band1_neg	cts s ⁻¹	Negative count rate error
Rate_band2	cts s ⁻¹	MB (1 – 2 keV) count rate
Rate_band2_pos	cts s ⁻¹	Positive count rate error
Rate_band2_neg	cts s ⁻¹	Negative count rate error
Rate_band3	cts s ⁻¹	HB (2 – 10 keV) count rate
Rate_band3_pos	cts s ⁻¹	Positive count rate error
Rate_band3_neg	cts s ⁻¹	Negative count rate error
FixedPowUnabsFlux	erg cm ⁻² s ⁻¹	FB X-ray flux (0.3 – 10 keV) assuming a photon index $\Gamma = 1.7$
FixedPowUnabsFlux_pos	erg cm ⁻² s ⁻¹	Positive flux error
FixedPowUnabsFlux_neg	erg cm ⁻² s ⁻¹	Negative flux error
R_Flux		Ratio of peak-to-mean flux
HR1		Hardness ratio between the MB and SB
HR1_pos		Positive error on hardness ratio
HR1_neg		Negative error of hardness ratio
HR2		Hardness ratio between the HB and MB
HR2_pos		Positive error on hardness ratio
HR2_neg		Negative error of hardness ratio
GalacticNH	cm ⁻²	Hydrogen column density in the source direction (Willingale et al. 2013)
Exposure	s	Cumulative DGPS exposure at the source position
X-ray Match		“Y” if known X-ray source, otherwise “N”
Variable		“Y” if known source is variable, otherwise “N”

Guillochon, J., Parrent, J., Kelley, L. Z., & Margutti, R. 2017, *ApJ*, 835, 64, doi: [10.3847/1538-4357/835/1/64](#)

Hasinger, G., Burg, R., Giacconi, R., et al. 1993, *A&A*, 275, 1

Hertz, P., & Grindlay, J. E. 1984, *ApJ*, 278, 137, doi: [10.1086/161775](#)

HI4PI Collaboration, Ben Bekhti, N., Flöer, L., et al. 2016, *A&A*, 594, A116, doi: [10.1051/0004-6361/201629178](#)

Hu, C.-P., Begiçarslan, B., Güver, T., et al. 2020, *ApJ*, 902, 1, doi: [10.3847/1538-4357/abb3c9](#)

Israel, G. L., Rea, N., Mangano, V., et al. 2004, *ApJL*, 603, L97, doi: [10.1086/382875](#)

Jackim, R., Szkody, P., Hazelton, B., & Benson, N. C. 2020, *Research Notes of the American Astronomical Society*, 4, 219, doi: [10.3847/2515-5172/abd104](#)

Jonker, P. G., Bassa, C. G., Nelemans, G., et al. 2011, *ApJS*, 194, 18, doi: [10.1088/0067-0049/194/2/18](#)

Kennea, J. A., Coe, M. J., Evans, P. A., Waters, J., & Jasko, R. E. 2018, *ApJ*, 868, 47, doi: [10.3847/1538-4357/aae839](#)

Kraft, R. P., Burrows, D. N., & Nousek, J. A. 1991, *ApJ*, 374, 344, doi: [10.1086/170124](#)

Krivonos, R. A., Tsygankov, S. S., Mereminskiy, I. A., et al. 2017, *MNRAS*, 470, 512, doi: [10.1093/mnras/stx1276](#)

Table 3. Contents of the non-LSXPS catalog. These are sources with no LSXPS counterpart. The catalog is accessible through VizieR (Ochsenbein et al. 2000).

