Project 3 - X-ray Astronomy

Basic Analysis of X-Ray Observations from NICER

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Contents

1 Installation

1.1 Installing NICER

The NICER package was installed along with HEASOFT which also contained an XSPEC build that was used later on when producing a spectrum. The output to the command `nicerversion` can be found in the associated *.txt* file.

1.2 CALDB

In order to run some of the data processing in later stages of the analysis, we needed to create a calibration database (CALDB) that contains required calibration files for running the NICER level 2 commands. The output of `caldbinfo INST NICER XTI` can be found in the associated *.txt* file.

Downloading the NICER *goodfiles* results in a collection of ARF and RMF files. From the data contained within the first ARF file, the spectral response as a function of energy is plotted in Figure 1.

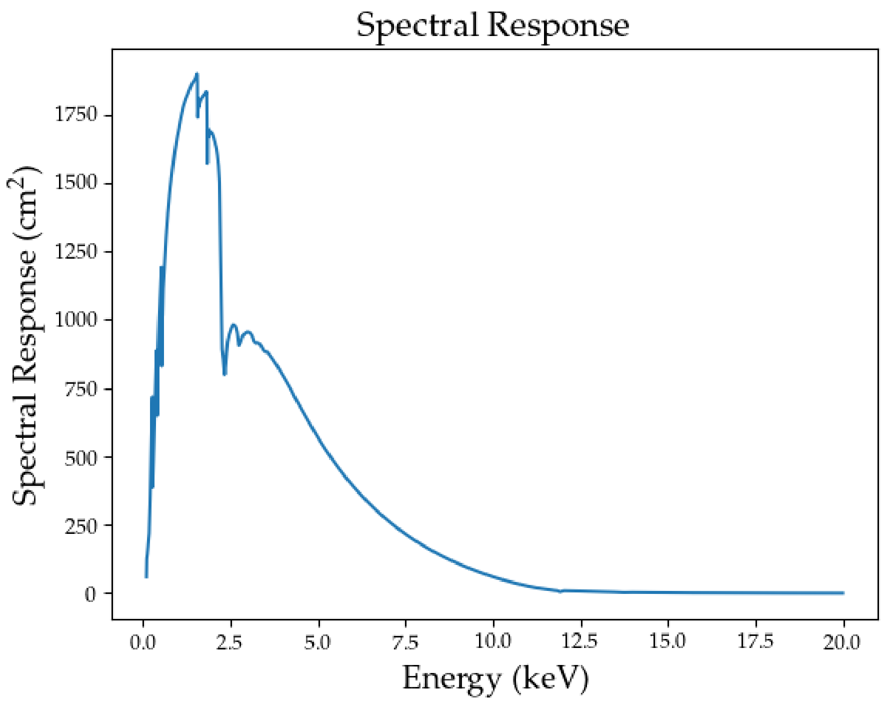

Figure 1: Spectral response as a function of energy pertaining to the NICER mission and X-ray Timing Instrument (XTI).

Since X-ray instruments inevitably measure the signal of incoming photons in units of counts, analysts require a method of converting modeled flux to units of counts. ARFs provide this conversion mechanism and contain the information about the total throughput of the instrument [1]. ARFs specifically represent the product of the energy independent detector area and the probability of a photon to produce a count in the detector.

Examining Figure 1, we can see a large peak around 2 keV. The response falls off sharply thereafter, before a smaller peak around 2.5 keV, followed by a more slowly varying decrease in detector response as we move to higher energies. These features correspond to the quoted abilities of the NICER mission (high-resolution observations between 0.2-12 keV), however, they also demonstrate NICER's increased sensitivity to soft X-rays.

Setting up the calibration database also involves downloading a set of Response Matrix Files (RMFs). These files on the other hand, contain information about the energy redistribution. These files are important because although the detector may record a particular count pulse height, this height may be skewed toward alternate values as a result of systematics like thermal noise. The response matrix contains information for the given mission (NICER in our case) regarding the known detector resolution and charge collection efficiency effects [1].

1.3 Geomagnetic Calibration Files

Running calibration steps in the NICER analysis also requires data sets pertaining to various geomagnetic quantities. Setting the path to *GEOMAG_PATH* and running the command `nigeodown` downloaded a collection of geomagnetic calibration files to the desired location on disk.

