

StrayCats: A catalog of NuSTAR Stray Light Observations

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ABSTRACT

We present **StrayCats**: a catalog of *NuSTAR* stray light observations of X-ray sources. Stray light observations arise for sources 1–4° away from the telescope pointing direction. At this off-axis angle, X-rays pass through a gap between optics and aperture stop and so do not interact with the X-ray optics but, instead, directly illuminate the *NuSTAR* focal plane. We have systematically identified and examined over 1400 potential observations resulting in a catalog of 436 telescope fields and 78 stray light sources that have been identified. The sources identified include historically known persistently bright X-ray sources, X-ray binaries in outburst, pulsars, and Type I X-ray bursters. In this paper we present an overview of the catalog and how we identified the **StrayCats** sources and the analysis techniques required to produce high level science products. Finally, we present a few brief examples of the science quality of these unique data.

Keywords: surveys

1. INTRODUCTION

Compact objects in our galaxy provide an excellent laboratory in which to study matter in extreme conditions. Of most interest are neutron stars (NS) and black holes (BH) in binary systems, where the compact object accretes material from its companion star either through Roche lobe overflow or through a stellar wind from the companion. The inflowing material forms an accretion disk around the compact object with tempera-

tures hot enough to produce copious amounts of thermal X-rays and giving rise to a corona of non-thermal electrons emitting in the hard X-ray band.

The hard X-ray ($E \geq 3$ keV) bandpass provides essential diagnostic information on the accretion state of the source and clues to the nature of the compact object in the system. The high energy ($E \geq 20$ keV) spectrum of the X-ray binaries in the Galactic plane have been surveyed with low spectral resolution instruments on the *INTERNATIONAL Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*, Winkler et al. 2003) and the Neil Gehrels *Swift* Observatory (Gehrels et al. 2004).

Targeted observations with *NuSTAR* (The *Nuclear Spectroscopic Telescope ARray* Harrison et al. 2013) have demonstrated the diagnostic power of a sensitive

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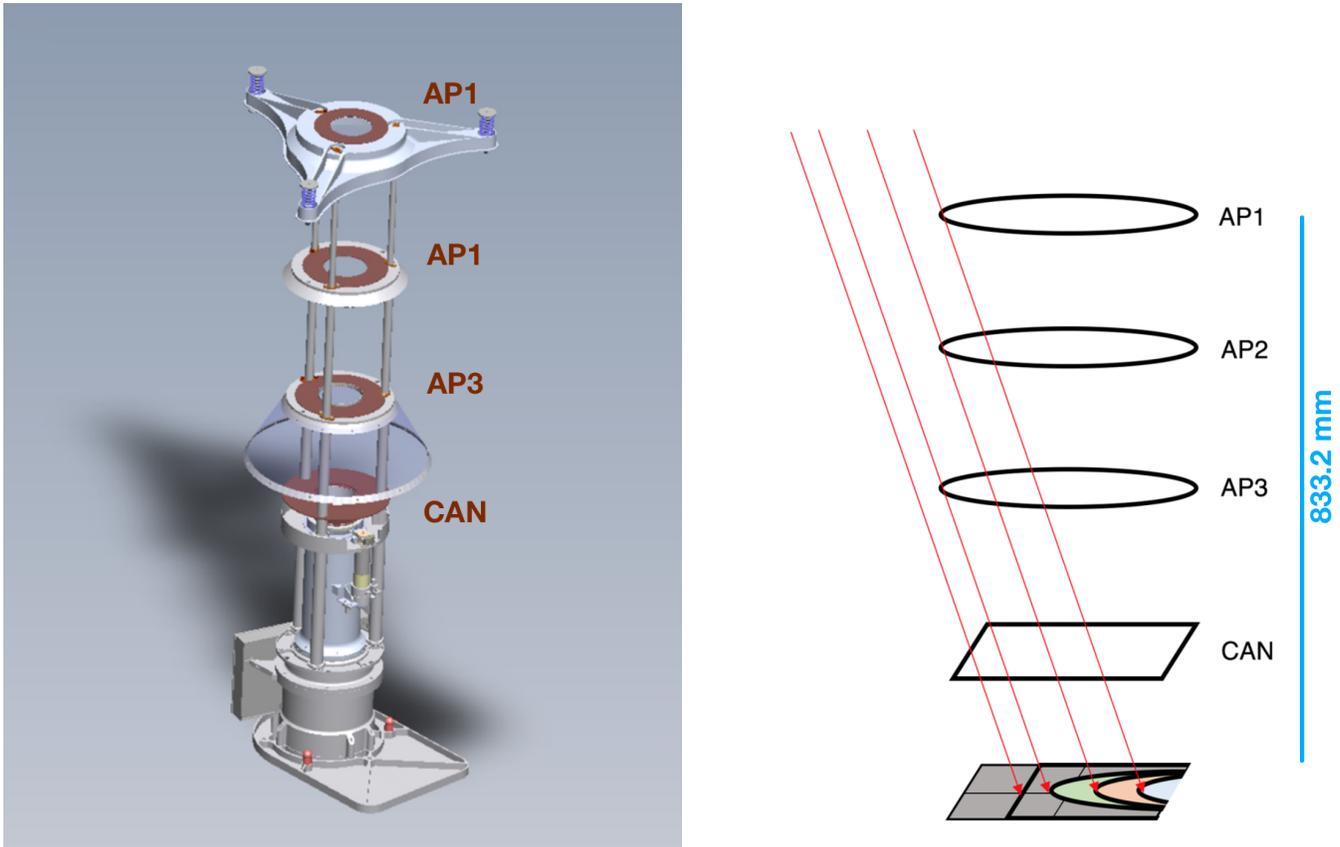


Figure 1. Schematic of the path of stray light photons. (*Left*): CAD rendering of the focal plane and the aperture stop assembly. (*Right*): Red traces show the stray light paths that survive to the focal plane after passing around the aperture stop (AP1, AP2, and AP3) rings and the “can” housing the detectors. The height offset from the focal plane to AP1 is shown on the right. Figures adapted from Madsen et al. (2017a).

instrument over the 3–80 keV bandpass. However, when these sources go into an X-ray bright state they result in extremely high count rates and correspondingly high telemetry loads. Because of this, many observations of bright sources are short in duration (≈ 20 -ks) to allow the spacecraft to transmit the data down to the ground without overwriting the storage drives onboard. Unlike *Swift*, *NuSTAR* is not a rapidly slewing instrument, so repeated short monitoring observations of the same target are not generally possible due to scheduling constraints and require “Target of Opportunity” programs that can take days or a week to get on target once an observation is triggered.

Fortunately, *NuSTAR* can also serendipitously observe bright X-ray binaries through “stray light.” While *NuSTAR* is well-known as the first focusing hard X-ray satellite in orbit, the open geometry of the mast that connects the optics to the detectors allows for the possibility of stray light (light that has not been focused by the optics) illuminating detectors. This is typically referred to as “aperture flux” since the light passes through the open area of the aperture stops (see Figure

1) and occurs for sources that are roughly $1\text{--}4^\circ$ from the center of the *NuSTAR* field-of-view (Madsen et al. 2017a).

For most *NuSTAR* observations, the dominant source of aperture X-ray emission is the cosmic X-ray background (hereafter “aperture” CXB, or aCXB). This is the superposition of X-ray light from a uniform background of (unresolved) AGN in the $1\text{--}4^\circ$ annulus. This contribution to the *NuSTAR* background has been well documented (e.g., Wik et al. 2014) and is generally described by a spatial gradient in the *NuSTAR* background across the field of view.

When stray light comes from a single off-axis source the emission geometry is much simpler. Instead of a “gradient” in the background, we instead observe an easily-identified shadow of the aperture stop sharply cutting off the source (Figure 2). Because the X-rays do not interact with the *NuSTAR* optics, the response of the instrument is somewhat more straightforward as well. This comes at the reduced effective area for stray light observations compared with pointed observations.

Recently, observations *intentionally* placing a target so that it is observed via stray light have been undertaken for a number of bright X-ray binaries. This was done to provide contiguous observations while reducing the count rate (and thus the telemetry load) and to potentially extend the spectral range covered by *NuSTAR* beyond the 78.4 keV cutoff in the optics response. One example is the observation of the Crab nebula seen via stray light which allows for a simple, unique measurement of the spectral shape and flux of the Crab (Madsen et al. 2017b).

In this paper we describe the *NuSTAR* StrayCats¹: a catalog of *NuSTAR* stray light observations (both serendipitous and intentional) throughout the mission. In §2 we describe the preliminary data processing and the stray light identification methodology. In §3 we discuss the particular response files needed for StrayCats spectroscopic analysis as well as the tools that we have developed for streamlining the extraction of StrayCats high level science products, such as spectra and lightcurves. In §4 we give an overview of the catalog itself, including source lists and demographics, and in §5 we present preliminary analyses of several StrayCats data sets to give a demonstration of the type and quality of data. However, we generally will reserve a more detailed follow-up analysis of individual sources to future work.

