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SURF 2021 Final Report

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ABSTRACT

The Nuclear Spectroscopic Telescope Array (NuSTAR) is NASA Small explorer mission and a focusing telescope covering the hard X-Ray bandpass (3-79 keV). NuSTAR observations of targets near the galactic plane can be contaminated by stray light from other sources. However, stray light can be valuable as they can give long term pictures of sources at a finer spectral resolution than other all-sky X-ray monitors. Using Stray Light, we present a X-ray analysis of GS 1826-24, a low mass X-Ray binary (LMXB). GS 1826-24 had been in a persistent hard spectral state, and was observed to transition into a soft spectral state recently from other observations. Through stray light, we were able to obtain multiple observations of the source both during its hard and soft state. We detected multiple X-Ray bursts during both states and made spectral fits to illustrate the difference between the two states. Further work would involve analysing the continuum spectrum and the X-ray bursts of the two states.

1. INTRODUCTION

1.1. *NuSTAR Stray Light*

The Harrison group works on a wide variety of topics in X-ray astronomy, including stellar and supermassive black holes, neutron stars, supernovae, and other high-energy transient phenomena. Fiona Harrison is the PI for the Nuclear Spectroscopic Telescope ARray (NuSTAR), a NASA Small Explorer mission which is the first focusing telescope in space covering the “hard” (3-79 keV) X-ray bandpass. The group includes postdocs and research scientists that are involved with the day-to-day operation of NuSTAR as well as the analysis of the data as it comes down from the satellite.

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, such as neutron stars and black hole binary systems, Grefenstette et al. (2021). However, when sources go into an X-ray bright state, they result in high count rates and correspondingly high telemetry loads. Because of this, many observations of bright sources are short in duration ($\approx$ 20-ks) to allow the spacecraft to transmit the data down to the ground without overwriting the storage drives onboard, Grefenstette et al. (2021).

Recently, NuSTAR has been serendipitously observing bright X-ray binaries through “stray light.” Stray light refers to the light that has not been focused by the optics. The open geometry of the mast, as show in Figure 1, that connects the optics to the detectors allows for the possibility of stray light illuminating detectors. This is typically referred to as “aperture flux”, Grefenstette et al. (2021). For most NuSTAR observations, the dominant source of aperture X-ray emission is the cosmic X-ray background. This contribution to the NuSTAR background is generally described by a spatial gradient in the NuSTAR background across the field of view.

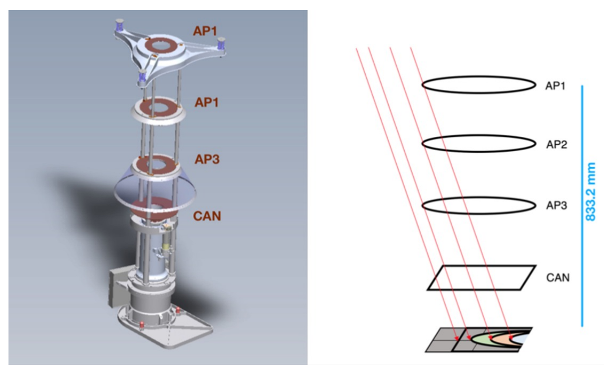


Figure 1: 3D CAD modelling of the mast of the NuSTAR Telescope

When NuStar observations of targets near the Galactic plane are contaminated by stray light from large X-ray binaries nearby. This stray light falls on different parts of the field of view in our image. In this case, the emission geometry is much simpler. Instead of a “gradient” in the background, we instead observe an easily-