This collection of geomagnetic quantities provides details on specific background events that would also result in events in the silicon detector in addition to the desired X-ray photon counts. Modeling these background events is crucial to be able to subtract the background from the signal of interest. Some examples of the background signals that are modeled are events caused by the detector traveling through radiation belts as well as solar and extra-solar cosmic rays [1].

2 Data Retrieval

To download the specific data from the event studied in Ref [3], the Observation ID, 2584010501, was used to locate the data in the NICERMASTR catalog and was downloaded using the `wget` command. This produced a directory titled 2584010501 containing subdirectories specific to the XTI and the files necessary to repeat the analysis from Ref [3].

3 Data Preparation and Data Investigation

3.1 Cleaning with NICER Level-2

The first step of data processing that was performed on the downloaded directory was the level 2 NICER analysis and was ran using the command `nicerl2`. This bundled script is a high level task that performs the following five processing steps and is outlined in the analysis threads in Ref [1]:

nicercal - apply standard NICER calibration: Since the data is broken up into 7 files corresponding to each Measurement Power Unit (MPU) slice, this step performs energy gain calibration and clock calibration on the data from each MPU slice at a time.

niprefilter2 - derive calibrated filter (MKF) file: This task performs two steps. First, it produces what NICER calls a NICER-specific filter file which is a file containing information about instrument related and background quantities that can be used for data screening. The niprefilter2 task augments this initial NICER-specific filter file by adding additional information that may be more useful when cleaning the data later on.

nimaketime - create standard screening good time intervals: This task creates a Good Time Interval (GTI) file that can be used to screen events during later analysis. It does not screen events, it only creates the file containing parameters on how one may want to perform the screening.

nicermergeclean - combine per-MPU data and filter/screen: This task runs sub-tasks consisting of first merging the provided 6 MPU files (that are calibrated, but not yet screened) and second, running the routine "nicerclean" which applies a set of screening criteria.

niautoscreen - automatically screen for problematic per-FPM and per-MPU conditions: This task performs an additional screening per Focal Plane Module and Measurement Power Unit and compares the individual results to the results of the screening of the whole group like in "nimaketime" using statistical measures. This is used to catch potential issues with a single FPM or MPU that the overall screening may have missed.

The whole routine produces a script with the extension *.cl* implying the collection of data files for each MPU has been cleaned and merged into a single file. The specific file for this NICER event was found to be **2584010501/xti/event_cl/ni2584010501_0mpu7_cl.evt**.

3.2 Examining the Cleaned (*.cl*) File

Taking a closer look at the cleaned file produced after running the level 2 NICER cleaning routine, we can see the file consists of the following information:

```
Filename: obs_id_data/2584010501/xti/event_cl/ni2584010501_0mpu7_cl.evt
No.    Name      Ver    Type      Cards   Dimensions   Format
  0  PRIMARY       1 PrimaryHDU      32   ()
  1  EVENTS        1 BinTableHDU    284   2415871R x 14C   [1D, 1B, 1B, 1I, 1I, 1B, 1B,
  2  FPM_SEL       1 BinTableHDU    122   22977R x 3C   [1D, 56B, 56I]
  3  GTI           1 BinTableHDU    254   25R x 2C   [D, D]
  4  GTI_DET10     1 BinTableHDU    229   24R x 2C   [D, D]
  5  GTI_MPU0      1 BinTableHDU    253   25R x 2C   [D, D]
  6  GTI_MPU1      1 BinTableHDU    253   25R x 2C   [D, D]
  7  GTI_MPU2      1 BinTableHDU    253   25R x 2C   [D, D]
  8  GTI_MPU3      1 BinTableHDU    253   25R x 2C   [D, D]
  9  GTI_MPU4      1 BinTableHDU    253   25R x 2C   [D, D]
 10  GTI_MPU5      1 BinTableHDU    253   25R x 2C   [D, D]
 11  GTI_MPU6      1 BinTableHDU    253   25R x 2C   [D, D],
```

which supports the output descriptions of the cleaning process from the previous section. We can see an EVENTS data set, which will contain the data pertaining to the observation itself. A data set for Focal Plane Module Selection is also evident under (FPM_SEL) that would have resulted from running the final command (`niautoscreen`) under the NICER level 2 analysis. Finally, there is a general Good Time Interval (GTI) general data set for screening events as well as a GTI table corresponding to each MPU. The individual GTI files for each MPU can be explained by review the description of the `niautoscreen` sub-task performed by the cleaning routine in the previous section.