2. DATA PROCESSING AND STRAY LIGHT IDENTIFICATION

Identifying observations contaminated by stray light is non-trivial, due to the variability in the *NuSTAR* background contributions, the presence of multiple sources in the field of view (FoV), and the different amounts of detector area illuminated by the stray light sources at different off-axis angles. We utilized two complementary methods: an *a priori* approach based on the location of known bright X-ray sources detected by *Swift*-BAT and *INTEGRAL*; and a “bottom up” approach using a statistical approach to identify potential stray light candidate observations.

2.1. An *a priori* approach

We use the *Swift*-BAT 105-month all-sky catalog (Oh et al. 2018) of sources along with the *INTEGRAL* 9-year galactic plane ($|b| < 17.5^\circ$) catalog (Krivonos et al. 2012). These catalogs are both used by the *NuSTAR* Science Operations Center (SOC) to identify and mitigate sources of stray light contamination for science observations. To estimate the amount of stray light in a

given observation, we utilize the `nustar_stray_light` IDL code². This contains a model of the size, shape, and relative positions of the focal plane structures (seen in Fig 1) and the bench that holds the *NuSTAR* optics. For a given *NuSTAR* pointing orientation and a given stray light target, the “shadow” from the aperture stop and the optics bench are projected onto the focal plane for each detector to estimate the stray light contribution.

Estimating the strength of the stray light is done by extrapolating the measured spectrum in the *Swift*-BAT / *INTEGRAL* bands down into the *NuSTAR* straylight bandpass (3–20 keV); a process which frequently results in overestimating the *NuSTAR* flux for sources that have curvature in the hard X-ray bandpass or have a predominantly thermal spectrum. Nonetheless, there is usually a reasonable match between the brightest catalog sources and the stray light in *NuSTAR*.

As a first step, we produce an estimate catalog of all *NuSTAR* observations within 4° of a “bright” X-ray source in one of our reference catalogs where we typically define the minimum flux level for a persistent, bright source to be > 5 mCrab as measured by the respective instruments on *INTEGRAL* and *Swift*. This results in several hundred *NuSTAR* stray light candidate observations. For each observation we produce the estimated stray light map, and visually compare the results to the observed data. As many of these sources are variable and the internal model of the structures may not be entirely accurate, this does require a human-in-the-loop for positive identification of a stray light candidate. While this process is able to positively identify dozens of stray light observations, it is both inefficient and does not catch any stray light observations of new or intermittently transient sources.

2.2. A more statistical approach

Rather than requiring any prior knowledge of a nearby bright target, we instead use the observed data to identify stray light candidates. Since the area of the sky accessible to each *NuSTAR* telescope for stray light are different, we treat the two separately.

We first remove contributions from the primary target by first excising all counts from within $3'$ of the estimated target location. This large exclusion region attempts to account for any astrometric errors between the estimated J2000 coordinates for the target and where the target is actually observed to reduce the “PSF bleed” from bright primary targets. For bright primary tar-

¹ <https://nustarstraycats.github.io/>

² <https://github.com/NuSTAR/nustar-gen-utils>

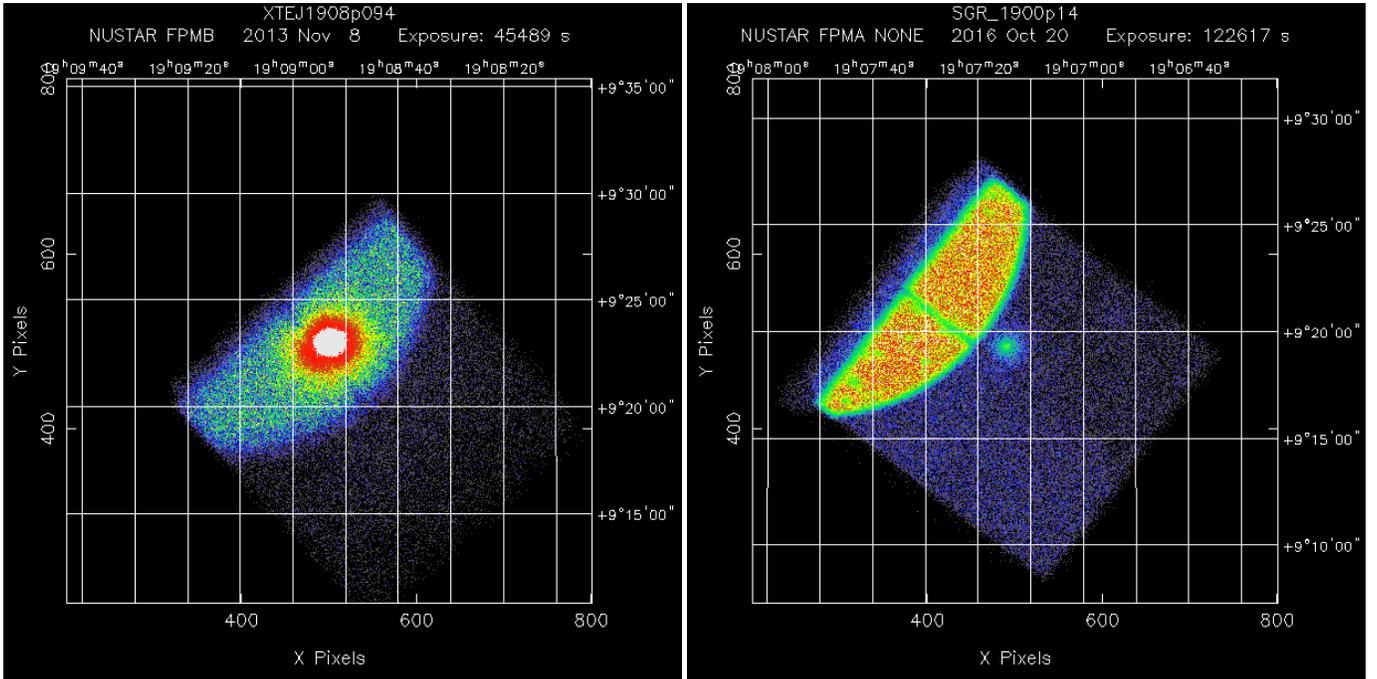


Figure 2. 3–79 keV *NuSTAR* quick look images in “sky” coordinates from the HEASARC showing the stray light from GRS1915+105 along with the X-rays from the targeted source for two epochs (the *intended* source target name is given in the figure titles). Unlike the point source which is contained on one detector, the stray light spans multiple detectors on the *NuSTAR* focal plane.

gets (those with focused count rates > 100 cps) we find that the primary source dominates over the entire FoV, so we exclude these observations from consideration. Once this is complete, we compute the 3–20 keV count rate for all four detectors on each FPM and combine them to account for the fact that the stray light patterns tend to illuminate one side (or all) of the FoV.

For the remaining sources we flag observations where the count rate measured by a particular detector combination deviates from the mean. Unfortunately, due to extended sources, fields with multiple point sources, and intrinsic variation in the *NuSTAR* background, all of the candidate **StrayCats** observations had to be further checked by eye. We do this by constructing DET1 images in the 3–20 keV bandpass and look for the signatures of stray light. Figure 3 shows a selection of **StrayCats** observations where the SL can clearly be seen.

We continue the iterative process to identify candidates described above until all of the candidates appear to be simply variations in the *NuSTAR* background and not clearly associated with stray light. Overall, more than 1400 candidate stray light observations were checked by hand for the presence of stray light.

We feel confident that we have thus identified all of the stray light sources that could (a) produce a strong enough signal to impact science analysis of the primary

target and (b) be useful for scientific analysis in their own right. These fully vetted **StrayCats** sources form the basis for the full catalog. In addition to stray light, we have also identified a number of observations where targets just outside of the *NuSTAR* FoV result in “ghost rays”, where photons perform a single-bounce off of the *NuSTAR* optics rather than the double-bounce for focused emission (Madsen et al. 2017a). These are included in **StrayCats** for completeness.

We do note that this human-in-the-loop approach does result in a bias where faint stray light sources are more easily seen during long exposures. Similarly, sources with transient flaring behavior on timescales of a few 100-s will be difficult to identify unless the quiescent flux level is greater than that of the standard *NuSTAR* background. We anticipate that a further investigation for transients could produce a number of additional **StrayCats** candidates, though this is beyond the scope of this first work.