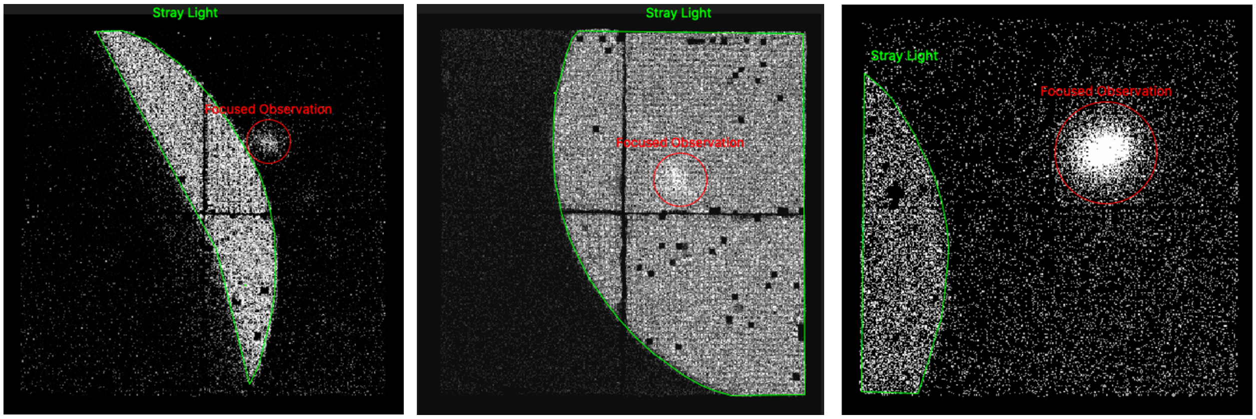


Figure 2: Stray Light Observations of a source

identified shadow of the aperture stop ring sharply cutting off the source, as shown in Figure 2. Because the X-rays do not interact with the NuSTAR optics, the response of the instrument is more straight forward as well.

The data from the stray light source was considered a nuisance and was often neglected or treated as a background for the targeted source. However, stray light sources are actually valuable as they can be used to track sources over long periods of time at an improved sensitivity and finer spectral resolution, giving us a unique window into their behaviour. The study of Galactic X-ray binaries has been limited by low spectral resolution of existing observations or the short target of opportunity 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, providing contiguous observations while reducing the count rate and to potentially extend the spectral range covered by NuSTAR beyond the 78.4 keV cutoff in the optics response, Grefenstette et al. (2021).

1.2. *GS 1826: Objectives*

The main objective of this project was to use Stray Light to study GS 1826-24, a low mass X-ray Binary (LMXB). A low-mass X-ray binary (LMXB) is a binary star system where one of the components is either a black hole or neutron star. The other component, a donor, transfers mass to the compact star. A typical low-mass X-ray binary emits almost all of its radiation in X-rays, so they are among the brightest objects in the X-ray sky. The variability of LXMBs are most commonly observed as X-ray bursters, which are created by thermonuclear explosions created by the accretion of Hydrogen and Helium. GS 1826, a neutron star X-Ray Binary, showed consistent Type I X-ray bursts since its discovery by GINGA in 1999, hence earning its nickname: the "Clocked Burster". The source was observed

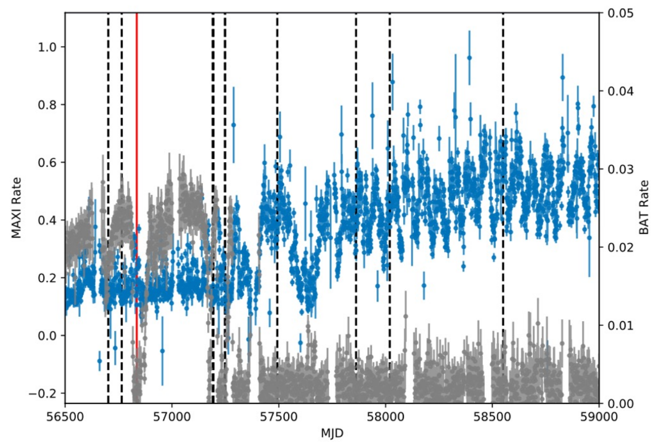


Figure 3: Long-term 2-20 keV MAXI lightcurve (blue); Swift-BAT transient monitor 15-50 keV lightcurve (grey); timing of focused NuSTAR observation (red) and timing of Stray Light observations (dashed black lines), Grefenstette et al. (2021)

in a hard spectral state for many years, until it suddenly transitioned into a soft state in 2014, then returning to the hard state after several months, Grefenstette et al. (2021). After this brief event, the source transitioned, again, into a soft state in 2016.

In Figure 3, we can see a sudden dip in the Swift-BAT 15-50 keV lightcurve, which resulted in a NuSTAR ToO observation of this source by 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 MAXI lightcurve increasing to a plateau in 2018 and the Swift-BAT lightcurve in an apparently quiescent state. We can note that the StrayCats observations cover the time periods prior to the dip in the BAT lightcurve and also span periods during the Swift-BAT minimum.

