Astrophysical Data Analysis

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Abstract

Black holes are one of the most popular areas of interest in astronomy. They are extremely compact, infinitely dense objects in space that apply immense gravitational field to their surroundings, bending space-time to the point of trapping anything, even electromagnetic lights, that falls beyond their event horizon. Since black holes do not emit any electromagnetic waves, observing them directly often proves to be a challenging task.

However, astronomers can observe and analyze the nature of black holes under special cases; one of these cases being the black hole-star binary systems. In black hole-star binaries, the material cascading towards the black hole from the companion star reaches millions of degrees temperatures, generating electromagnetic waves, predominantly in the form of X-rays. Black hole-star binary systems often have certain structural components such as the accretion disk, corona, jet, and winds. These binary systems are often analyzed under categories called states, where each state is characterized by the existence/absence or strengthening/weakening of certain structural components, changes in the overall luminosity, spectrum and certain timing properties like quasi-periodic oscillations. Instabilities in their structural components, changing accretion rates along with other effects often cause black holes to transition states. To analyze and observe the nature and the properties of these black hole systems, astronomers make use of X-ray telescopes that are in outer space as a result of the Earth's X-ray absorbing atmosphere.

Keywords: *X-ray binaries, blackholes, Python, spectral fitting.*

1 Introduction

In the realm of black hole binary systems, X-ray data and observatories are pivotal for understanding these binary systems - comprising a black hole and an ordinary star, exhibit distinct behaviors during accretion processes, shedding light on the underlying astrophysical mechanisms. Our project centers on the analysis of X-ray data from observatories, specifically examining the characteristics of black hole binaries in their different states.

As material accretes from companion stars, it forms an accretion disk around black holes, producing X-ray emissions that provide valuable insights into the internal dynamics of these systems. Understanding the timing, spectral properties, and evolutionary paths of black hole binaries is essential for advancing our comprehension of fundamental astrophysical phenomena.

Despite challenges like the high energy of photons and the need for space-based observatories due to atmospheric absorption, technological advancements, notably through observatories like Chandra and Swift, have enhanced our capacity to investigate X-ray binaries. These observatories offer high-resolution imaging and facilitate nuanced analyses of spectral features.

Our project employs advanced data analysis techniques, including fitting various models for hard and soft states, generating time series analyses and analytical charts. While testing some models manually, we also integrate scripting approaches using programming languages like Python, to automate the process and gain better results. In this paper, we will explain the methods and platforms we have utilized to process and analyze the observational data collected by X-ray telescopes from a database called Xamin. Then, we will provide our spectral and timing analysis findings about two black hole binary systems, GX 339-4, MAXIJ1820+070..

2 Installation of the Necessary Software

For our studies, version 6.32.1 of HEASoft which is a software suite developed by NASA's High Energy Astrophysics Science Archive Research Center (HEASARC) was installed from source code distribution to Sabancı University's server used for astronomical research, Cosmos, to be used for data analysis. The software was downloaded to the server with necessary tools for the analysis of data coming from high energy astrophysics observatories INTEGRAL, IXPE, MAXI, NICER, NuSTAR, Swift, and XTE along with the HEASARC's latest calibration database (CALDB) files for corresponding observatories to ensure accurate calibration of astronomical data.

During the installation, the configure script was made sure to select the correct set of compilers for the build of the software by setting environment variables CC (C compiler), CXX (C++ compiler), FC (Fortran compiler), PERL (Perl interpreter), and PYTHON (Python interpreter) to the corresponding paths of gcc (v7.5.0), gfortran (v7.5.0), g++ (v7.5.0), perl (v5.26.1) and python3 (v3.7.5) which was a set of compatible compilers.

After the installation of the software, the Python packages AstroPy, NumPy, SciPy, and MatPlotLib which were needed for some HEASoft packages such as IXPE and NICER, already existed in the server and were updated locally using pip (the package installer for Python) to avoid disturbing other projects running with the already available versions of these.

To ensure that the required environment variables which provide a path to HEASoft and CALDB installations called HEADAS and CALDB respectively are set, and their corresponding initialization scripts are executed every time logged into the server, we have included the following lines:

```
export HEADAS=/cdata3/software/heasoft-6.32.1/x86_64-pc-linux-gnu-libc2.27

source $HEADAS/headas-init.sh

export CALDB=/cdata3/software/CALDB

source $CALDB/software/tools/caldbinit.sh
```

in our ".bashrc" files. The command "export" was used to set the environment variables HEADAS and CALDB to specific paths where HEASoft and CALDB are installed in the server Cosmos and the command "source" was used to execute the initialization scripts associated with these variables.

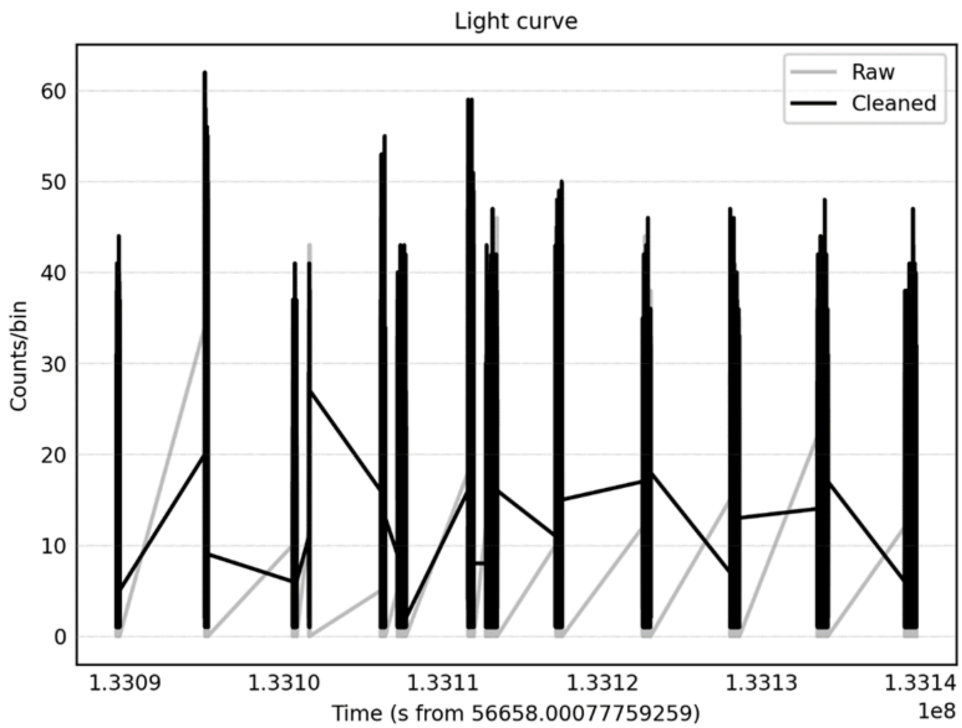
In the course of analysis, version 12.13.1 of the software XSPEC (An X-Ray Spectral Fitting Package) which is included in the HEASoft distribution, was utilized for spectral fitting of the data from HEASARC archives coming from high energy astrophysics observatories.