3. THE **StrayCats** CATALOG

The **StrayCats** Catalog is intended to be used by observers looking for serendipitous observations of bright galactic (including the LMC and SMC) sources beyond what is available through traditional monitoring observations. The catalog is available via a simple web inter-

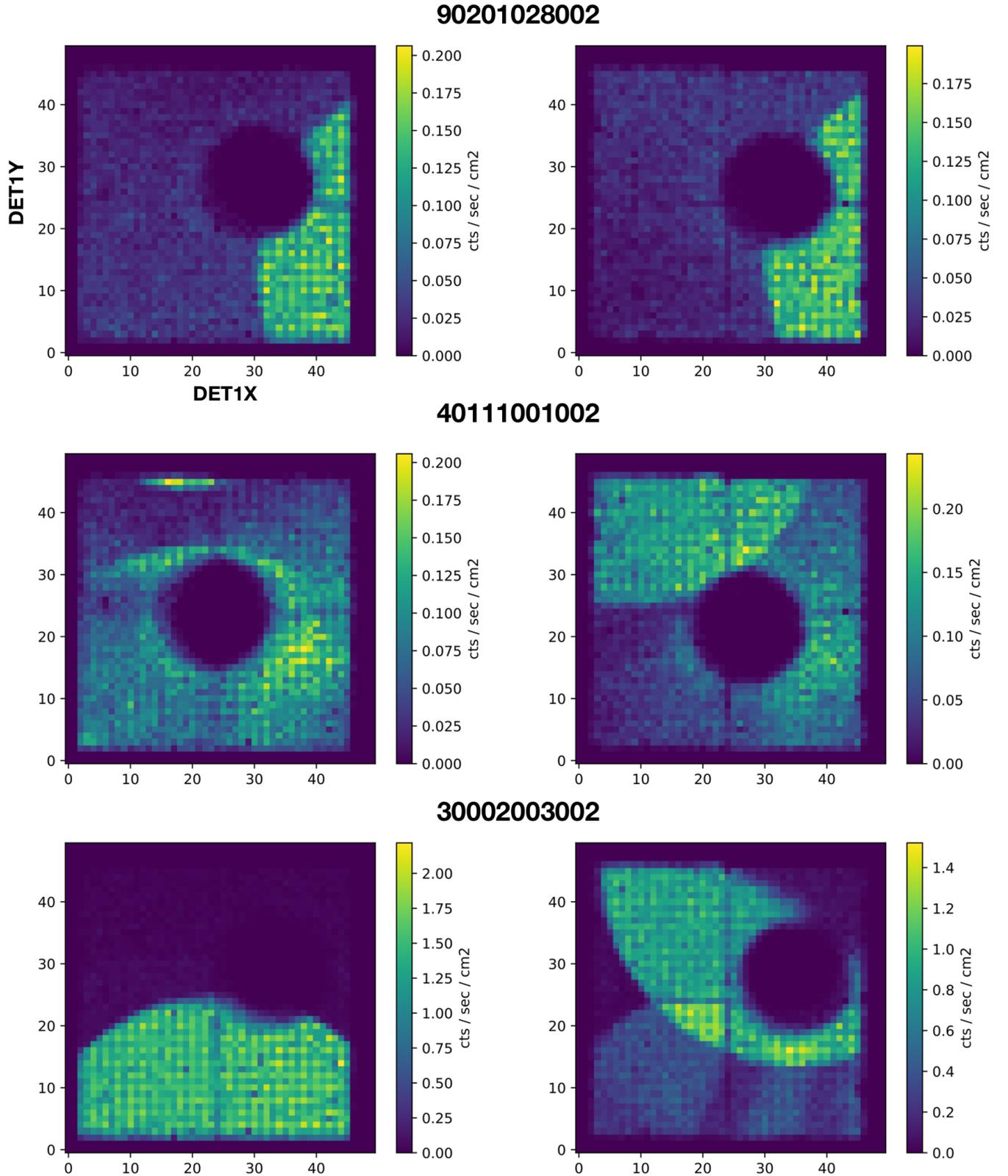


Figure 3. A rogue’s gallery of 3–20 keV *NuSTAR* images in DET1 pixel coordinates (1 pixel = $2.54'' = 120.96 \mu\text{m}$) for three *StrayCats* observations showing some of the variety of the stray light patterns in FPMA (*left column*) and FPMB (*right column*). The primary source has been masked out and the linear colorscale shows the fluence (counts per second per cm^2) across the field of view for each detector. (*Top*) One of the cases where stray light (here from the LMXB 4U 1624-490) is seen in both FPMs. (*Middle*) A more complex geometry where multiple overlapping or partially blocked stray light sources (the strongest being 4U 1708-2 in FPMA and 4U 1700-377 in FPMB) overlay the extended primary source (RX J1713.7-3946). (*Bottom*) Strong and overlapping stray light from GX 5-1 (lower SL) and GX 3+1 (upper right in FPMB).

face³ or simply through a FITS file that identifies which *NuSTAR* sequence IDs contain **StrayCats** sources. For observations that contain multiple **StrayCats** sources the web interface also contains diagnostic information that can be used to determine which stray light pattern is associated with a particular source (i.e., the images shown in Fig 3). An excerpt of the table is given in the Appendix in Table 4.

The first version of **StrayCats** includes the following columns:

- **StrayID**: The **StrayCats** catalog identifier, which is **StrayCatsLXX** where **XX** is the row number after the catalog is sorted the RA and Dec for the *NuSTAR* sequence ID.
- **Classification**
 1. **SL**: The source has been positively identified as a **StrayCats** target
 2. **Complex**: Stray light is present, but there are multiple overlapping stray light regions that make the sources difficult to identify
 3. **Faint**: Stray light is present, but is too faint to be positively identified.
 4. **GR**: The observation contains ghost-rays from sources just outside of the FoV
 5. **Unkn**: A stray light pattern is present, but the source of the stray light remains unknown.
- **SEQID**: The *NuSTAR* sequence ID
- **Module**: The *NuSTAR* FPM that contains the stray light (A or B)
- **Exposure**: The exposure time for this observation in seconds
- **Multi**: Whether the sequence ID contains multiple stray light patterns (Y or N)
- **Primary**: The name of the primary target for the pointed science observation
- **TIME / END_TIME**: The MJD start/end of the observation
- **RA/DEC_Primary**: RA/Dec of the *primary* target
- **SL Source**: The name of the source of SL if we have identified it

- **SL Type**

For sources with a positive identification, we have made an effort to sample the literature and provide a source classification. Many of these are relatively famous sources identified by *GINGA* or *Uhuru* with a large literature background, so we do not provide prime references for the classifications in **StrayCats**. For sources with Classification other than SL, this defaults to “?”. Classification types are:

1. AGN: Active Galaxy
2. LMXB (low-mass X-ray binary) with -NS or -BH if the compact object type is known
3. HMXB (high-mass X-ray binary) with -NS or -BH if the compact object type is known
4. Pulsar / PWNe (Pulsar Wind Nebula) / NS
5. BHC (Black Hole Candidate)
6. SNR (Supernova Remnant)
7. Cluster (Galaxy cluster)
8. Radio Galaxy

- **SIMBAD_ID**: The identifier that can be used via SIMBAD to identify the source. This can often be different than the source name in the all-sky catalogs used to identify the source (if known, otherwise defaults to NA)
- **RA/DEC_SL**: RA/Dec of the source of the stray light (if known, otherwise defaults to -999).

StrayCats contains 436 telescope fields (with A and B counted separately) containing stray light from 78 confirmed **StrayCats** sources. During the visual inspection of the stray light candidates, we compare the observed stray light patterns with those predicted for that observation using the same code used in §2.1. For a majority of sources, this is sufficient to identify the source of stray light. For a few dozen cases, the stray light is associated with a source *not* present in either catalog. This was either because the source was a new transient (e.g., a number of MAXI-identified transients that went into outburst over the last few years), the source is only occasionally detected by the all-sky hard X-ray detectors (e.g., sources contained in the “*Swift*-BAT historically detected” list), or the source is typically too soft to be detected by *Swift*-BAT or *INTEGRAL*. We have not yet identified any previously unknown **StrayCats** sources.

We can estimate the source location using the projected shape of the aperture stop on the focal plane. Fig 4 gives an example of this for a simple case. Here, the curvature of the aperture stop shadow is clearly seen on the

³ <https://nustarstraycats.github.io/>

focal plane. We generate a “SL” region that matches the known curve, and compute the offset between this and the center of the FoV (the “Aperture Stop” region in Fig 4). We can compute the offset on the focal plane (in mm) and leverage the fact that we know that the deployed aperture stop is 833.2 mm (Fiona Harrison, priv comm.) away from the focal plane to convert this offset to angular offset. The direction of the shift (in sky coordinates) allows us to determine the position angle of the shift. In the example shown here, we were able to reproduce the location of Cir X-1 to better than $10'$, which is generally good enough to identify the source. For cases where multiple overlapping stray light patterns are seen and we cannot unambiguously identify the source we assign the “Complex” classification pending a detailed analysis.