Raw (uncalibrated) energy and time histograms from the cleaned data table can be seen in Figure 2. From the uncalibrated energy plot, it is straightforward to see that the measured energies are collected around a particular channel (around channel 750) with a skewed distribution toward higher energy channels. Alternatively, we can see that the times measured correspond not to a continuum of times, but rather to specific times corresponding to measured events spaced out by roughly 5000 seconds or close to 1.4 hours.

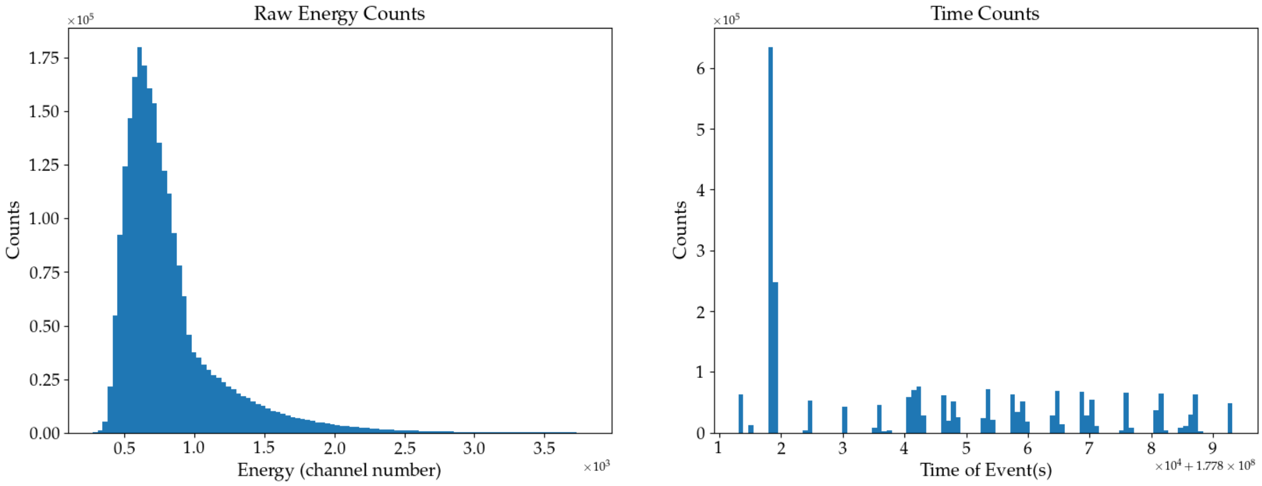

Figure 2: Raw energy counts corresponding to uncalibrated, slow signal chain events (left). Counts corresponding to the time of events (Right). Both plots correspond to the observation data analyzed in Ref [3].

3.3 Barycenter Correction

At this stage, barycenter correction using the routine `barycorr` was applied to the directory containing the X-ray observation data. Barycentering is the process of calibrating time values corresponding to events at a detector to correct for the non-inertial frame of the detector [2]. This NICER task calculates and adjusts for the time that an event would have occurred at the detector as if the event had occurred at the solar system barycenter from the target. Without barycentering, the arrival times of photons may not correspond to the true emission times at the target as a result of the detector's (non-inertial) motion through the solar system. It is important to obtain a precise picture of the timing between successive X-ray events.

In Figure 3, we can see the difference between the original and barycenter corrected times. The size of the time correction times is very small compared to the spacing of the times of events themselves, demonstrating the small, but noticeable effect that the Earth's motion has on arrival times of photons from the X-ray pulsar SAX J1808.4–3658.