3 Converting the IDL Code for PDS to Stingray

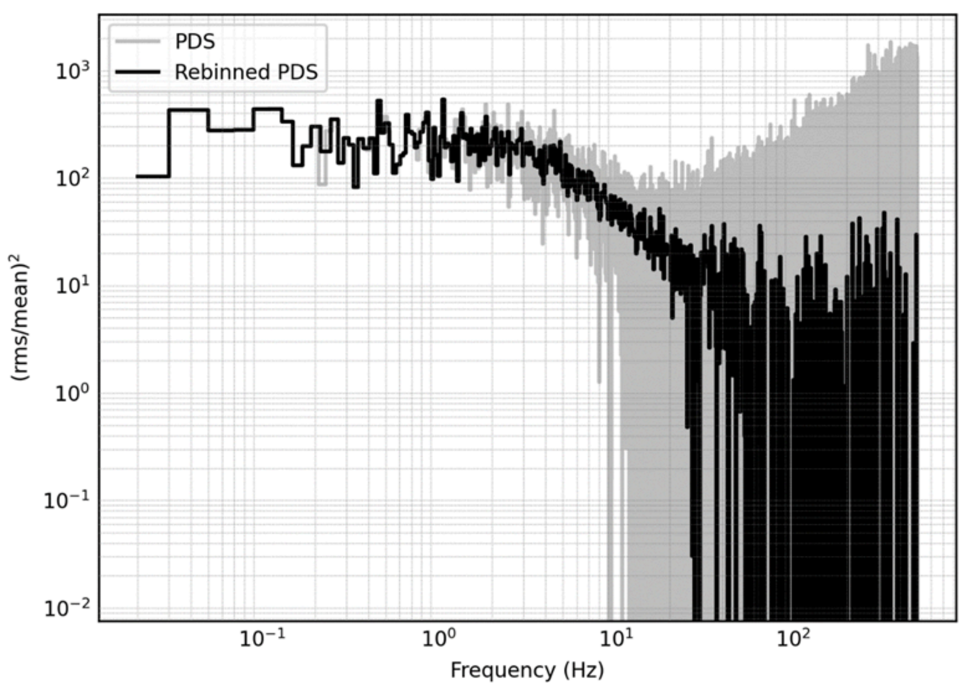
The primary objective was to transition from utilizing IDL (Interactive Data Language) to adopting Python for the comprehensive analysis of X-ray observations. Utilizing the wide capabilities of the Stingray library, a Python package designed for time series analysis in astrophysics, a detailed investigation into the observed X-ray events was performed.

The process began with the preprocessing of raw event data, which was obtained from the MAXI-J 1820+070 X-ray observation (obsId 1200120106). The data, stored in the form of an event file, was processed using the Stingray library's ‘EventList’ and ‘Lightcurve’ (Figure 1a) classes. A cleaning procedure was implemented by creating Good Time Intervals (GTIs) based on the temporal condition that the counts exceeded a threshold, ensuring the exclusion of undesirable time intervals. For further analysis, the Power Spectral Density (PSD) (Figure 1b) of the cleaned light curve was computed. The ‘AveragedPowerspectrum’ class from Stingray was employed, allowing us to examine the frequency domain characteristics of the observed X-ray emission. Poisson noise levels were calculated to assess the significance of detected variations in the PSD.

This task demonstrated the efficacy of the Stingray library in conducting advanced time series analysis of astrophysical data. The insights gained contribute to our understanding of the dynamic behavior of X-ray binary sources observed in the X-ray regime.



(Figure 1a, the light curve obtained from the event file of observation with ID 1200120106)



(Figure 1b, the power spectrum obtained from the light curve of observation with ID 1200120106)

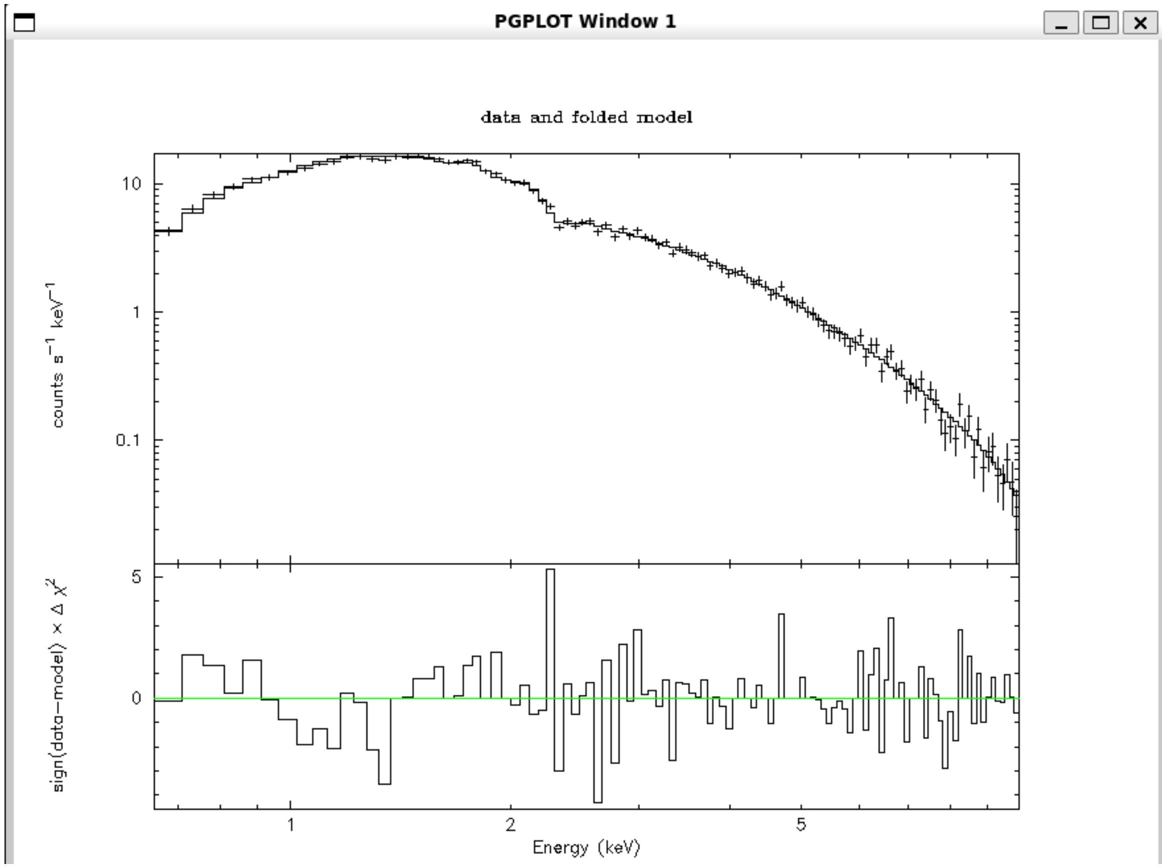
4 Spectral Fitting of Black Hole Binary Systems (MAXI,GX)

4.1 GX339-4

GX339-4 is an X-ray binary source which undergoes state transitions periodically. (Zdziarski et al., 2004). It is estimated to have a mass of 7 solar masses (Yamada et al., 2009) and its companion star is yet to be observed (Dunn et al., 2008). The objective of this part of the project was to identify models yielding a strong correlation with observational data, using these findings for spectral and temporal analysis of the source.

The first step was to obtain data from archives. The Xamin Web Interface from HEASARC was utilized with focusing on data from the NICER observatory, specifically selecting from the nicermastr catalogue. After careful examination of the literature, it was concluded that GX339-4 was in the hard state for two months between January 20, 2021, and March 20, 2021 (*The Astronomer's Telegram*, March 2021.). All the observations during this period have been retrieved for testing of the model. After that period, the source underwent a rapid state transition, in which the hard-intermediate state lasted for about a weeks' time (Liu et al., 2022).