Obs #	Sequence ID	Obs. Date	MJD	FPM	Exp. (ks)	Area (cm^2)
1	80002012002	2014-02-14T00:36:07	56702.0	A	24.05	1.84
2	80002012004	2014-04-17T22:46:07	56765.0	A	26.42	2.30
3	30101053002	2015-06-17T16:06:07	57190.7	A	131.32	2.71
4	30101053004	2015-06-21T07:11:07	57194.3	A	51.52	2.56
5	90102011002	2015-08-14T12:21:08	57248.5	A	30.65	1.77
6	90102011002	2015-08-14T12:21:08	57248.5	B	30.60	3.39
7	60160692002	2016-04-14T18:26:08	57492.8	B	21.78	1.66
8	10202005002	2017-04-18T13:06:09	57861.6	A	156.51	2.38
9	10202005004	2017-09-23T08:36:09	58019.4	B	155.37	8.71
10	80460628002	2019-03-08T20:21:09	58550.9	B	41.05	1.65

Table 1: Basic information of all the NuSTAR Stray Light observations of GS 1826-24

Sequence ID	10202005004
Obs. Date	2017-09-23T08:36:09
MJD	58019.4
Primary Target	PSR_B1821m24
Exposure Time	155.37s
Stray Light Area	8.71cm^2
Count rate (3-10 keV)	1.844 ± 0.003 counts / s
Count rate (10-20 keV)	0.2288 ± 0.0012 counts / s
Count rate (3-10 keV) per area	0.2117 ± 0.0003 counts / s / cm^2

Table 2: Information included in the observation report

2. OBSERVATIONS AND DATA REDUCTION

There has been 10 Stray Light observations of GS 1826 and Table 1 shows a brief summary of all the observations. We have obtained several long observations of more than 100 ks both during the hard state and the soft state. Note that in Table 1, there are two observations from the sequence ID 90102011002, one each from Focal Plane Module (FPM) A and B. For this observation, the stray light data from both FPM A and FPM B were reprocessed and included in the observation report, but the analysis was carried out only using FPM A, which has a higher count rate. The stray light extraction regions were created using DS9 and a Stray Light Wrapper notebook was used to process the data and create higher level products, such as light curves at different time bins and a spectrum at NuSTAR's full energy band of 3-79 keV. An example of the selection of the extraction region is shown in Figure 4. The key information about each observation was compiled into an observation report, as shown in Table 2 and the following page.

In order to carry out a spectral analysis of the X-Ray bursts and the spectrum in its quiescent state (when the source is not undergoing an X-Ray burst), the GTI (Good Time Interval) files were needed, which records the start and stop times of the X-Ray bursts. These start/stop times were obtained by noting down the approximate times of the bursts by eye. Likewise the GTI files for the quiescent state were created, which contains the times when the source is not bursting. The spectral analysis was carried out by taking one observation