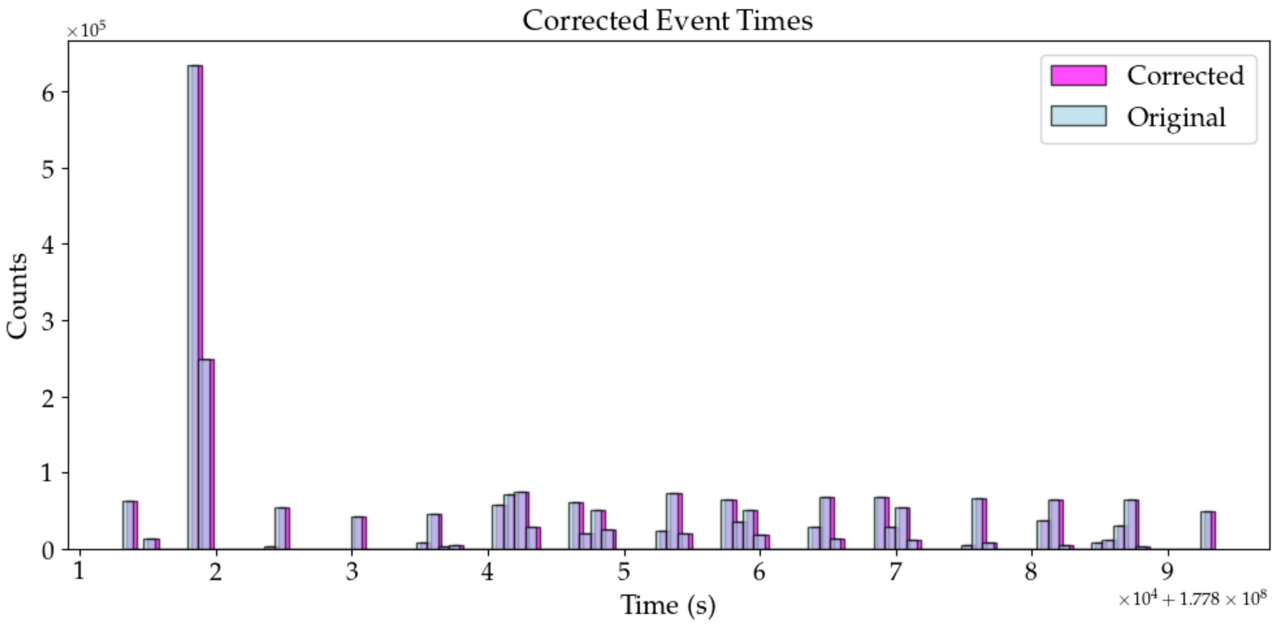

Figure 3: Comparison between original and barycenter corrected arrival times of events. From this plot, it is clear that the correction to time is far smaller than the typical arrival time scales involved when considering successive collections of events.

4 Light Curves

4.1 NICER Level 3 Analysis - Light Curve

The NICER level 3 analysis contains the option to extract the light curve from a cleaned data file using the command `nicerl3-lc` and creates two files. One is the extracted light curve from the cleaned event, and the other is a background light curve. We wanted to produce light curves with the following configurations:

1. 0.1 time bins, 0.3 - 10 keV
2. 0.1 time bins, 3 - 10 keV
3. 0.1 time bins, 0.3 - 1 keV.

The `nicerl3-lc` command, however, requires the energy units to be in units of calibrated channel number or “Pulse Invariant” (PI) number. According to Ref [1], each energy bin corresponds to 10 eV or 0.01 keV on a linear scale. This means that the configurations should be entered as:

1. 0.1 time bins, 30 - 1000
2. 0.1 time bins, 300 - 1000
3. 0.1 time bins, 30 - 100.

4.2 Light Curve and Hardness Ratio

The flare of interest dominates roughly 60 seconds worth of data. Through trial and error, this was found to correspond to an index in the time array of 12030. Since we chose the time bins to be 0.1 seconds each, that meant that flare occurred over roughly 600 time bins in the light curve data for a right most bin of 12630.