After all the data was uploaded to the Cosmos server, the automated python script was used to process the observation data. For hard state observations, the default model of tbabs*(powerlaw+diskbb) was used and the relevant components were determined automatically with applying f-test. For the first observations (obsIDs ranging from 3133010101 to 3133010113), tbabs*(powerlaw) or tbabs*(powerlaw+diskbb) models were sufficient to fit the data. For the remaining observations, around 6.4 keV iron K emission lines were being started to be observed and chi-squared values were starting to differ greatly from degrees of freedom. Therefore, it was decided to add a gaussian component to the model to acknowledge this K line. For the remaining of hard state observations, this model was used. For hard-intermediate state observations (obsIDs ranging from 4133010103 to 4133010110) the same model was used. The reduced chi-square value slightly changed but the model still provided reasonable fits, however hard-intermediate state observations need more examination and some enhancements to the model might be required.



(Figure 2a, an automatic fit of a hard-state observation from obsID: 3133010101, chi-square method is used)

```
Parameters defined:
========================================================================
Model TBabs<1>*powerlaw<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.640331     +/-  1.27659E-02
   2    2   powerlaw   PhoIndex            1.55190      +/-  1.79484E-02
   3    2   powerlaw   norm                3.90900E-02  +/-  7.88700E-04
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                   107.31     using 112 bins.

Test statistic : Chi-Squared                   107.31     using 112 bins.
 Null hypothesis probability of 5.28e-01 with 109 degrees of freedom
```
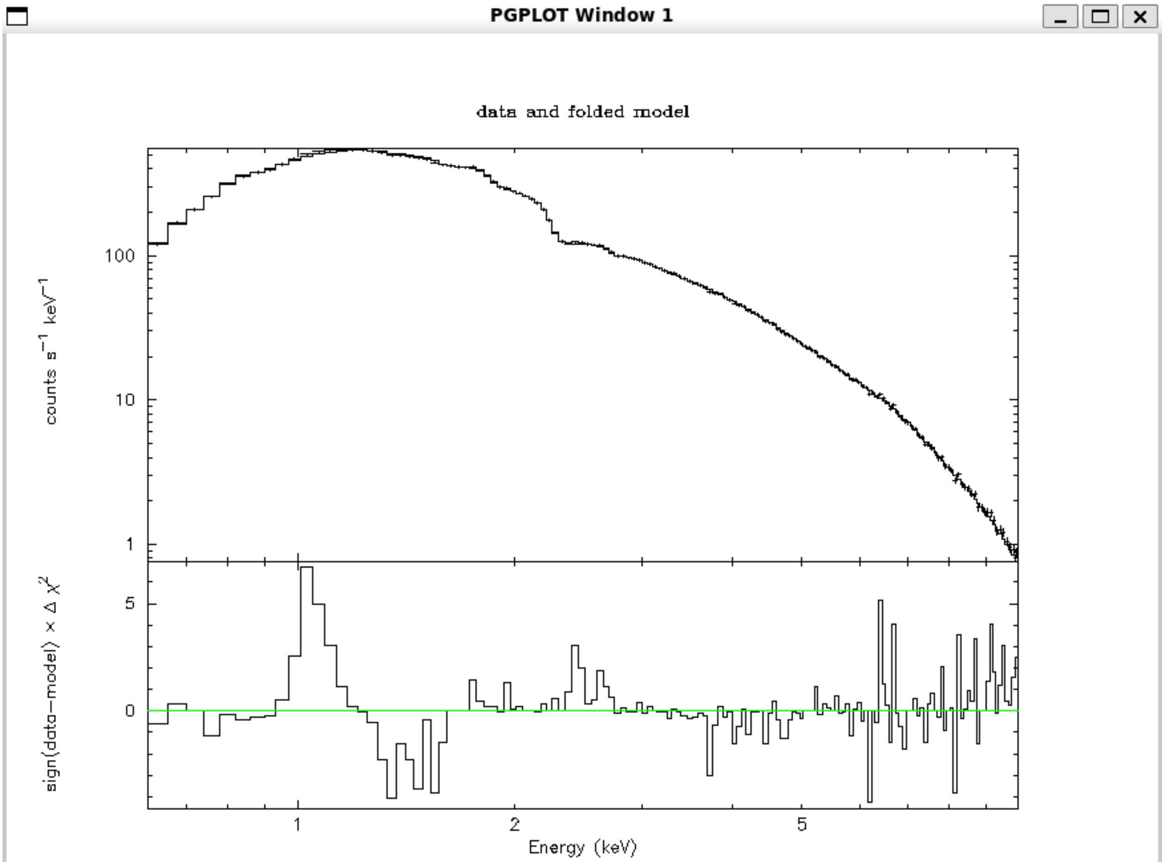

(Figure 2b, parameters and models in use for obsID: 3133010101)



(Figure 3a, an automatic fit of a hard state observation from obsID: 3558010601)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.663763     +/-  9.79064E-03
   2    2   powerlaw   PhoIndex            1.64021      +/-  1.25039E-02
   3    2   powerlaw   norm                0.639250     +/-  1.13204E-02
   4    3   diskbb     Tin        keV      0.299632     +/-  1.07840E-02
   5    3   diskbb     norm                6107.79      +/-  1237.79
   6    4   gaussian   LineE      keV      6.63603      +/-  7.35854E-02
   7    4   gaussian   Sigma      keV      0.627146     +/-  9.32020E-02
   8    4   gaussian   norm                4.45168E-03  +/-  7.82094E-04
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                 136.27     using 153 bins.