Column	Units	Description
RA	deg	Right Ascension (J2000)
DEC	deg	Declination (J2000)
Err90	arcsec	90% source position uncertainty
X-ray Match		“Y” if known X-ray source, otherwise “N”
band0_KNB91_Detected		Source retrospectively detected in FB using LSXPS Upper Limit Server (0 = not detected; 1 = detected)
band3_KNB91_Detected		Source retrospectively detected in HB using LSXPS Upper Limit Server
band2_KNB91_Detected		Source retrospectively detected in MB using LSXPS Upper Limit Server
band1_KNB91_Detected		Source retrospectively detected in SB using LSXPS Upper Limit Server
band0_IsDetected		Source blindly detected in FB through iterative source detection on mosaics (0 = not detected; 1 = detected)
band3_IsDetected		Source blindly detected in HB through iterative source detection on mosaics
band2_IsDetected		Source blindly detected in MB through iterative source detection on mosaics
band1_IsDetected		Source blindly detected in SB through iterative source detection on mosaics
Rate_band0	cts s ⁻¹	FB (0.3 – 10 keV) count rate
Rate_band0_pos	cts s ⁻¹	Positive count rate error
Rate_band0_neg	cts s ⁻¹	Negative count rate error
Rate_band3	cts s ⁻¹	HB (2 – 10 keV) count rate
Rate_band3_pos	cts s ⁻¹	Positive count rate error
Rate_band3_neg	cts s ⁻¹	Negative count rate error
Rate_band2	cts s ⁻¹	MB (1 – 2 keV) count rate
Rate_band2_pos	cts s ⁻¹	Positive count rate error
Rate_band2_neg	cts s ⁻¹	Negative count rate error
Rate_band1	cts s ⁻¹	SB (0.3 – 1 keV) count rate
Rate_band1_pos	cts s ⁻¹	Positive count rate error
Rate_band1_neg	cts s ⁻¹	Negative count rate error
FixedPowUnabsFlux	erg cm ⁻² s ⁻¹	FB X-ray flux (0.3 – 10 keV) assuming a photon index $\Gamma = 1.7$
FixedPowUnabsFlux_pos	erg cm ⁻² s ⁻¹	Positive flux error
FixedPowUnabsFlux_neg	erg cm ⁻² s ⁻¹	Negative flux error

La Parola, V., Cusumano, G., Segreto, A., et al. 2013, *ApJL*, 775, L24, doi: [10.1088/2041-8205/775/1/L24](https://doi.org/10.1088/2041-8205/775/1/L24)

Lacy, M., Baum, S. A., Chandler, C. J., et al. 2020, *PASP*, 132, 035001, doi: [10.1088/1538-3873/ab63eb](https://doi.org/10.1088/1538-3873/ab63eb)

Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, *MNRAS*, 379, 1599, doi: [10.1111/j.1365-2966.2007.12040.x](https://doi.org/10.1111/j.1365-2966.2007.12040.x)

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2006, *A&A*, 455, 1165, doi: [10.1051/0004-6361:20064987](https://doi.org/10.1051/0004-6361:20064987)

—. 2007, *A&A*, 469, 807, doi: [10.1051/0004-6361:20077303](https://doi.org/10.1051/0004-6361:20077303)

Luo, B., Brandt, W. N., Xue, Y. Q., et al. 2017, *ApJS*, 228, 2, doi: [10.3847/1538-4365/228/1/2](https://doi.org/10.3847/1538-4365/228/1/2)

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, *AJ*, 129, 1993, doi: [10.1086/428488](https://doi.org/10.1086/428488)

Markwardt, C. B., Ransom, S., Woods, P., et al. 2003, *The Astronomer’s Telegram*, 188, 1

Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, *AJ*, 125, 984, doi: [10.1086/345888](https://doi.org/10.1086/345888)

Moretti, A., Pagani, C., Cusumano, G., et al. 2009, *A&A*, 493, 501, doi: [10.1051/0004-6361:200811197](https://doi.org/10.1051/0004-6361:200811197)

Muno, M. P., Gaensler, B. M., Nechita, A., Miller, J. M., & Slane, P. O. 2008, *ApJ*, 680, 639, doi: [10.1086/527316](https://doi.org/10.1086/527316)

Muno, M. P., Lu, J. R., Baganoff, F. K., et al. 2005a, *ApJ*, 633, 228, doi: [10.1086/444586](https://doi.org/10.1086/444586)

Muno, M. P., Pfahl, E., Baganoff, F. K., et al. 2005b, *ApJL*, 622, L113, doi: [10.1086/429721](https://doi.org/10.1086/429721)

Mushotzky, R., Aird, J., Barger, A. J., et al. 2019, in *Bulletin of the American Astronomical Society*, Vol. 51, 107. <https://arxiv.org/abs/1903.04083>

Nandra, K., Barret, D., Barcons, X., et al. 2013, *arXiv e-prints*, arXiv:1306.2307. <https://arxiv.org/abs/1306.2307>