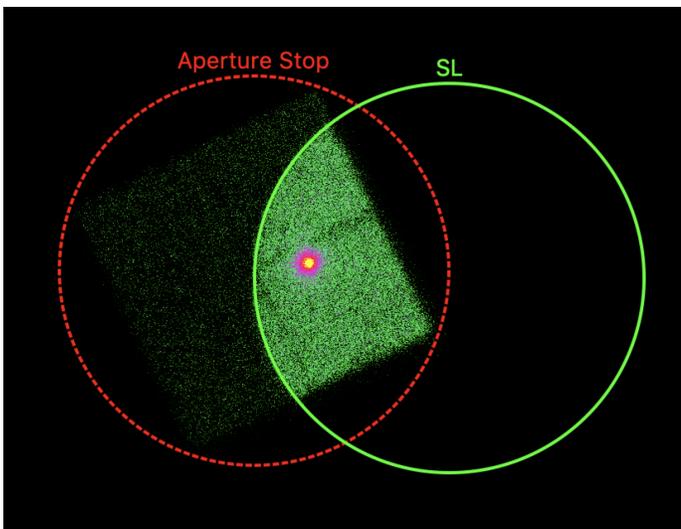


Figure 4. An example of the “stray light” (SL, green) region and the “aperture stop” region (red, dashed) that can be used to identify the source location on the sky. See text for details.

The catalog contains seven AGN and one galaxy cluster, several pulsar wind nebulae and supernova remnants, roughly 17 accreting black holes (including black hole candidates), as well as over forty accreting neutron stars including several pulsars and a number of known Type I X-ray bursters. Figure 5 shows the galactic distribution of these sources, where the density of sources near the galactic plane and the LMC and SMC can clearly be seen.

4. StrayCats DATA ANALYSIS TOOLS AND RESPONSE FILES

StrayCats require subtly different analysis methods than those typically used for focused *NuSTAR* obser-

vations. Rather than working in “SKY” coordinates like focused observations, for stray light observations we instead work in “detector” coordinates (DET1 coordinates in *NuSTAR* vernacular). This coordinate system is fixed with respect to the *NuSTAR* CdZnTe detectors and, in these coordinates, the pattern of stray light on the focal plane is predominantly sensitive to the observatory orientation and is extremely weakly coupled to any motion of the *NuSTAR* mast. For pointed observations, the \sim mm-scale motion of the *NuSTAR* mast affects the throughput of the optics by changing the distance of the source from the optical axis (“vignetting” Harrison et al. 2013). In non-focused observations the mast motion only minimally changes the shadow pattern as observed by the detectors and can be neglected.

Producing high-level science products for a StrayCats observation is relatively straightforward. These mostly deal with properly tracking the production of “source” regions files and applying spatial filtering on the *NuSTAR* data in DET1 coordinates. Our goal is to make the resulting products as similar to standard *NuSTAR* products as possible for the ease of use.

To date, we have contributed a number of high-level “wrappers” to the *NuSTAR* community-contributed GitHub page⁴. These are largely written in python and significantly leverage the existing astropy framework (Robitaille et al. 2013; Collaboration et al. 2018), as well as the multi-mission FTOOLS distributed by the HEASARC, such as XSELECT. Final high-level products are mostly generated using NUPRODUCTS from the NUSTARDAS software with a number of non-standard configuration settings. This allows a user to easily produce standard spectrum (PHA) and lightcurve files as well as response matrix functions (RMFs) which can directly be loaded into downstream analysis software such as XSPEC (Arnaud 1996) or ISIS (Houck & Denicola 2000) for spectral analysis or STINGRAY (Huppenkothen et al. 2019) for timing analysis.

4.1. Response Files

The one unique requirement for the analysis of StrayCats observations is the production of the response files. For a focused observation, each count is first “projected” onto the sky and the optics response (i.e. the ancillary response file, or ARF) is produced so that it accounts for the time-dependent drift in the location of the optical axis due to the thermal motion of the *NuSTAR* mast. The ARF is generated starting with an on-axis optics response, which is then convolved with

⁴ <https://github.com/NuSTAR/nustar-gen-utils>

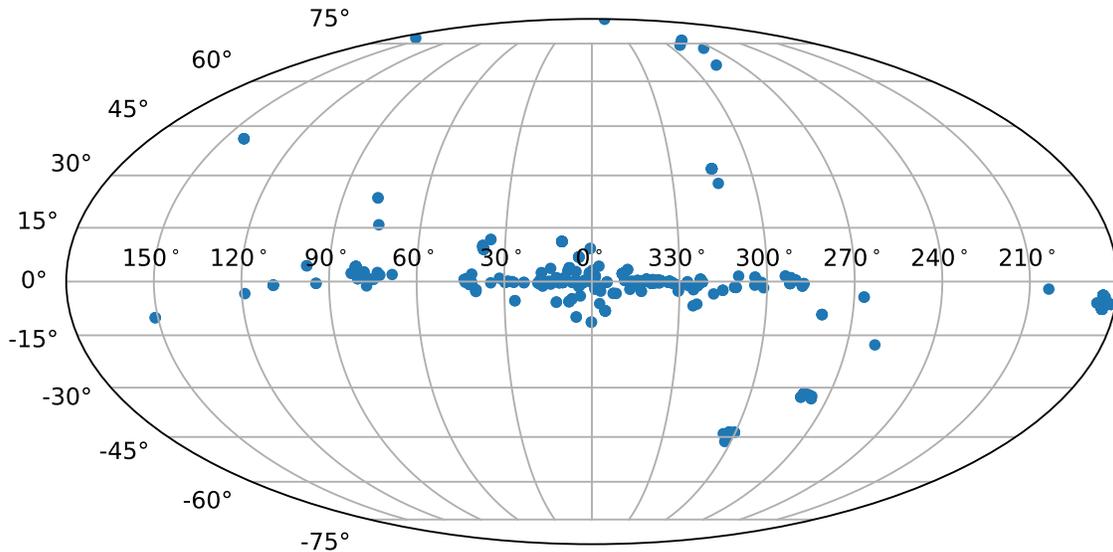


Figure 5. Distribution of the **StrayCats** in galactic coordinates showing the clustering of these sources near the Galactic plane, the contribution from bright sources in the LMC and SMC, and a few AGN located out of the plane of the Galaxy. The coordinates shown here are the for the primary (focused target).

energy-dependent vignetting function based on the off-axis angles sampled by the source. Finally, the ARF also includes the attenuation along the photon path due to the optics thermal covers, the Be window protecting the detectors, and the absorption features in the CdZnTe detectors themselves⁵.

Since for **StrayCats** observations we are working in DET1 coordinates, we no longer need to account for the time-dependent variations in the ARF, nor (obviously) the response of the optics themselves. The **StrayCats** ARF, instead, only needs to account for the amount of illuminated area on the focal plane (for overall normalization, given in cm^2) and any energy-dependent absorption due to the Be window and losses in the CdZnTe detectors. All of these contributions are currently stored in the *NuSTAR* CALDB files (with the exception of the Be window attenuation, which is subsumed into the on-axis ARF in the CALDB). The ARF generation tool for **StrayCats** analysis properly reads these files from the *NuSTAR* CALDB and weights the response based on the illuminated area on each focal plane detector. The resulting file can be directly imported into XSPEC along with the other spectral files above for analysis. This

approach has been validated against observations of the Crab (Madsen et al. 2017b).

Absorbed stray light (stray light that partially penetrates through the aperture stops, see Madsen et al. 2017a) is not accounted for here. These response files only account for the unabsorbed stray light that reaches the focal plane. In addition, two of the sources in **StrayCats** are extended sources (Cas A and the Coma Cluster). Analyzing data from extended sources is more complex and beyond the scope of this analysis. Analyzing these sources in detail will likely require bespoke ray-trace simulations to properly interpret the stray light spectrum.

4.2. Region Files

While all of the **StrayCats** clearly show the effects of stray light, the scientific usefulness of the observations will depend on how much of the FoV is covered by stray light. In the case of the intentional stray light observations mentioned above, the *NuSTAR* observations was designed to maximize the amount of detector area illuminated by stray light, which results in roughly half of the 16 cm^2 detector area being illuminated (compared with the on-axis effective area of $\approx 400 \text{ cm}^2$ for each *NuSTAR* telescope). For standard observations, the *NuSTAR* SOC attempts to minimize this coverage when possible, so the illuminated detector area for the serendipitous **StrayCats** observations varies dramati-

⁵ see the *NuSTAR* software user's guide: https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf

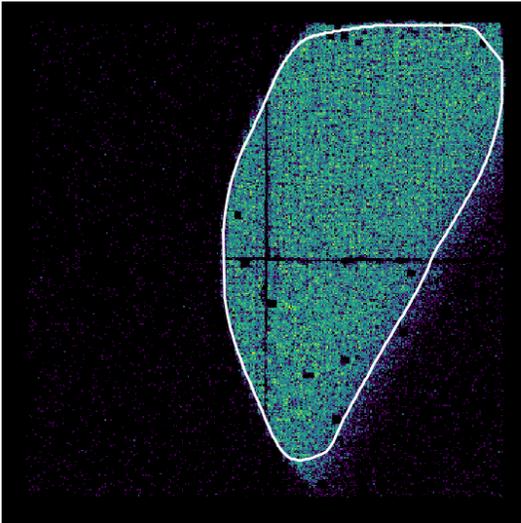


Figure 6. Example of a semi-automatically-generated region for a `StrayCats` observation of the Crab.

cally. Because the stray light pattern depends on the shadowing of the detectors by the optical bench, *NuSTAR* is also rarely in an orientation where stray light is present on *both* *NuSTAR* FPMs.