Test statistic : Chi-Squared                 136.27     using 153 bins.
 Null hypothesis probability of 6.86e-01 with 145 degrees of freedom
```
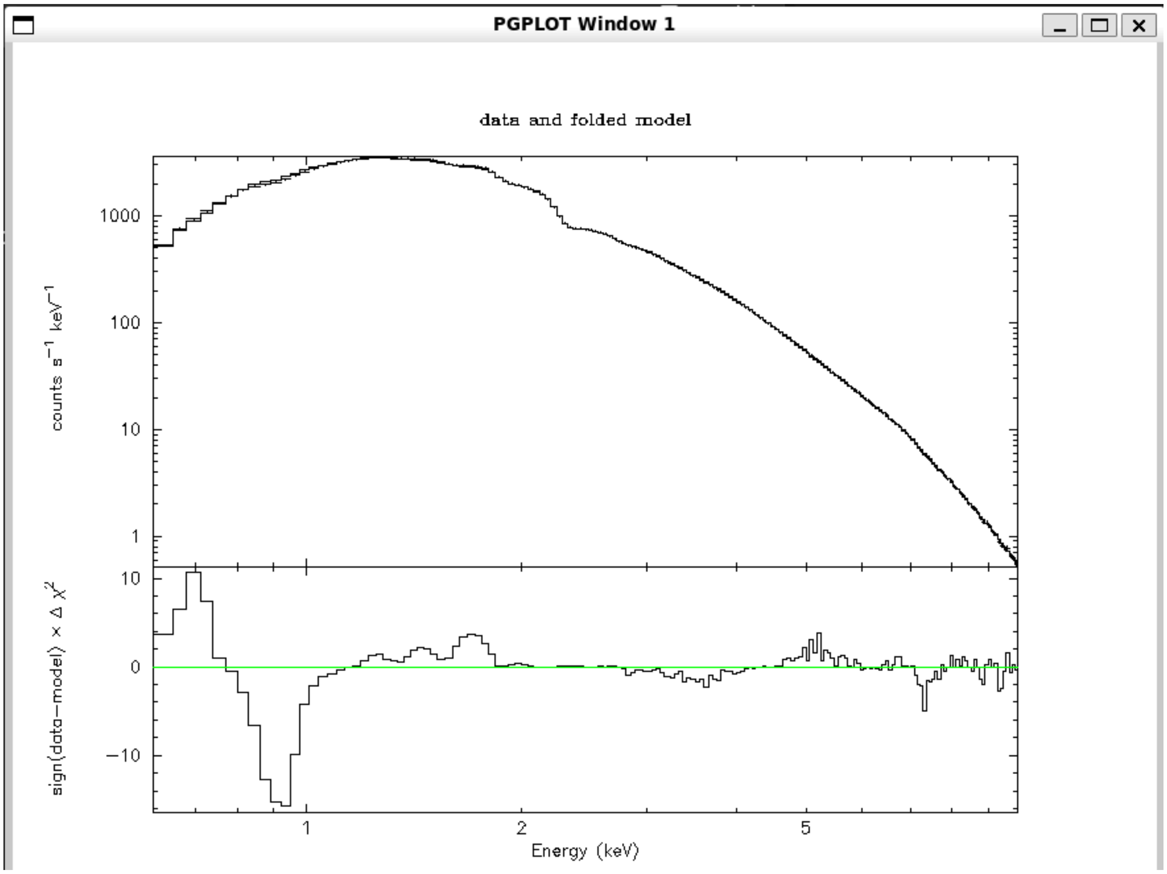

(Figure 3b, parameters and models in use for obsID: 3558010601)



(Figure 4a, an automatic fit of a hard-intermediate state observation from obsID: 4133010105)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.768809     +/-  8.84861E-03
   2    2   powerlaw   PhoIndex            2.56017      +/-  2.14605E-02
   3    2   powerlaw   norm                3.61402      +/-  0.168949
   4    3   diskbb     Tin        keV      0.798839     +/-  3.30698E-03
   5    3   diskbb     norm                1388.04      +/-  44.7915
   6    4   gaussian   LineE      keV      6.40000      +/-  0.100136
   7    4   gaussian   Sigma      keV      0.882276     +/-  5.28871E-02
   8    4   gaussian   norm                1.50910E-02  +/-  1.36097E-03
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                  230.82     using 175 bins.

Test statistic : Chi-Squared                  230.82     using 175 bins.
 Null hypothesis probability of 7.85e-04 with 167 degrees of freedom
```
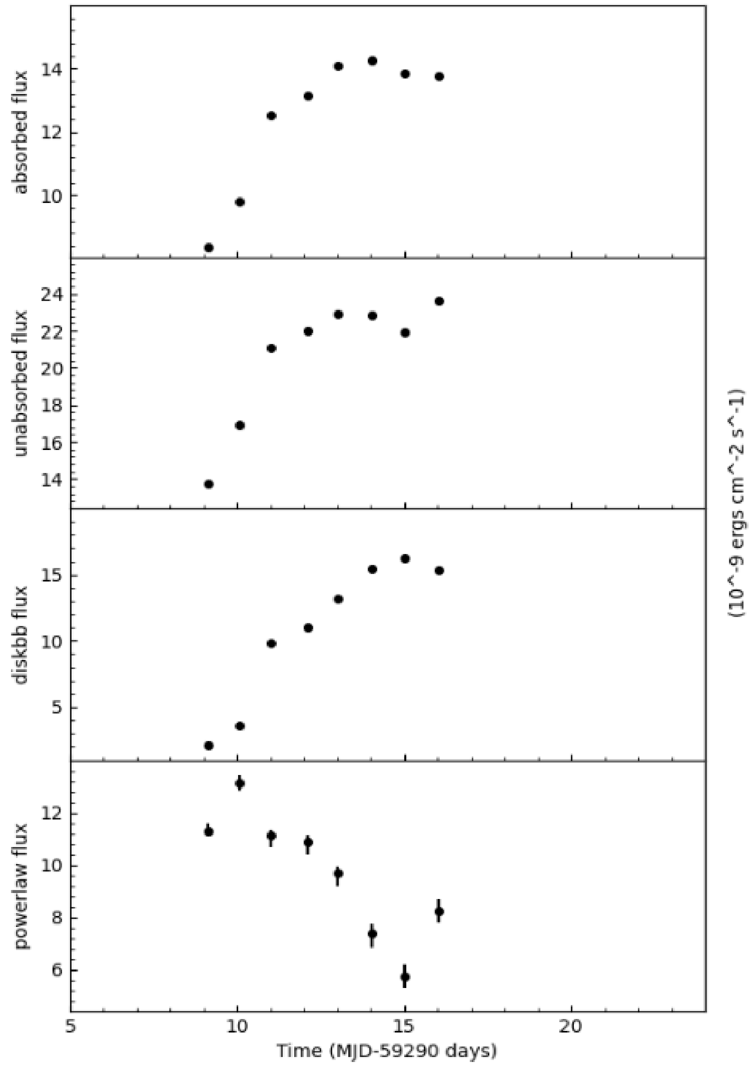

(Figure 4b, parameters and models in use for obsID: 4133010105)



(Figure 5, evolution of parameters shown for hard-intermediate state observations)

4.2 MAXIJ1820+070

Another black hole binary system that was analyzed is MAXIJ1820p070, which has a black hole with around 7-8 solar masses (Torres et al, 2019) and a companion star with less than 1 solar mass (Tucker et al, 2018). Like GX339-4, this source goes into state transitions periodically. The state of the source is determined by the hardness value – which is ratio of fluxes coming from X-ray in two adjacent energy bands. Hard state corresponds to a higher energy value, where the non-thermal emission created by comptonization dominates. Soft state is observed at high luminosities, dominated by the thermal component which is emissions from accretion disk.

Like GX339-4, the goal is to produce a good fit for the X-ray data of the black hole binary, coming from observatories – which is then further analyzed to understand properties of the system. For gathering data, Nicer observatory's data downloaded from NASA's data archives in HEASARC's Xamin Web Interface was used. The X-ray data of this source coming from Nicer has a particularly bright display, which further increases the instrumental errors on the model.

In order to find observations corresponding to specific states, various resources and literature were analyzed, and the following date ranges were used for analysis (Shidatsu et al, 2019):

From 13.03.2018 to 05.07.2018 the source is in hard state.

From 05.07.2018 to around 15.07.2018, the source is in brief intermediate state.

From 18.07.2018 to 17.09.2018, the source is in soft state.

The data for these date ranges were then uploaded to Cosmos server, which was fitted by the automated script written in Python. The default model's chi-squared value for the source was not as good as expected because of the instrumental errors as well as a component in high energy bands, therefore in addition to the parameters in default model, a gaussian component was added in order to tackle the strong iron emission line at 6.4 kEV. New model is tbabs*(powerlaw+diskbb+gaussian), and results in a satisfactory fit. The values of the parameters, as well as the output fits are added as figures.