- Nebot Gómez-Morán, A., & Oskinova, L. M. 2018, *A&A*, 620, A89, doi: [10.1051/0004-6361/201833453](https://doi.org/10.1051/0004-6361/201833453)
- Nebot Gómez-Morán, A., Motch, C., Barcons, X., et al. 2013, *A&A*, 553, A12, doi: [10.1051/0004-6361/201220308](https://doi.org/10.1051/0004-6361/201220308)
- Ng, C. Y., Slane, P. O., Gaensler, B. M., & Hughes, J. P. 2008, *ApJ*, 686, 508, doi: [10.1086/591146](https://doi.org/10.1086/591146)
- Ochsenbein, F., Bauer, P., & Marcout, J. 2000, *A&AS*, 143, 23, doi: [10.1051/aas:2000169](https://doi.org/10.1051/aas:2000169)
- O’Connor, B., Göğüş, E., Huppenkothen, D., et al. 2022, *ApJ*, 927, 139, doi: [10.3847/1538-4357/ac5032](https://doi.org/10.3847/1538-4357/ac5032)
- O’Connor, B., Brink, J., Buckley, D. A. H., et al. 2023, arXiv e-prints, arXiv:2306.05576, doi: [10.48550/arXiv.2306.05576](https://doi.org/10.48550/arXiv.2306.05576)
- Olausen, S. A., & Kaspi, V. M. 2014, *ApJS*, 212, 6, doi: [10.1088/0067-0049/212/1/6](https://doi.org/10.1088/0067-0049/212/1/6)
- Polidan, R. S., Pollard, G. S. G., Sanford, P. W., & Locke, M. C. 1978, *Nature*, 275, 296, doi: [10.1038/275296a0](https://doi.org/10.1038/275296a0)
- Pretorius, M. L., Knigge, C., & Schwope, A. D. 2013, *MNRAS*, 432, 570, doi: [10.1093/mnras/stt499](https://doi.org/10.1093/mnras/stt499)
- Revnivtsev, M., Sazonov, S., Churazov, E., et al. 2009, *Nature*, 458, 1142, doi: [10.1038/nature07946](https://doi.org/10.1038/nature07946)
- Reynolds, M. T., Miller, J. M., Maitra, D., et al. 2013, *The Astronomer’s Telegram*, 5200, 1
- Rigoselli, M., Mereghetti, S., & Tresoldi, C. 2022, *MNRAS*, 509, 1217, doi: [10.1093/mnras/stab2974](https://doi.org/10.1093/mnras/stab2974)
- Shaw, A. W., Heinke, C. O., Maccarone, T. J., et al. 2020, *MNRAS*, 492, 4344, doi: [10.1093/mnras/staa105](https://doi.org/10.1093/mnras/staa105)
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163, doi: [10.1086/498708](https://doi.org/10.1086/498708)
- Sugizaki, M., Mitsuda, K., Kaneda, H., et al. 2001, *ApJS*, 134, 77, doi: [10.1086/320358](https://doi.org/10.1086/320358)
- Tranin, H., Godet, O., Webb, N., & Primorac, D. 2022, *A&A*, 657, A138, doi: [10.1051/0004-6361/202141259](https://doi.org/10.1051/0004-6361/202141259)
- Traulsen, I., Schwope, A. D., Lamer, G., et al. 2020, *A&A*, 641, A137, doi: [10.1051/0004-6361/202037706](https://doi.org/10.1051/0004-6361/202037706)
- Ueda, Y., Takahashi, T., Inoue, H., et al. 1999, *ApJ*, 518, 656, doi: [10.1086/307291](https://doi.org/10.1086/307291)
- Wang, Q. D., Gotthelf, E. V., & Lang, C. C. 2002, *Nature*, 415, 148, doi: [10.1038/415148a](https://doi.org/10.1038/415148a)
- Webb, N. A., Coriat, M., Traulsen, I., et al. 2020, *A&A*, 641, A136, doi: [10.1051/0004-6361/201937353](https://doi.org/10.1051/0004-6361/201937353)
- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, 143, 9, doi: [10.1051/aas:2000332](https://doi.org/10.1051/aas:2000332)
- Wijnands, R., in’t Zand, J. J. M., Rupen, M., et al. 2006, *A&A*, 449, 1117, doi: [10.1051/0004-6361:20054129](https://doi.org/10.1051/0004-6361:20054129)
- Willingale, R., Starling, R. L. C., Beardmore, A. P., Tanvir, N. R., & O’Brien, P. T. 2013, *MNRAS*, 431, 394, doi: [10.1093/mnras/stt175](https://doi.org/10.1093/mnras/stt175)
- Yang, H., Hare, J., Kargaltsev, O., et al. 2022, arXiv e-prints, arXiv:2206.13656, <https://arxiv.org/abs/2206.13656>
- Yang, H., Hare, J., Volkov, I., & Kargaltsev, O. 2021, *Research Notes of the American Astronomical Society*, 5, 102, doi: [10.3847/2515-5172/abfcd4](https://doi.org/10.3847/2515-5172/abfcd4)