Due to the large number of `StrayCats`, and the geometrically complex region shapes, we developed a semi-automated approach to reduce the amount of manual effort involved in generating the optimal extraction region. The “wrapper” for this approach is available in the aforementioned *NuSTAR* GitHub page. For `StrayCats` containing a bright point source the first step of this process is point source removal. This is done first by determining the position of the *targeted* source in DET1 coordinates (using the `nuskycodet` FTOOL). This location depends on the motion of the *NuSTAR* mast and any changes in the *NuSTAR* pointing, so we determine the radial distance from each observation count from this position. We screen events within r -arcminutes of the source (if necessary, and where the choice of r is chosen on a case-by-case basis) and generate an image in an adjustable energy band (the 3–10 keV band is default).

We use Canny edge detection from `scikit-image`⁶ to generate the polygons used to estimate the source region where the width of the Gaussian filter used by the

Canny edge detection (σ) is an adjustable parameter. Again, this is chosen on a case-by-case basis such that the filter accurately identifies the edges of the stray light region. Polygon region corners in image coordinates are determined from the detected edge pixels and used to write a region file in SAOImageDS9 standard format using the `regions` astropy-affiliated module.

This approach is particularly useful for stray light regions with an angular cutaway resulting from the shadow of the optical bench (i.e., Fig 6). This process is most efficient for intentional stray light observations and serendipitous observations containing a single stray light pattern only from the “SL Target” source (i.e., entries in the `StrayCats` catalog with the Classification “SL” and Multi value “N”). Currently, this approach is most limited by the σ parameter, which approximately ranges between 3 and 12 for optimal stray light observations but can vary greatly for weak stray light regions. Discontinuities in the edges identified by the Canny filter occasionally result in the created polygon region omitting (sometimes negligibly thin) slices of the stray light region; these anomalies can often be corrected by fine-tuning σ . However, there are no optimal σ values for the Canny filter to properly identify the stray light region for observations in which the fluxes of the background and the stray light are comparable. Future improvements to this process that eliminate the manual determination of the point source removal limit and Canny edge detector sigma would allow for fully-automated region extraction.

4.3. Background

Dealing with background for `StrayCats` sources is not trivial. For standard *NuSTAR* pointed observations, standard techniques such as using a neighboring source-free region to estimate the background and/or estimating the *NuSTAR* background through tools such as `nuskybgd` (Wik et al. 2014) can be used “out of the box”. However, as we are using *NuSTAR* as a collimator rather than a focusing telescope, the background must be treated with more care.

The `StrayCats` source regions cover a large region of the FoV (and there may be multiple `StrayCats` sources as well as the primary source in the FoV), so selecting a background region may be difficult. In addition, for bright `StrayCats` sources, some stray light may also be transmitted through the aperture stop at higher energies, making it impractical to select a neighboring “source free” region of the FoV to use to estimate the background (see Madsen et al. 2017a,b, for further discussion).

Modeling the background contributions also must be handled with care. Because many of the `StrayCats`

⁶ <https://scikit-image.org>

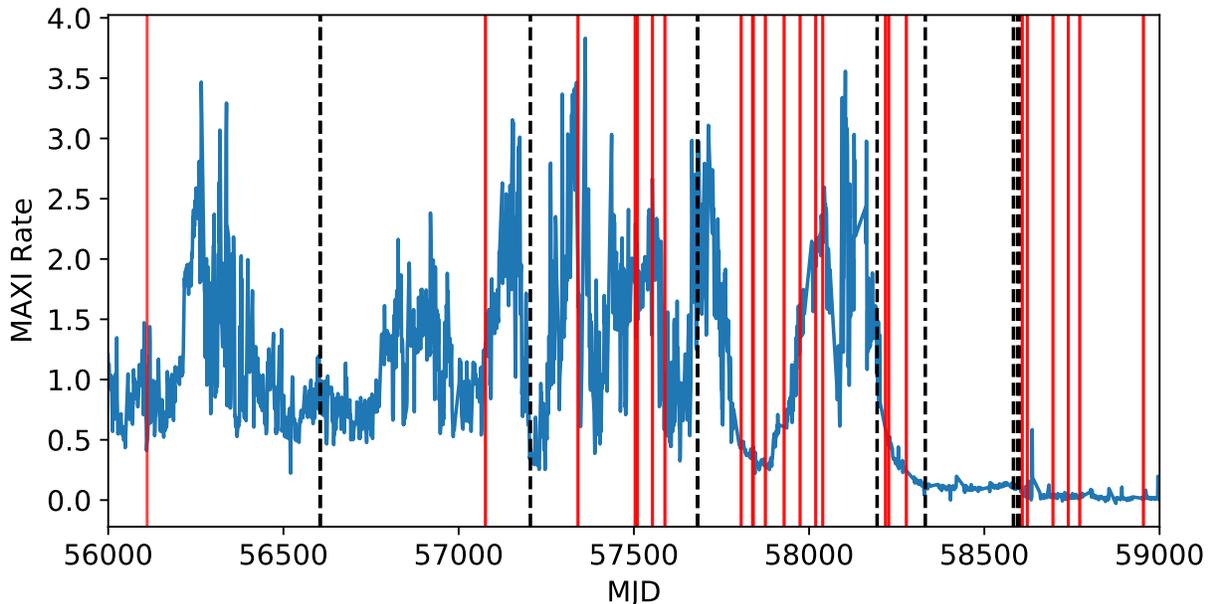


Figure 7. The long-term 2-10 keV lightcurve of GRS 1915+105 as measured by MAXI (blue histogram) along with the timing of focused *NuSTAR* observations (red lines) and the *StrayCats* observations (dashed black lines). The final three epochs are clustered in the 16 days just before MJD 58600.

sources are near the Galactic plane, the standard models of the spatial variation of the *NuSTAR* background used by `nuskybgd` to model the contributions from the Galactic ridge X-ray emission (Krivonos et al. 2007, GRXE) are largely untested and may need to be adapted for the non-isotropic shape of the GRXE.

The exact method used to handle the presence of background will necessarily vary depending on the science goals for the individual analysis. For bright, hard sources, even without the aid of the *NuSTAR* optics, the backgrounds in *NuSTAR* are so low that the background may be neglected up to high energies. For fainter sources (or soft sources) the energy at which the background starts to significantly contribute (and therefore the background component which matters the most for spectral analysis) will depend on the details of the source flux. We do not expect there to be a universal solution or recommendation for how to handle the backgrounds.

In the selected preliminary results below, spectral analysis is typically halted when the source flux falls so that the background is estimated to be $\sim 10\%$ of the source flux, but we stress that a thorough treatment of the background must be considered.

5. SELECTED PRELIMINARY *StrayCats* RESULTS

5.1. *GRS 1915+105*

GRS 1915+105 is a LMXB system which has been in outburst since its discovery in 1992 (Castro-Tirado

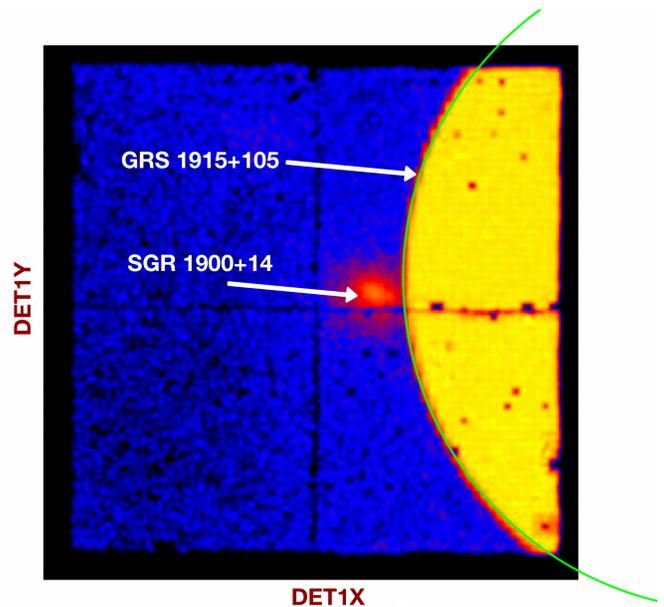


Figure 8. The 3-20 keV DET1 image for sequence ID 30201013002. The faint primary source is shown, as is the stray light pattern for GRS 1915+105 along with the region showing the shadow of the aperture stop.