Observations and their corresponding date & state is as follows with the given graph:

LOW HARD 1: 1200120109 - 2018.03.24 – b

LOW HARD 2: 1200120179 – 2018.06.14

INTERMEDIATE (from hard to soft) 7: 1200120196 – 2018.07.05 – d

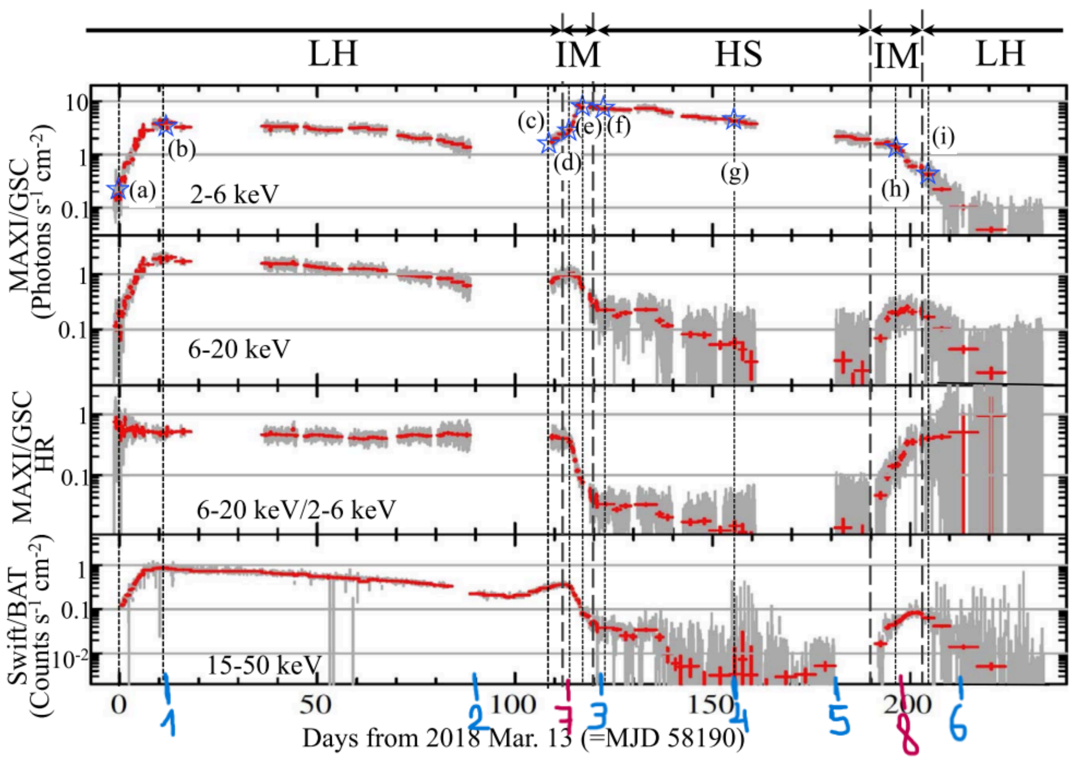
HIGH SOFT 3: 1200120210 - 2018.07.18 - f

HIGH SOFT 4: 1200120236 - 2018.08.13 - g

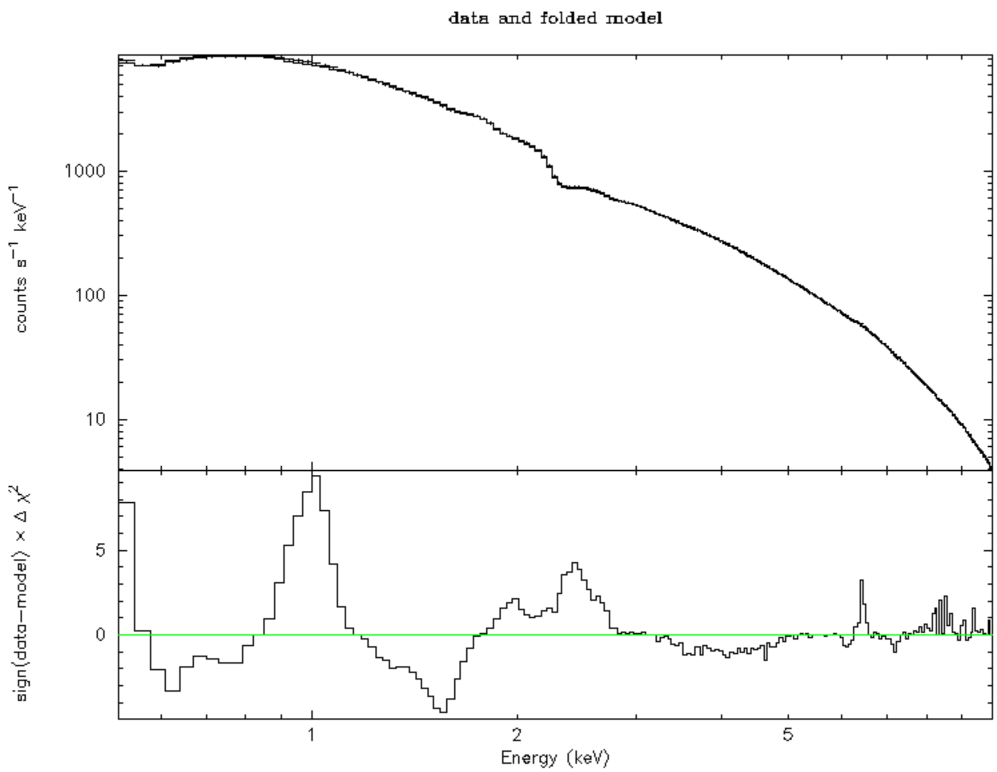
HIGH SOFT 5: 1200120257 - 2018.09.12

INTERMEDIATE (from soft to hard) 8: 1200120266 – 2018.09.27 – h

LOW HARD 6: 1200120275 – 2018.10.12 – i



(Chart from Shidatsu et al's paper, hand written numbers are observations used.)



(hard state observation 1200120109 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.157337     +/-  4.30273E-03
   2    2   powerlaw   PhoIndex            1.63660      +/-  5.02004E-03
   3    2   powerlaw   norm                6.69009      +/-  5.25168E-02
   4    3   diskbb     Tin        keV      0.280513     +/-  4.33865E-03
   5    3   diskbb     norm                1.33329E+05  +/-  1.21640E+04
   6    4   gaussian   LineE      keV      6.60740      +/-  4.41810E-02
   7    4   gaussian   Sigma      keV      0.612097     +/-  5.11946E-02
   8    4   gaussian   norm                3.88944E-02  +/-  3.56708E-03
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                 216.65     using 187 bins.