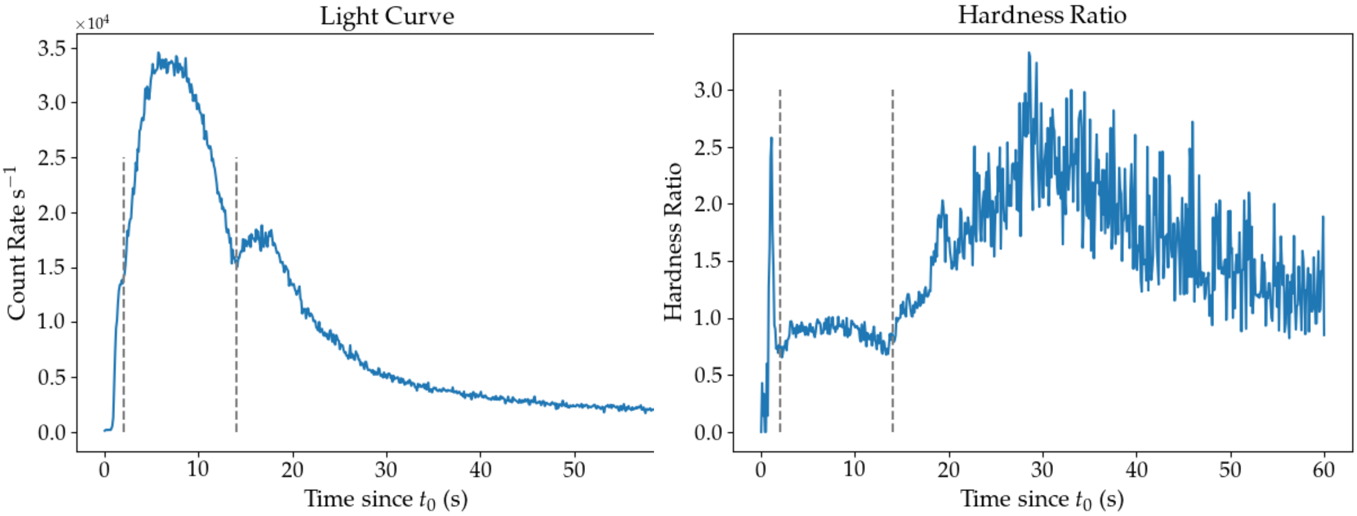

Figure 4: Light curve (left) and hardness ratio (right) correspond to the X-ray flare observation data analyzed in Ref [3]. The full energy range for the light curve is from 0.3 eV to 10 eV and the hardness ratio is determined by dividing the light curve data from the range 3 - 10 eV by the range 0.3 - 1 eV. Vertical dashed grey lines are drawn at the same time values of 2 seconds and 14 seconds in each plot to demonstrate the shared location of features. Both plots begin at begin at $t_0 = 5562.5$ TDB.

The left plot in Figure 4 (the light curve) shows the count rate of photons from the flare analyzed in Ref [3] over the 60 second window of highest activity. It shows that close to 3.5×10^4 photons were detected in the first 10-12 seconds of the burst and also shows several other important features like a secondary peak at roughly 16 seconds and a slight pause in count rate during the initial increase in events at the start of the burst. The light curve effectively provides us with information about the flux of emission as a function of time at the location of the detector and allows us to predict which physical processes could result in the features present in the plot.

The right plot in Figure 4 (the hardness ratio) provides a clear picture of the dominant energy range of photons detected as a function of the same time interval as the light curve. Where as the light curve consists of data from events across the whole energy band, the hardness ratio calculates the ratio of "hard" or high-energy X-rays over "soft" or low energy X-rays. From the hardness ratio in Figure 4, we can see that the initial large peak of events over the first 10-15 seconds is dominated by mostly low-energy X-rays in the energy range of 0.3-10 keV. Conversely, as the count rate decreases, the events are made up of far greater high-energy events in the energy range of 3-10 keV.

5 Spectrum

5.1 Generating the GTI File

In order to run the Level 3 NICER - Spectrum routine, we required a *.gti* file that consisted of information regarding the correct time bins for our observation, and a corresponding *.header* file providing information about the date and time in the MJD system, along with a time offset value or variable TIMEZERO. This information was located in the header of the light curve dataset used to produce the plot in Figure 4.

5.2 SAX J1808.4–3658 Spectrum

Using *xspec* and loading the file that was output by the *nicerl3-spec* routine, the spectrum corresponding to the X-ray burst from SAX J1808.4–3658 analyzed by Ref [3] is shown in Figure 5. To plot the spectrum in *xspec*, the following commands were used [1]:

cpd /xs: This sets the "current plotting device" to the device where the user would like to send the graphical output to. In this case is sets the the "X windows" device.

setplot energy: This command changes the x-axis of the plot to be in units of log energy.

setplot rebin 10 10: Performs visual rebinning.

plot ldata: Plots the data with a log Y scale.