et al. 1992) and shows a wide range of source spectral and timing states (e.g., Belloni et al. 2000). The system is known to host a near-maximally spinning black hole (McClintock et al. 2006) and observations of the

Table 1. GRS 1915+105 StrayCats Observations

Obs #	Sequence ID	Obs. Date	(MJD)	FPM	Exp. (ks)	area (cm ²)
1A	80001014002	2013-11-08T18:11:07	56604.8	A	45.15	3.9
1B	-	-	-	B	45.49	4.0
2	30101050002	2015-07-01T15:31:08	57204.6	A	41.34	**
3A*	30201013002	2016-10-20T16:56:08	57681.7	A	122.3	2.2
3B	-	-	-	B	122.6	3.6
4	40301001002	2018-03-17T01:46:09	58194.1	A	125.6	5.9
5	30401018002	2018-08-01T12:41:09	58331.5	B	78.3	4.9
6	90501317002	2019-04-10T01:26:09	58583.1	A	40.8	5.7
7	30402026002	2019-04-22T00:11:09	58595.0	A	18.83	**
8	30402026004	2019-04-26T13:41:09	58599.6	A	23.31	**

*:Used for the analysis in this work; **:Small stray light area

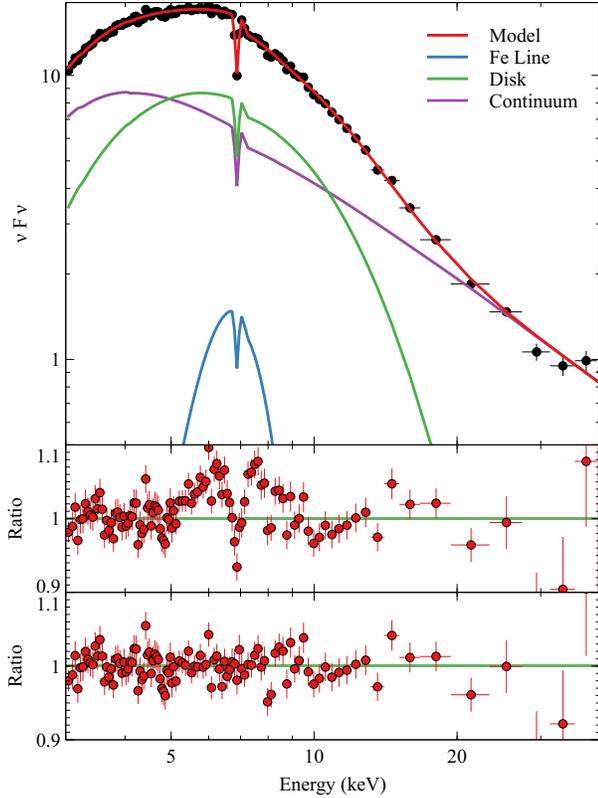


Figure 9. The integrated spectrum from Obs3A from a portion of the stray light region. A similar sized region was used to estimate the background. The base model spectrum here consists of a hot accretion disk component and a soft non-thermal power-law, though this leaves strong residuals near the Fe line (*middle*). We find that after the addition of a broad Fe line and absorption features associated with disk winds in this system that we obtain a reasonable fit to the data.

absorption features also reveal the presence of a complex outflowing disk wind (Miller et al. 2016). How-

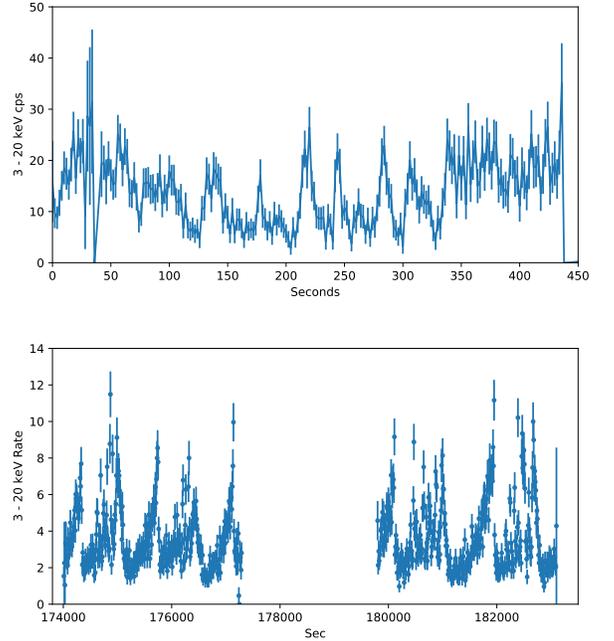


Figure 10. The 3-20 keV lightcurve for the first 450-s of the first orbit, binned at 2-s resolution shows the presence of transient slow (mHz) QPO signals. (*Bottom*) The 3-20 keV of two later orbits binned at 10-s resolution showing that the source has transitioned to its θ -state.

ever, the source began a decay to either a quiescent or a highly absorbed state between 2018 and 2020 (Miller et al. 2020; Neilsen et al. 2020). Since 2012, *NuSTAR* has observed the source a number of times at varying flux levels (Fig 7). However, the high count rates from this source present two key problems that affect the scientific return from these data: (1) *NuSTAR* has a fixed 2.5-ms deadtime-per-event, resulting in a maximum throughput of 400 cts s⁻¹. In high rate sources

this deadtime also results in the effective exposure being much lower than the time spent observing the target; (2) As mentioned above, the high count rates result in high telemetry loads that require short duration observations to avoid data loss on board. GRS 1915+105 also appears in 6 *StrayCats* epochs, covering a wide range of flux states (Figure 10) as measured by the Monitor of All-sky X-ray Image (MAXI) instrument on the *International Space Station* (Matsuoka et al. 2009). The duration of the *StrayCats* observations vary, with several snapshots roughly 20-ks effective exposure to several deep observations with over 120-ks of exposure. A summary of the *StrayCats* for GRS 1915+105 is given in Table 1.

As an example, we show preliminary results from one epoch (Obs 3A, 30201013002, Figure 8), which had an effective exposure of 122 ks spanning over roughly 240 ks (over two and a half days) of clock time. The epoch-averaged source spectrum (Figure 9) shows that the source is clearly detected up to at least 40 keV before background becomes a significant contribution to the spectrum. At low energies we clearly see evidence for a Fe-line features and absorption features typically associated with disk winds in this system (e.g. Miller et al. 2016; Neilsen et al. 2018).

However, the spectrum for this source is known to be highly variable with the source hardness varying with the apparent emission states and throughout this extended observation the source showed a variety of emission states. For example, during the first orbit we clearly observe QPOs in the form of 10 to 20-s recurrent ‘‘pulsations’’ of emission, while in later orbits during the same observation the source has transitioned to its θ -state, showing emission building up over the span of a few hundred seconds before sharply dropping away (Fig 10). A detailed analysis of the spectral changes throughout this system is beyond the scope of this work (e.g., Zoghbi et al. 2016), but shows the utility of only one of the several observations of GRS 1915+105.

5.2. GX 3+1

GX 3+1 is a persistently accreting ‘atoll’ source. Atoll sources trace out regions on hardness-intensity diagrams that resemble ‘islands’ (for which they are named: Hasinger & van der Klis 1989) or ‘banana’ shapes. GX 3+1 exclusively occupies the banana branch (Seifina & Titarchuk 2012) and was serendipitously observed via straylight in *NuSTAR* nineteen times between 2012 July and 2020 May. Table 2 shows the sequence ID, observation date, FPM that the straylight occurred on, exposure time, and area on the FPM for observations with an area greater than 1 cm² of straylight from the

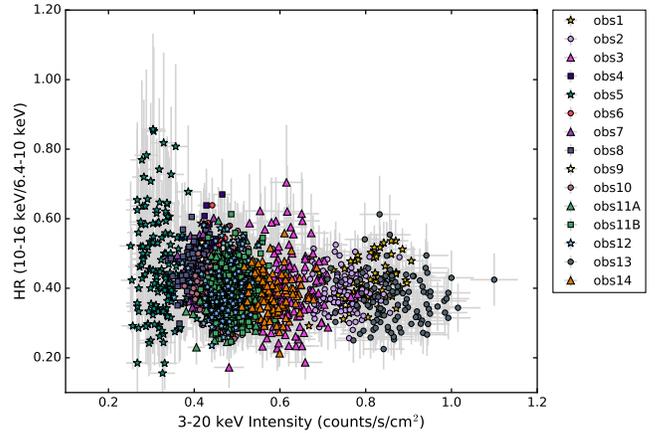


Figure 11. Hardness-Intensity diagram of the straylight observations of GX 3+1. Observation numbers refer to the sequence IDs in Table 2. Data are binned to 300 s. The ‘banana’ branch is traced out by the data.