Test statistic : Chi-Squared                 216.65     using 187 bins.
 Null hypothesis probability of 2.87e-02 with 179 degrees of freedom
```
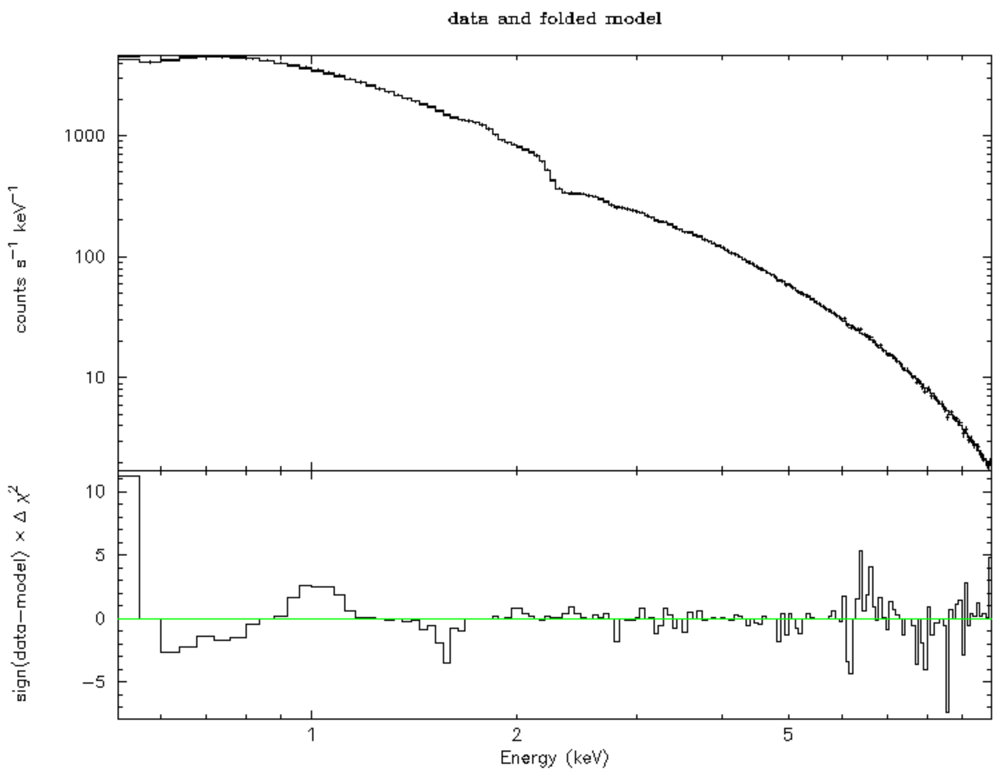

(parameters and models in use for obsID: 1200120109)



(hard state observation 1200120179 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.154366     +/-  1.11390E-02
   2    2   powerlaw   PhoIndex            1.85872      +/-  6.01836E-02
   3    2   powerlaw   norm                2.33386      +/-  0.118719
   4    3   diskbb     Tin        keV      0.229201     +/-  1.18031E-02
   5    3   diskbb     norm                8.83038E+04  +/-  2.25362E+04
   6    4   gaussian   LineE      keV      6.70000      +/-  0.815381
   7    4   gaussian   Sigma      keV      2.44926      +/-  0.635070
   8    4   gaussian   norm                8.17566E-02  +/-  4.69394E-02
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                 134.66     using 155 bins.

Test statistic : Chi-Squared                 134.66     using 155 bins.
 Null hypothesis probability of 7.59e-01 with 147 degrees of freedom
```
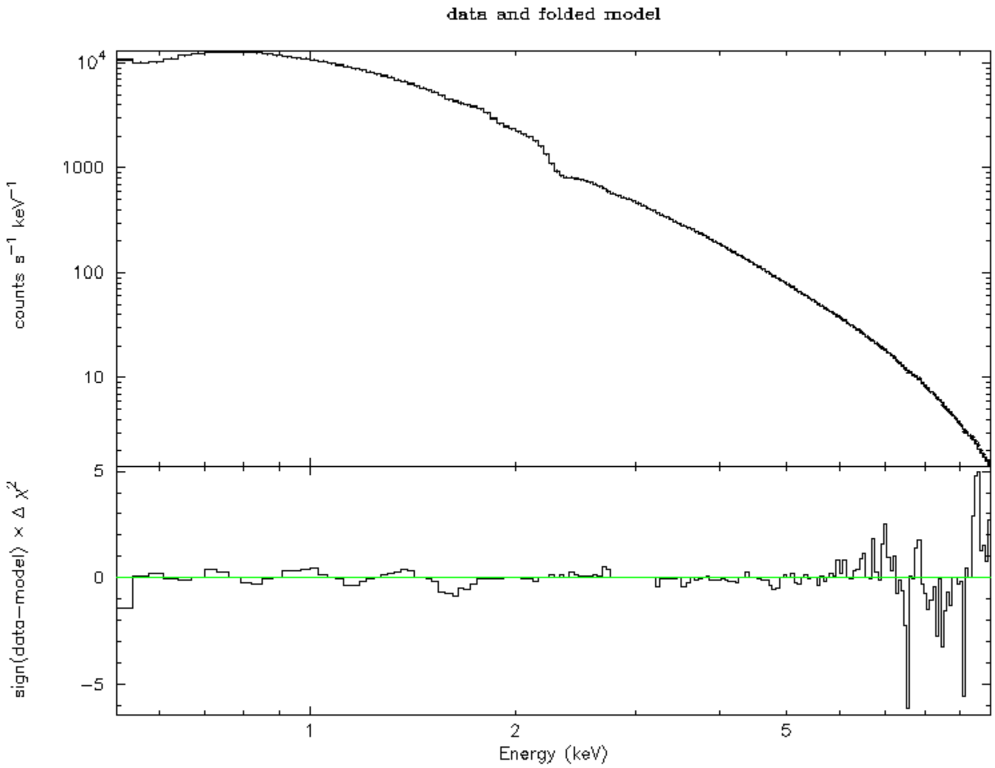

(parameters and models in use for obsID: 1200120179)



(intermediate - hard state observation 1200120196 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.266311     +/-  1.09842E-02
   2    2   powerlaw   PhoIndex            2.70417      +/-  5.26178E-02
   3    2   powerlaw   norm                24.9412      +/-  1.27343
   4    3   diskbb     Tin        keV      0.439433     +/-  4.72146E-02
   5    3   diskbb     norm                8556.62      +/-  6194.82
   6    4   gaussian   LineE      keV      6.40000      +/-  0.639840
   7    4   gaussian   Sigma      keV      2.55753      +/-  0.280664
   8    4   gaussian   norm                0.371949     +/-  9.34148E-02
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                   85.46     using 176 bins.