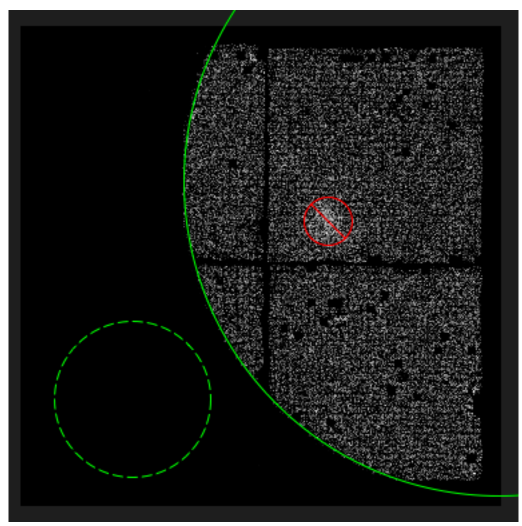
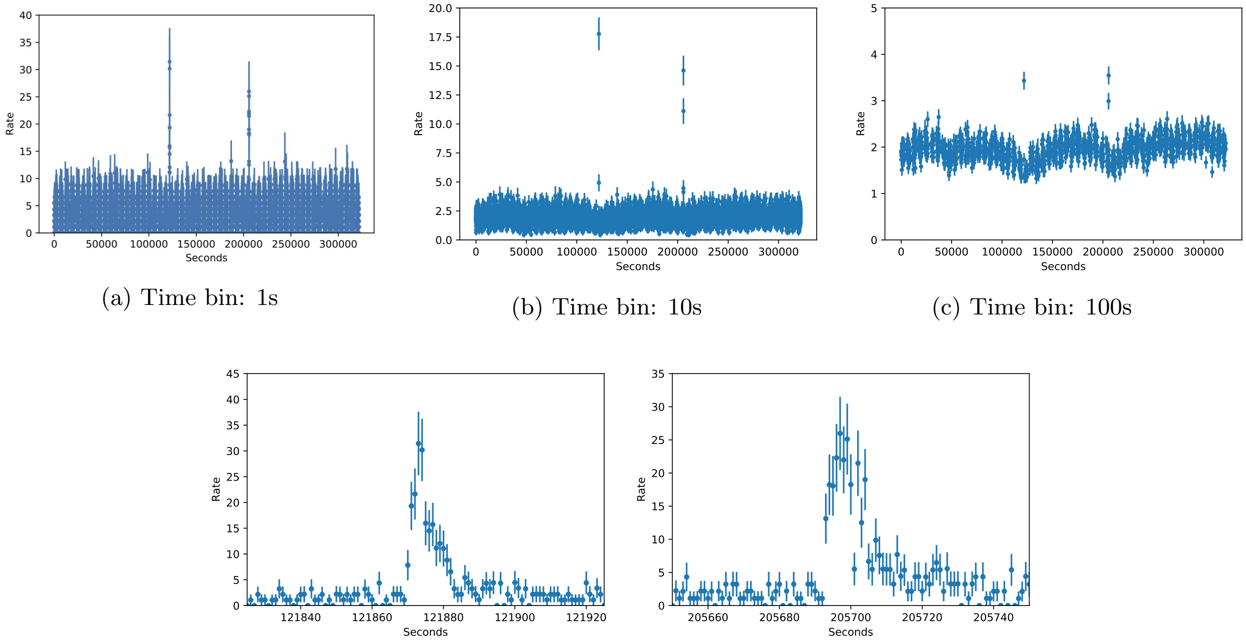


Figure 4: Extraction region for nu10202005004. Green Solid line refers to the Stray Light region, green dashed line is the background region, and the red solid line is the focused observation, which is excluded in the analysis



(a) Time bin: 1s

(b) Time bin: 10s

(c) Time bin: 100s

(d)

(e)

Figure 5: (a), (b), (c): Light curves of nu10202005004B01, full FoV, 3-10keV. Note the spikes in the full light curve. These, when zoomed in, turn out to be type 1 X-Ray bursts, characterised by their Fast Rise Exponential Decay (FRED) shape. (d) and (e) are the zoomed in Type 1 X-Ray burst light curves, at time bins of 1s, 3-10keV

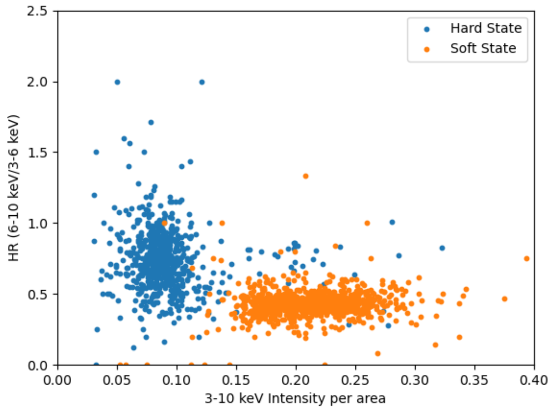
from the hard and soft state each. nu80002012002 was chosen for the observation during the hard state and nu10202005004 for the soft state, based on their higher count rates compared to the other observations.

Hardness intensity diagrams can be used to see if GS 1826 was doing anything odd during the observation and determine whether we can proceed with using the entire observation for the continuum spectrum. I created and took a ratio of the hard spectrum (6-10 keV) against the soft spectrum (3-6 keV), at 500s time bins. The source wasn't appearing to be changing much throughout time, hence I proceeded to use the entire observation for the continuum spectrum.