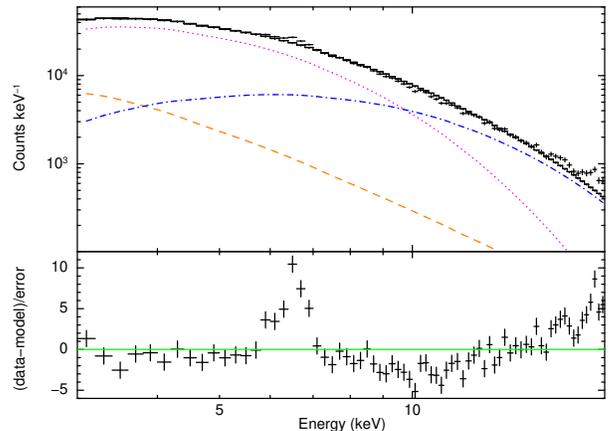


Figure 12. The 3–20 keV straylight spectrum of GX 3+1 obs10 and residuals divided by the error. The orange dashed line indicates the power-law component, the blue dot-dashed line is the single-temperature blackbody, the dotted line is the multi-temperature blackbody. A prominent Fe line feature is present between 6–7 keV. The background begins to dominate above 15 keV.

source. Lightcurves were generated in three different energy bands (3–20 keV, 6.4–10 keV, and 10–16 keV) with a binsize of 300 s. Figure 11 shows the hardness-intensity diagram for GX 3+1. The hardness ratio (HR) is defined as the 10–16 keV band divided by the 6.4–10 keV band (Coughenour et al. 2018). The source traces out the ‘banana’ branch.

To demonstrate the spectral utility of straylight observations for studying NS LMXBs, we extract a spectrum from the longest observation, obs10. The data are fit with the three component model of Lin et al.

Table 2. GX 3+1 StrayCats Observations

Obs #	Sequence ID	Obs. Date	FPM	Exp. (ks)	area (cm ²)
1	30002003003	2013-06-19T09:31:07	B	~ 29	3.51
2	80002017002	2014-02-15T05:36:07	A	~ 39	4.64
3	90101012002	2015-08-11T22:51:08	B	~ 49	1.46
4	90101022002	2016-02-18T22:26:08	A	~ 36.7	3.79
5	40112003002	2016-03-17T00:31:08	A	~ 52	1.35
6	80102101002	2016-09-29T21:21:08	B	~ 29.5	6.33
7	80102101004	2016-10-19T15:01:08	B	~ 28	7.15
8	80102101005	2016-10-31T20:11:08	B	~ 29	6.66
9	80202027002	2017-02-18T14:31:09	A	~ 31	4.69
10*	40112002002	2017-04-03T18:31:09	A	~ 100.7	4.18
11	90402313004	2018-04-14T02:56:09	A	~ 61	3.40
	-	-	B	~ 61	3.43
12	90501329001	2019-06-22T07:51:09	B	~ 40	3.35
13	90501343002	2019-10-01T22:36:09	B	~ 37	1.65
14	90601317002	2020-05-07T07:06:09	A	~ 49	4.12

*:Used for the analysis in this work

(2007) that was used in Ludlam et al. (2019) for the pointed observation of GX 3+1. This is comprised of a multi-temperature blackbody for thermal emission from the accretion disk, single-temperature blackbody for a boundary layer or emission from the NS surface, and power-law for weak Comptonized emission. For direct comparison to the intentional *NuSTAR* observation, we model the continuum emission by fixing the absorption column along the line of sight, blackbody temperatures, and photon index to the values reported in Table 2 of Ludlam et al. (2019) while allowing for the normalizations of each spectral component to vary. The spectrum and continuum components are shown in Figure 12. The color scheme and line types correspond to those in Ludlam et al. (2019). Indeed, a prominent Fe line emission feature can be seen in the straylight observations akin to the one observed from the pointed observations (see Fig 1 of Ludlam et al. 2019). Further details of the variations in this source over time will be addressed in future work.

5.3. GS 1826-24

GS 1826-24 is a LMXB which showed remarkable consistent Type I X-ray bursts since its discovery by *GINGA* (e.g. Ubertaini et al. 1999). The Type I X-ray bursts were so regular as to earn this source the ‘‘Clocked Burster’’ moniker. A sudden dip in the *Swift*-BAT 15-50 keV lightcurve resulted in a *NuSTAR* ToO observation of this source in 2014 (Chenevez et al. 2016). After briefly returning to a hard state, the source appears to have transitioned into a ‘‘soft’’ state in 2016 with the

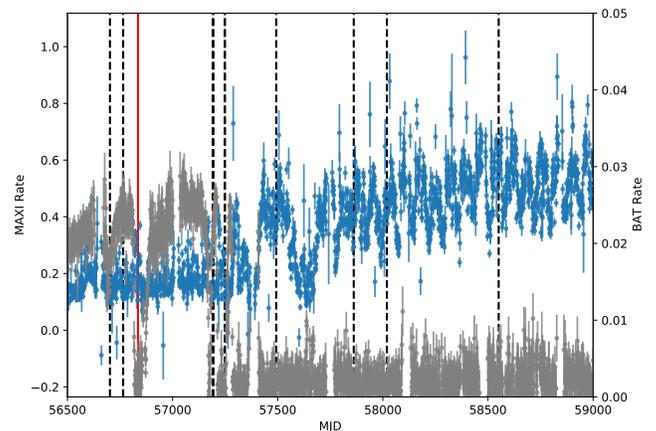


Figure 13. The long-term 2–20 keV MAXI lightcurve (blue) and the *Swift*-BAT transient monitor 15–50 keV lightcurve for GS 1826–24 (grey). The timing of the focused *NuSTAR* observations are shown in solid red lines while the timing of the *StrayCats* observations are shown in dashed black lines.

MAXI lightcurve increasing to a plateau in 2018 and the *Swift*-BAT lightcurve in an apparently quiescent state (Fig 13). While there have not been any subsequent targeted observations with either *NuSTAR* or *XMM-Newton*, *NICER* has monitored the source and found evidence for mHz QPOs (Strohmayer et al. 2018).

The *StrayCats* observations (Table 3) span both the pre-dip observations and include several long observa-

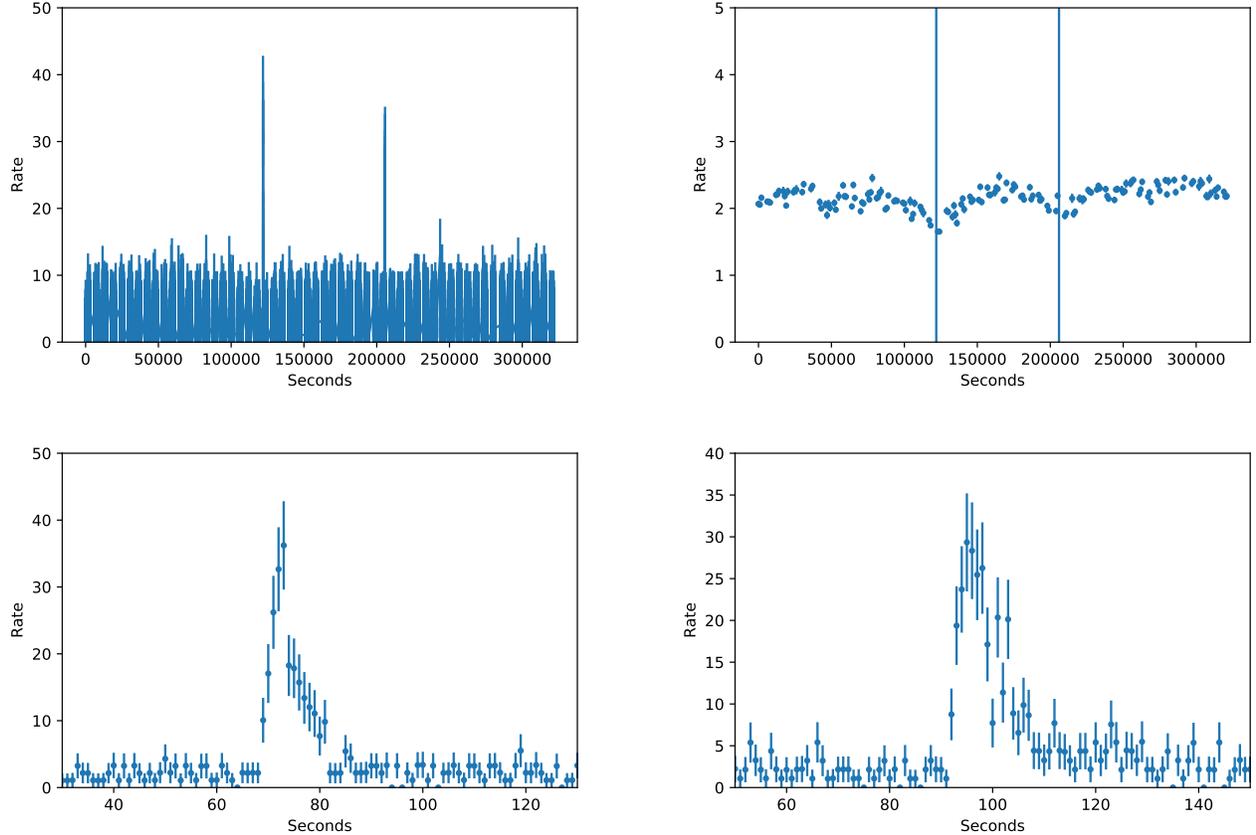


Figure 14. All panels show the 3–20 keV lightcurve of Obs7 and show: (*Top Left*) The full observation using 1-s bins clearly shows the two Type I X-ray bursts; (*Top Right*) The same data, but using 1-ks bins; (*Bottom panels*) The zoomed in view of the first (*left*) and second (*right*) Type I X-ray burst.