Test statistic : Chi-Squared                   85.46     using 176 bins.
 Null hypothesis probability of 1.00e+00 with 168 degrees of freedom
```
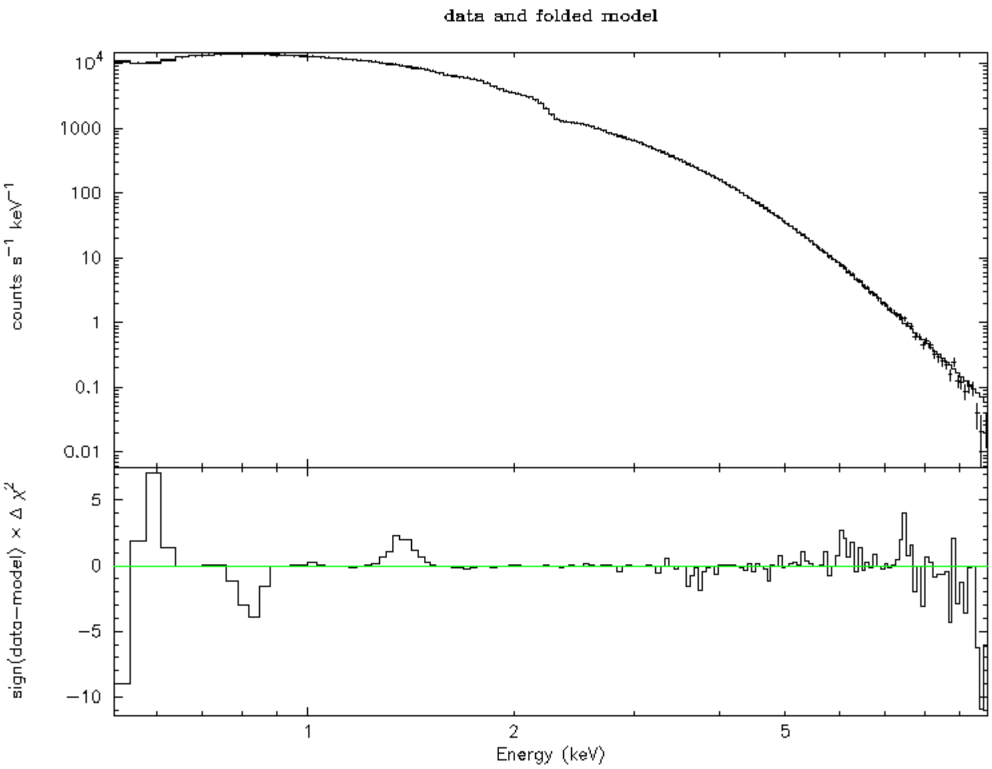

(parameters and models in use for obsID: 1200120196)



(soft state observation 1200120236 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.395696     +/-  6.77968E-03
   2    2   powerlaw   PhoIndex            3.99914      +/-  2.40421E-02
   3    2   powerlaw   norm                23.4863      +/-  0.672396
   4    3   diskbb     Tin        keV      0.696881     +/-  1.48752E-03
   5    3   diskbb     norm                1.43266E+04  +/-  175.355
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                 124.45     using 158 bins.

Test statistic : Chi-Squared                 124.45     using 158 bins.
 Null hypothesis probability of 9.56e-01 with 153 degrees of freedom
```
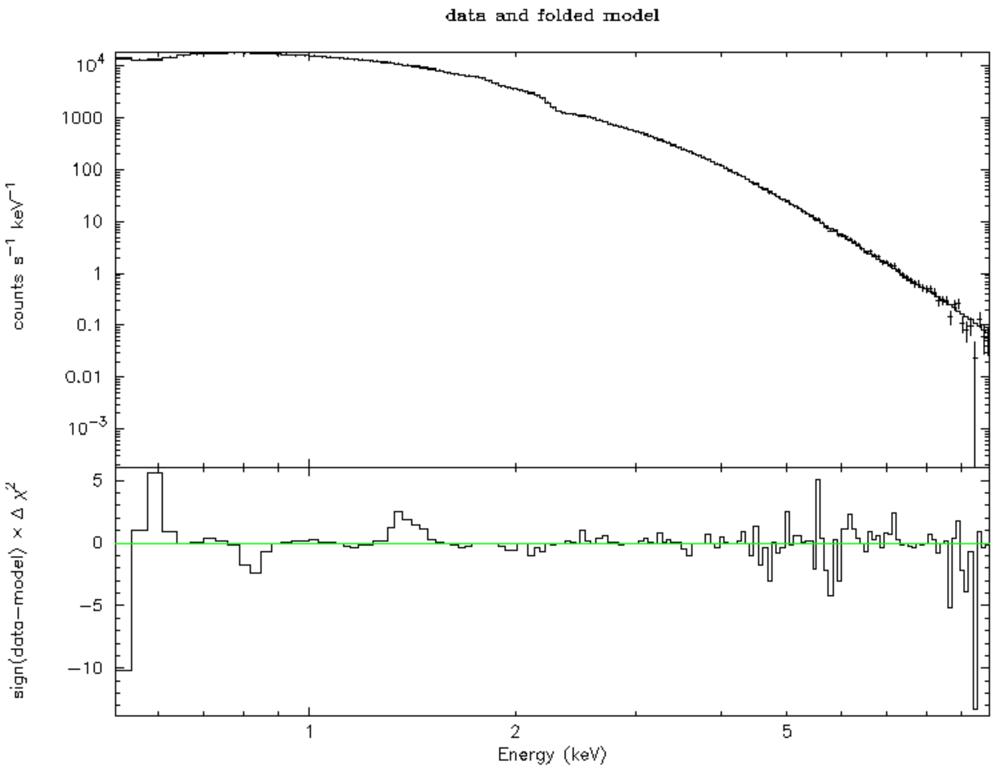

(parameters and models in use for obsID: 1200120236)



(soft state observation 1200120257 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.381168     +/-  6.80676E-03
   2    2   powerlaw   PhoIndex            3.97194      +/-  2.25517E-02
   3    2   powerlaw   norm                16.3463      +/-  0.488348
   4    3   diskbb     Tin        keV      0.602473     +/-  1.70587E-03
   5    3   diskbb     norm                1.53786E+04  +/-  266.408
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                  122.28     using 150 bins.

Test statistic : Chi-Squared                  122.28     using 150 bins.
 Null hypothesis probability of 9.15e-01 with 145 degrees of freedom
```
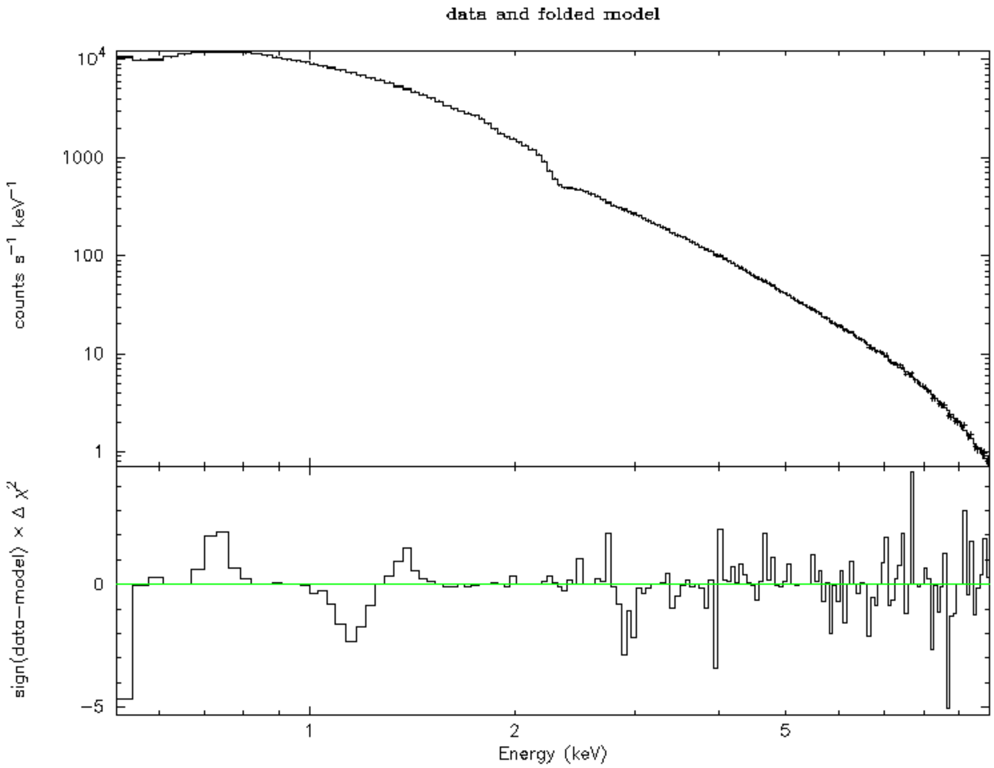

(parameters and models in use for obsID: 1200120257)



(intermediate - soft state observation 1200120266 from automatic fit)

```
Parameters defined:
========================================================================
Model TBabs<1>(powerlaw<2> + diskbb<3> + gaussian<4>) Source No.: 1   Active/(
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.272852     +/-  1.39773E-02
   2    2   powerlaw   PhoIndex            3.03515      +/-  6.79030E-02
   3    2   powerlaw   norm                9.95140      +/-  0.701503
   4    3   diskbb     Tin        keV      0.335441     +/-  1.43425E-02
   5    3   diskbb     norm                1.91631E+04  +/-  8028.45
   6    4   gaussian   LineE      keV      6.40000      +/-  0.588572
   7    4   gaussian   Sigma      keV      2.66624      +/-  0.274929
   8    4   gaussian   norm                0.141738     +/-  2.72448E-02
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!XSPEC12>show fit

Fit statistic  : Chi-Squared                   100.77     using 157 bins.