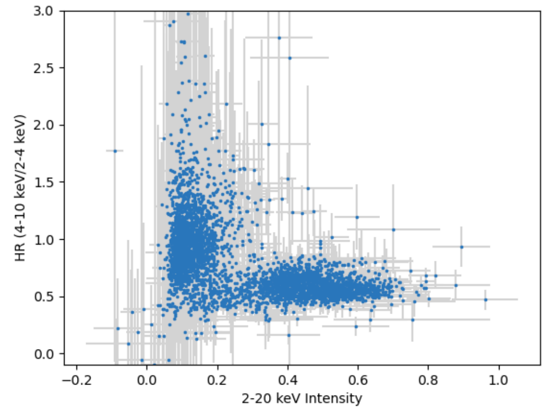
3. ANALYSIS

There were Type 1 X-Ray bursts observed in other stray light observations, similar to those in Figure 5. Upon looking through all the observations, I obtained zoomed in light curves of 31 X-Ray bursts; 22 in which the source was in its hard state and 9 when the source was in its soft state. The rogues gallary of all the Type 1 X-Ray bursts is shown in Figure 9 in the Appendix. There are significant differences between the burst profiles when the source is in its hard state and soft state. The main differences are that the burst durations are longer when the source is in its hard state (100-150 seconds) than that during the soft state (50 seconds). Another difference is that the peak intensity of the burst is generally higher when the source was in its soft state than that during its hard state. I was also able to detect some potential double bursts, such as the first two from the right on the 5th row in Figure 9.

Hardness intensity to Ratio Diagrams (HIDs) can be another good proxy for determining the spectral states of sources. GS 1824 is known to be an atoll source. Atoll sources show two states on the HR-intensity diagram. One is an island state, meaning that the source is in a hard spectral state and the other is the banana state, as it is characterised by a fuzzy upwardly curved branch and is observed during the soft spectral state, Hasinger & van der Klis (1989). The ratio of the hard color (6-10 keV) against the soft color (3-6 keV) was plotted against intensity per area for all the observations, as shown in Figure 6 (a). Previous observations of GS1826 has found the source to be in a hard spectral state, or the island state, Chenevez et al. (2016). The same was observed during the hard state observations in stray light. With the soft state observations, the plots branch out, and shows the possibility of it being a part of the banana branch. Similar plots were made using the MAXI, Monitor of All Sky X-Ray Image, taking the ratio of the 4-10 keV against 2-4 keV and plotting the hardness ratio against 2-20 keV, shown in Figure 6 (b).



(a)



(b)

Figure 6: (a) Hardness Ratio (6-10 keV / 3-6 keV) vs Intensity (3-10 keV) Diagram from the NuSTAR Stray Light observations. Blue data points correspond to the hard state observations and the orange points correspond to the soft state observations. (b) Hardness Ratio (4-10 keV / 2-4 keV) vs Intensity (2-20 keV) Diagram using the MAXI (Monitor of All Sky X-Ray Image) data.