tions during the BAT X-ray minimum. We highlight one of these (Obs7), which had a substantial amount of stray light covering over half of FPMB and a long exposure of over 150-ks, resulting in nearly 300-ks of elapsed clock time. During this observation *NuSTAR* clearly detected two Type I X-ray bursts lasting ~ 10 s of seconds (Fig 14). Simultaneously, the X-ray flux in the 3–20 keV lightcurve dipped leading up to the burst itself. We only find two Type I X-ray bursts, while we would have expected over a dozen had the source been regularly bursting with a recurrence time of ~ 5.7 hours (Ubertini et al. 1999). This confirmed the results of the single set of pointed *NuSTAR* observations that the “clocked” nature of the source has disappeared in the soft state (Chenevez et al. 2016). A more complete survey of the bursting state over all 7 epochs and correlations with the spectral changes in the source will be the topic of a future paper.

6. SUMMARY AND FUTURE WORK

In this paper we have presented a summary of a unique, untapped set of *NuSTAR* observations. The *StrayCats* observations found thus far are predominantly associated with known bright sources and transient X-ray binaries as they go into outburst.

StrayCats is based on a systematic approach to mining the database of *NuSTAR* observations. While previously these observations were considered a nuisance, we have now produced a set of publicly available tools for analyzing these data and producing high-level science products. In addition, we provided access to scripts that help in the generation of region files, which often requires some fine tuning based on the projected “shadow” of the optics bench.

The *StrayCats* catalog that we present here we consider to be version 1.0. We intend to extend the current version of *StrayCats* to include additional summary data products (such as count rates, hardness ratios, and source and background extraction regions) for all *StrayCats* observations where the source is bright enough and enough of the focal plane is covered by stray

Table 3. GS 1826-24 StrayCats Observations

Obs #	Sequence ID	Obs. Date	(MJD)	FPM	Exp. (ks)	area (cm ²)
1	80002012002	2014-02-14T00:36:07.184	56702.0	A	24.05	2.2
2	80002012004	2014-04-17T22:46:07.184	56764.9	A	26.42	2.3
3	30101053002	2015-06-17T16:06:07.184	57190.7	A	131.32	2.75
4	30101053004	2015-06-21T07:11:07.184	57194.3	A	51.52	2.5
5	60160692002	2016-04-14T18:26:08.184	57492.8	B	21.88	1.7
6	10202005002	2017-04-18T13:06:09.184	57861.5	A	156.51	2.52
7*	10202005004	2017-09-23T08:36:09.184	58019.4	B	156.54	8.8
8	80460628002	2019-03-08T20:21:09.184	58550.8	B	41.39	1.6

*:Used for the analysis in this work

light. This work is on-going and will be provided in a future release.

Finally, our brief survey of the science potential from **StrayCats** observations shows the power of these observations. Through these highlights of a few selected observations we have shown that these data can be used to track sources over long periods of time and provide a unique window into their behavior by providing improved sensitivity and finer spectral resolution compared to other all-sky monitors such as MAXI and *Swift*-BAT.

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Facilities: NuSTAR, Swift, MAXI, HEASARC

Software: astropy (Robitaille et al. 2013; Collaboration et al. 2018), astroquery (Ginsburg et al. 2019), HEASoft/FTOOLS, IDL⁷, matplotlib (Hunter 2007), numpy⁸, pandas (Pandas Development Team 2020), plotly⁹, scikit-image¹⁰, Veusz¹¹

APPENDIX

⁷ <https://www.harrisgeospatial.com/Software-Technology/IDL>

⁸ <https://numpy.org>

⁹ <https://plotly.com/python/>

¹⁰ <https://scikit-image.org>

¹¹ <https://veusz.github.io>

Table 4. StrayCats Excerpt

STRAYID	Classif.	SEQID	Mod.	Primary	TSTART	Exp	SL Source	SL Type	RA _{SL}	DEC _{SL}	RA _{P-ri}	DEC _{P-ri}
StrayCatsL0	Faint	30001014002	B	IC10_X1	56967.8	88.47	NA	??	-999	-999	5.074	59.274
StrayCatsL1	Unkn	90101010002	A	IGR_J00291p5934	57231.5	38.10	NA	??	-999	-999	7.275	59.598
StrayCatsL2	SL	90201030002	A	SWIFT_J003233d6m7306	57586.7	54.92	SMC X-1	HMXB-NS	19.271	-73.443	8.197	-73.096
StrayCatsL3	SL	90201041002	A	SMC_X3	57704.7	38.60	SMC X-1	HMXB-NS	19.271	-73.443	13.030	-72.457
StrayCatsL4	SL	30361002002	A	SXP_15d3	58087.0	70.65	SMC X-1	HMXB-NS	19.271	-73.443	13.112	-73.373
StrayCatsL5	SL	30361002004	A	SXP_15d3	58418.9	58.35	SMC X-1	HMXB-NS	19.271	-73.443	13.141	-73.350
StrayCatsL6	Faint	30361002004	B	SXP_15d3	58418.9	58.13	NA	??	-999	-999	13.141	-73.350
StrayCatsL7	Faint	50311003002	A	SMC_Deep_MOS03	57876.1	172.39	NA	??	-999	-999	13.264	-72.488
StrayCatsL8	SL	60301029006	A	IRAS_00521m7054	58074.7	74.41	SMC X-1	HMXB-NS	19.271	-73.443	13.498	-70.667
StrayCatsL9	SL	90101017002	A	SMC_X2	57316.9	26.72	SMC X-1	HMXB-NS	19.271	-73.443	13.740	-73.707
StrayCatsL10	SL	90102014004	A	SMC_X2	57307.9	23.05	SMC X-1	HMXB-NS	19.271	-73.443	13.744	-73.695
StrayCatsL11	SL	50311001002	B	SMC_Deep_MOS01	57867.1	153.16	SMC X-1	HMXB-NS	19.271	-73.443	13.930	-72.439
StrayCatsL12	SL	30202004006	B	SMC_X1	57662.0	20.38	SMC X-3	HMXB-NS	13.023	-72.435	19.351	-73.462
StrayCatsL13	SL	30202004002	A	SMC_X1	57639.9	22.46	RX J0053.8-7226	HMXB-NS	13.480	-72.446	19.378	-73.442
StrayCatsL14	SL	30202004002	B	SMC_X1	57639.9	22.53	RX J0053.8-7226	HMXB-NS	13.480	-72.446	19.378	-73.442
StrayCatsL15	SL	30202004004	B	SMC_X1	57650.3	21.18	RX J0053.8-7226	HMXB-NS	13.480	-72.446	19.380	-73.454
StrayCatsL16	SL	90001008002	A	GK_Per	57116.1	42.35	NGC 1275	AGN	49.951	41.512	52.784	43.870
StrayCatsL17	SL	30101021002	A	GK_Per	57273.7	72.30	NGC 1275	AGN	49.951	41.512	52.812	43.933
StrayCatsL18	SL	30101021002	B	GK_Per	57273.7	72.16	NGC 1275	AGN	49.951	41.512	52.812	43.933
StrayCatsL19	SL	10601407002	A	N132D	58921.4	82.69	LMC X-2	LMXB-NS	80.117	-71.965	81.197	-69.695
StrayCatsL20	SL	40101010002	B	N132D	57366.2	68.85	LMC X-4	NS	83.206	-66.370	81.311	-69.666
StrayCatsL21	SL	40101010002	B	N132D	57366.2	68.85	LMC X-2	LMXB-NS	80.117	-71.965	81.311	-69.666
StrayCatsL22	SL	30460020002	A	1RXS_J052523d2p241331	58563.6	58.79	Crab	PWNe	83.633	22.015	81.316	24.192
StrayCatsL23	SL	30460020002	B	1RXS_J052523d2p241331	58563.6	58.29	Crab	PWNe	83.633	22.015	81.316	24.192
StrayCatsL24	SL	30301014002	A	SGR_0526m66	58156.9	47.03	LMC X-3	LMXB-BH	84.736	-64.084	81.500	-66.100
StrayCatsL25	SL	30301014002	B	SGR_0526m66	58156.9	46.90	LMC X-3	LMXB-BH	84.736	-64.084	81.500	-66.100

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