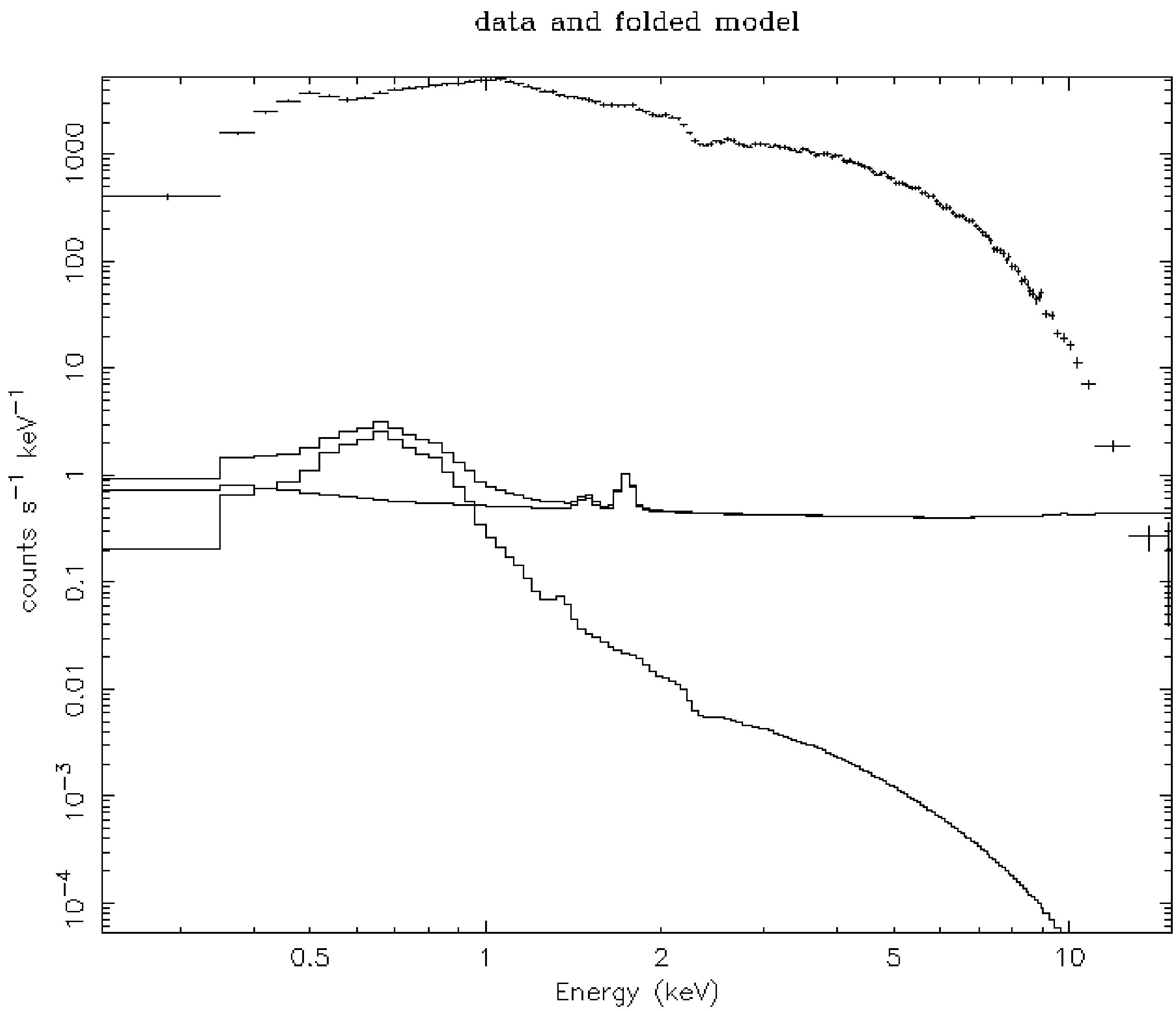

Figure 5: XSPEC output corresponding to the X-ray burst spectrum from the pulsar SAX J1808.4–3658 observed on August 21st, 2019 and analyzed in Ref [3].

Examining the spectrum in Figure 5, we can see a clear distinction between the true X-ray spectrum from the pulsar emission, and another set of lines at a much lower count rate across the energy band as well. These latter 3 lines likely comprise the X-ray and non X-ray background, though they are difficult to distinguish in this plot. Most notably, we can see a clear set of counts corresponding to the X-ray emission that is fairly uniformly peaked across the energy band with a drop off that begins around 5 keV and a set of lines denoting the background (both X-ray and non X-ray) events at a much lower count rate, that also occurs across the range of energies.

6 References

[1] URL: https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_analysis.html.

[2] URL: https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Pulsars/barycentric_correction.html.

[3] Peter Bult, Gaurava K. Jaisawal, Tolga Güver, Tod E. Strohmayer, Diego Altamirano, Zaven Arzoumanian, David R. Ballantyne, Deepto Chakrabarty, Jérôme Chenevez, Keith C. Gendreau, Sebastien Guillot, and Renee M. Ludlam. A nicer thermonuclear burst from the millisecond x-ray pulsar sax j1808.4–3658. *The Astrophysical Journal Letters*, 885(1):L1, October 2019. URL: http://dx.doi.org/10.3847/2041-8213/ab4ae1, doi:10.3847/2041-8213/ab4ae1.