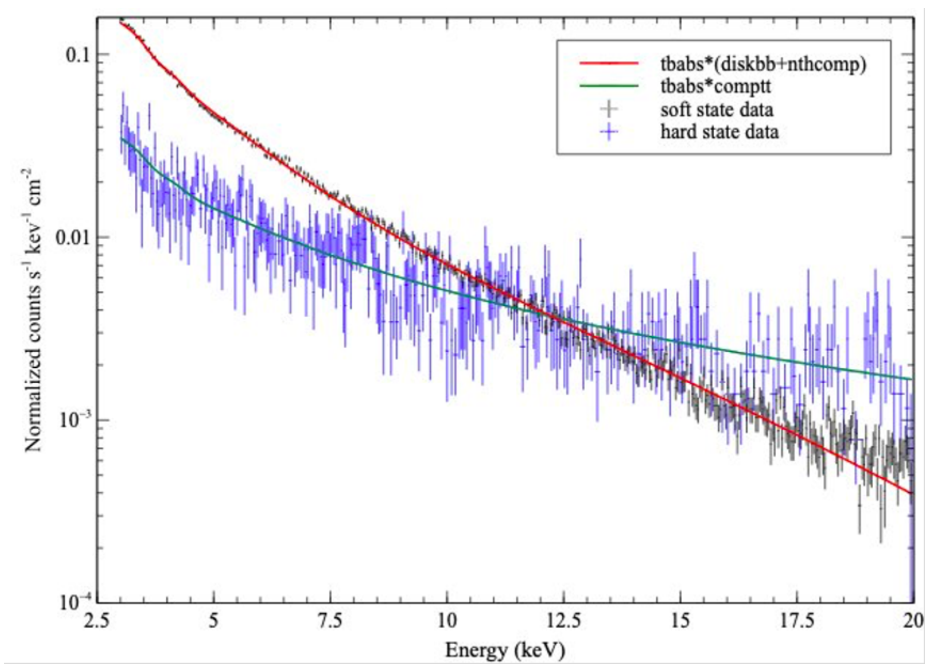


Figure 7: Spectrum modelling of the hard and soft state spectrum of GS 1826. The hard state data (blue) has been fitted with `tbabs*comptt` (green solid line) and the soft state data (black) with the `tbabs*(diskbb+nthcomp)` model (red solid line)

The shape obtained is very similar to the Stray Light HID diagram, which verifies that the stray light HID is in the correct shape.

An attempt to model the spectrum of GS 1826 was also made using the background subtracted spectrum of the quiescent state of the source in its hard and soft state. The first `tbabs` component is the absorption by gas in the galaxy between us and the source. The hard spectrum is supposed to look like a cutoff powerlaw, hence using a comptonization model `comptt`, which is an analytic model of the comptonization of soft photons in a hot plasma. The plot showing the spectral fittings of the hard state is shown below.

Obs. Date	Hard / Soft	Instrument	Absorbed / Unabsorbed	E (keV)	Flux (10-9 erg/s-1/cm-2)	Reference
2002 July	Hard	RXTE	Absorbed	2.5 ~ 25	2.2	Galloway et al. (2004)
2014 Feb		Stray Light			2.09	-
2017 Sep	Soft	NICER		2.5~9	3.6	Strohmayer et al. (2018)
		Stray Light			3.17	-
		NICER	Unabsorbed	0.6 ~ 9	5.0 ~ 5.2	Strohmayer et al. (2018)
		Stray Light			5.61	-

Figure 8: Flux calculations of the hard and soft state of GS 1826 and its comparison to existing literature values

In the soft state, the spectra are generally described by models that include a soft/thermal and a hard/Comptonized component. Hence, we added in a blackbody (bb) component coming from the NS surface. We used `tbabs*(diskbb+nthcomp)` which is a typical model for a soft state atoll source, Lin et al. (2007). The plots fit fairly well, for the hard state, we have a reduced χ^2 of 1.23 and for the soft state, we have a reduced χ^2 of 1.43. These fits are mainly to illustrate the spectral differences between the hard and soft states and there are refinements that need to be done.

For other atoll sources, the soft "banana" persistent spectral state is usually interpreted as indicating a higher accretion rate, and seemingly, a higher average burst rate for GS 1826–24, Chenevez et al. (2016). Hence, I also made some flux calculations and compared them to existing literature. I calculated and compared the absorbed flux of GS 1826 during the hard spectral state and compared it to the value in Galloway et al. (2004) and the soft state flux against the values from NICER by Strohmayer et al. (2018). The stray light values each do not differ to much from literature, and we can note that in the flux values are higher in the soft state, which agrees with our expectations.

4. DISCUSSION

The Stray Light observations provide us a unique window into the long term behaviour of GS 1826-24. The different Type I X-Ray burst profiles, the two distinct island and banana shapes in the HID diagram and the different spectral fits all add evidence to GS 1826's transition from the hard state to the soft state. The next step would be to refine the spectral fittings for the continuum and to model the X-Ray bursts as well. From here, the goal would be to connect the change in accretion, due to the change in state, with the change in Type I X-Ray burst behavior, and gaining a better understanding of the source and its sudden transition from the hard to soft state.

I would like to thank Brian Grefenstette for the helpful guidance this summer, and I would also like to acknowledge Renee Ludlam for the helpful insights towards the Hardness Intensity Diagrams and the spectral fits; and Sean Pike for the advice on how to proceed with Type 1 X-Ray burst analysis. Lastly, I would like to thank the NuSTAR group and the SURF 2021 program for providing a valuable experience this summer.