Test statistic : Chi-Squared                   100.77     using 157 bins.
 Null hypothesis probability of 9.99e-01 with 149 degrees of freedom
```
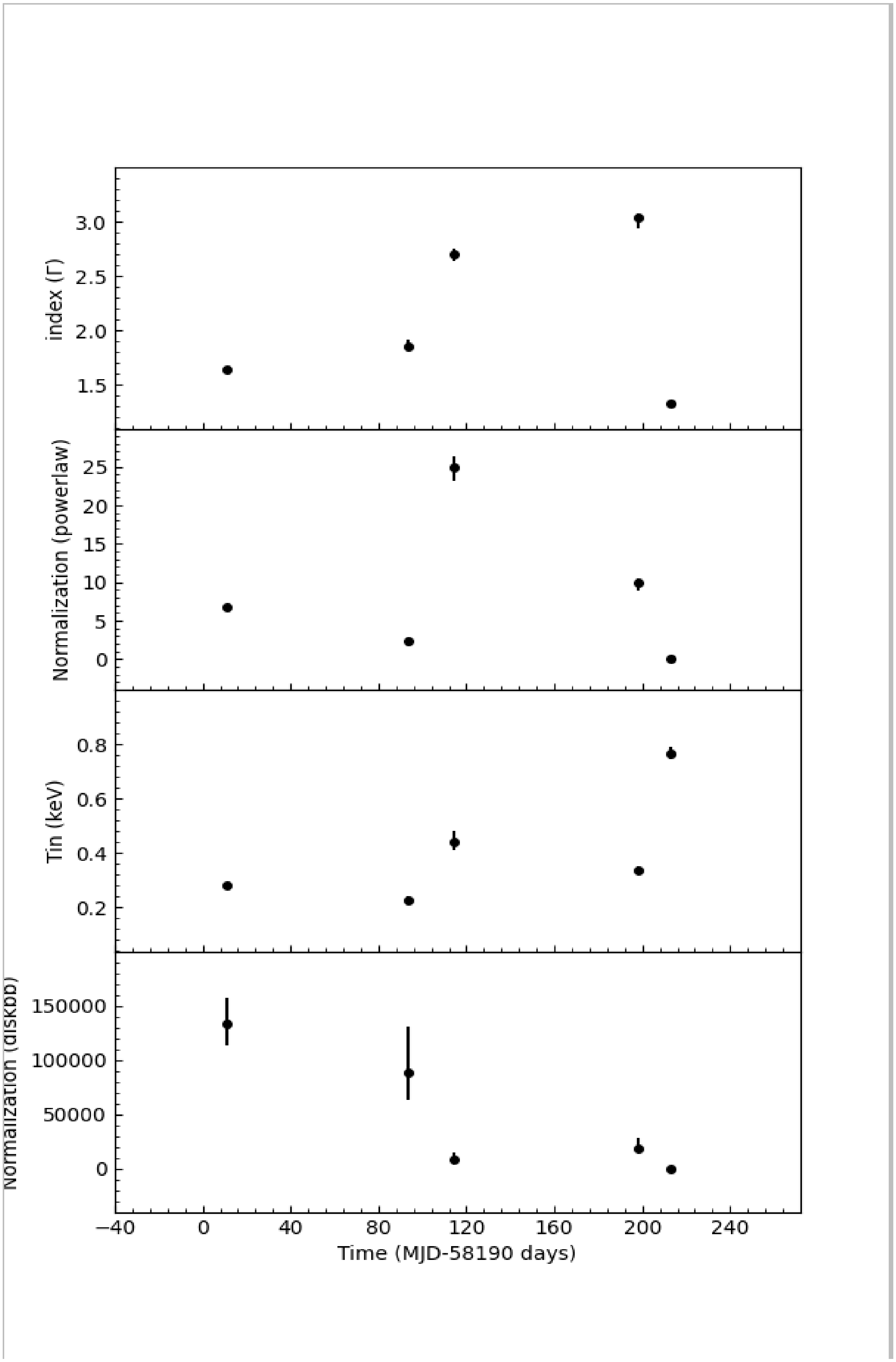

(parameters and models in use for obsID: 1200120266)



(evolution of parameters shown for observations)

5 Discussion and Conclusion

This research project focused on the detailed analysis of X-ray data from black hole binary systems, particularly targeting GX 339-4 and MAXIJ1820+070. The transition from IDL to Python, using the Stingray library, showcased the flexibility and efficiency gained in conducting time series analysis. Through spectral fitting, we identified models that strongly correlated with observational data, highlighting the adaptability of our approach.

The analysis of GX 339-4 revealed periodic state transitions, and our approach demonstrated the importance of accurately modeling instrumental errors. The analysis of MAXIJ1820+070, considering different states based on hardness values, emphasized the need for detailed models. This project successfully implemented advanced data analysis techniques, providing valuable insights into the structural components and state transitions of these black hole binary systems.

The installation of HEASoft, XSPEC, and the use of Python packages ensured a robust analysis environment. As a future direction, expanding the analysis to include more black hole binary systems and exploring additional modeling techniques could enhance our understanding further. This research contributes to astrophysics by providing a detailed methodology for X-ray data analysis.

References

Dunn, R., Fender, R. P., & Körding, E. (2008). An X-ray Study of the Disc in GX339 4. *Proceedings of Science*. https://doi.org/10.22323/1.056.0015

Liu, H., Jiang, J., Zhang, Z., Bambi, C., Ji, L., Kong, L. D., & Shu, Z. (2022). Rapidly alternating flux states of GX 339–4 during its 2021 outburst captured by Insight–HXMT. Monthly Notices of the Royal Astronomical Society, 513(3), 4308–4317. https://doi.org/10.1093/mnras/stac1178

M.A.P. Torres, J. Casares, F. Jiménez-Ibarra, et al.: Dynamical confirmation of a black hole in MAXI J1820+070, ApJL, 882, L21 (2019).

M.A.Tucker, B.J. Shappee, T.W.-S. Holoien, et al., ASASSN-18ey: The Rise of a New Black Hole X-Ray Binary, ApJL, 867, L9 (2018).

Megumi Shidatsu, Satoshi Nakahira, Katsuhiro L. Murata, Ryo Adachi, Nobuyuki Kawai, Yoshihiro Ueda, and Hitoshi Negoro, "X-Ray and Optical Monitoring of State Transitions in MAXI J1820+070," The Astrophysical Journal, Volume 874, Number 2, 2019 April 5, Pages 183, DOI: 10.3847/1538-4357/ab09ff.

HEASARC, NASA. (n.d.). How To Install HEAsoft On Linux. Retrieved January 10, 2024, from https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/linux.html

Yamada, S., Makishima, K., Uehara, Y., Nakazawa, K., Takahashi, H., Dotani, T., Ueda, Y., Ebisawa, K., Kubota, A., & Gandhi, P. (2009). IS THE BLACK HOLE IN GX 339–4 REALLY SPINNING RAPIDLY? *The Astrophysical Journal*, *707*(2), L109–L113. https://doi.org/10.1088/0004-637x/707/2/l109

Zdziarski, A. A., Gierliński, M., Mikołajewska, J., Wardziński, G., Smith, D. M., Harmon, B. A., & Kitamoto, S. (2004). GX 339−4: the distance, state transitions, hysteresis and spectral correlations. Monthly Notices of the Royal Astronomical Society, 351(3), 791–807. https://doi.org/10.1111/j.1365-2966.2004.07830.x

Belloni T. M., Bhattacharya D., (2022). Basics of Fourier Analysis for High-Energy Astronomy *Arxiv.org*. https://doi.org/10.1007/978-981-16-4544-0_136-1

Kalemci, E. Summary of the past, present and future of the X-ray astronomy. Eur. Phys. J. Plus 133, 407 (2018). https://doi.org/10.1140/epjp/i2018-12284-6