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5. APPENDIX

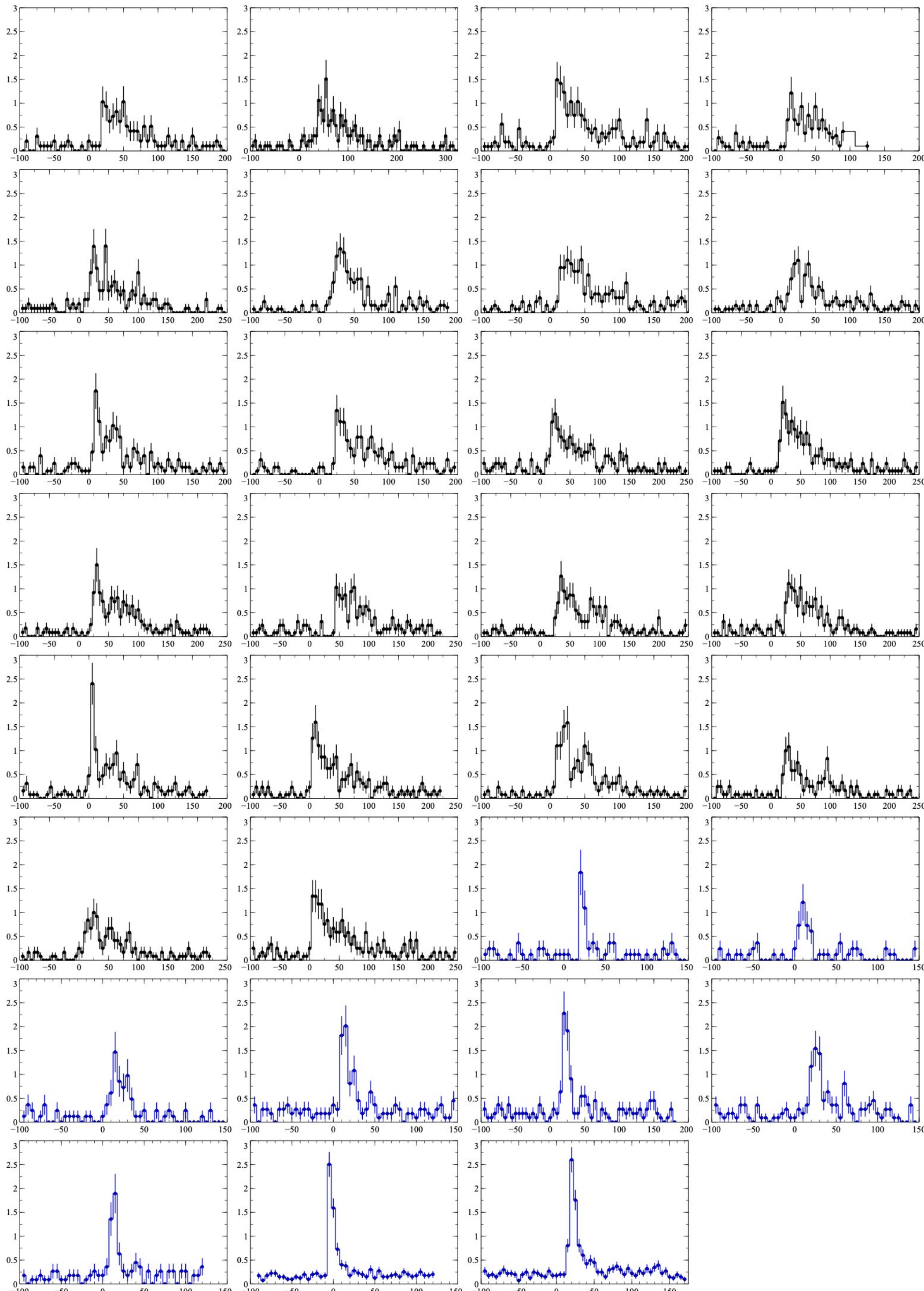

Figure 9: A rogues gallary of all the Type 1 X-Ray bursts observed in the 9 observations of GS 1826. The hard state bursts are in black and the soft state bursts are in blue