RXTE Studies: PCA Spectral Analysis for Spectral States in 4U 1630-47

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ABSTRACT

We analyze spectral data from the Low-Mass X-Ray Binary 4U 1630-47 (X Nor X-1). This is a black hole candidate located at $\alpha = 16°34'01.61"$, $\delta = -47°23'34.8"$. We analyze data for the period between MJD 53829.3638299 and MJD 53950.93011. This period corresponds to an outburst in the source between 2005-12-24, 10:45:54.7 and 2006-04-23, 22:19:21.5 hrs. The data is taken from the RXTE GOF archives. We extract the 3-30 keV spectra from the binned mode Standard 2 Data which has a time resolution of 16s. We then fit the spectra obtained with a theoretical model which in addition to the main radiation mechanism takes into account, interstellar extinction along the line of sight. The model for the main radiation mechanism consists of thermal emission from a geometrically thin and optically thick disk, and non-thermal radiation modeled by a power-law, presumably from the high energy Comptonizing cloud located inside the truncated disk, as well as reflection of the Compton radiation from the disk. We obtain best fit values of various parameters like the internal radius of the accretion disk, the internal temperature, flux in various bandpasses, relative magnitudes of the non-thermal Compton component and the thermal blackbody component. We provide the plots of various parameters ton understand the underlying physical mechanism giving rise to emission during this outburst phase.

Subject headings: X-ray binaries, accretion, disk blackbody, power-law reflection, fitting spectra, three spectral states.

1. THEORY

When a compact object accretes from the surrounding medium, or from a binary companion, the accreting plasma invariably settles into a disk perpendicular to its net angular momentum vector $\vec{L}$ known as accretion disk. Such objects are usually luminous in X-rays, and hence are also called X-ray binaries.

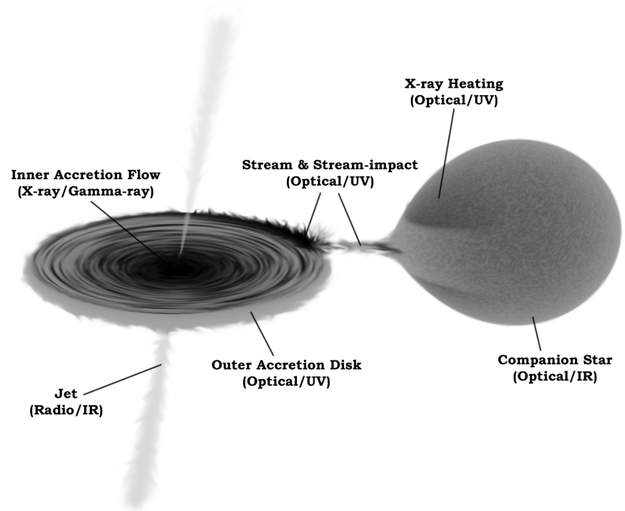

Fig. 1.—: A simple schematic of a Low-Mass X-Ray Binary

X-Ray Binaries are classified into two broad categories on the basis of the secondary star mass as follows:

1. **High-Mass X-Ray Binaries:** In these binaries the material for transfer onto the compact object is provided by a powerful stellar wind from an early type massive star.

2. **Low-Mass X-Ray Binaries:** If the donor star is of low mass, then its stellar wind is not strong enough to power the X-ray source as in HMXBs. Here, the companion star has evolved to fill it's Roche lobe completely and is transferring material through the inner Lagrangian point L1, onto the compact object. Such mass transfer is only stable if the donor star is less massive than the compact object.

1.1. Radiative Processes in X-Ray Binaries

Radiative processes can be classified into two main categories: thermal and non-thermal emission. The thermal component is given by Planck's radiation law. The other components arise from a variety of phenomena like Compton Scattering, Inverse Compton Scattering, and Bremsstrahlung. The non-thermal part of the spectrum is modeled using a power-law.

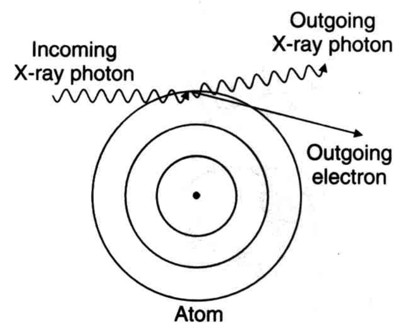

Fig. 2.—: Compton Scattering

The spectrum of a typical X-Ray binary is a superposition of a thermal and a non-thermal component. The thermal component is thought to exist because of the temperature of the accretion disk itself. The disk spectrum can be thought of as a sum of blackbodies, each produced by a particular ring with its own characteristic temperature. The residual of the spectrum is fit by a power-law, which is assumed to be the characteristic form of the non-thermal component. This non-thermal part is assumed originate from reflection of the emission from a Comptonising cloud around the accreting compact object from the accretion disk in the line of sight. Based on the relative magnitude of the two spectra the source can be classified to be in one of five spectral states.

1.2. The Detector: RXTE

The Rossi X-Ray Timing Explorer (RXTE, 1995-2012) has provided us with useful data about emission at 3 keV to 30 keV energy range. The RXTE satellite has three components: the Proportional Counter Array (PCA), the High-Energy X-ray Timing Experiment (HEXTE), and the All Sky Monitor (ASM). Out if these we are concerned with only the PCA and the ASM.

1.2.1. The ASM:

The ASM scans the entire sky in X-Rays. When an X-Ray source comes within the field of view of the ASM, the flux increases and this flux increase can be used to detect if that particular source is in outburst or in a quiescent state.

1.2.2. The PCA:

The PCA is an array of proportional counters. The goal here is to return as much information as possible about the X-rays incident on the detector. These data could include the energy of the X-ray photons, their arrival time, their number, the location where they were detected. At its simplest, a proportional counter is a grounded box of gas, with a high voltage wire through the middle, and a window of plastic or some other material which will admit most of the incident X-rays while keeping the gas in.

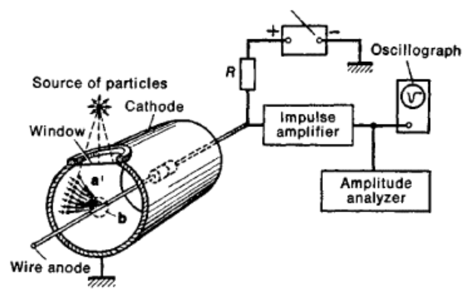

Fig. 3.—: A simple schematic of a Proportional Counter

At X-Ray energies, the most probable interaction of a photon with matter is the photoelectric effect, in which the photon is absorbed by a single atom, and its energy goes into ejecting a single primary electron. The leftover kinetic energy will be used by the primary photoelectron to ionize other gas atoms, producing a population of secondary electrons. This collection of primary and secondary electrons then begin to drift towards the high-voltage anode wires. As soon as they have enough energy, they will ionize further gas atoms. Depending on the gas mixture and the high-voltage setting, this amplification effect, called the gas gain, can be substantial: often two or three orders of magnitude. The spectral response of a proportional counter is described by the distribution of pulse-height values which can be produced for a given incident X-Ray energy. The system gain (the conversion between mean pulse height and photon energy) can be non-linear. Hence, it is not generally possible to invert pulse height distribution to obtain directly an estimate of the input X-Ray photon energy spectrum. Instead, pulse-height distributions for monochromatic X-Rays are collected into a calibration file called a response matrix file. The subdivided counter design can also be used to improve the background rejection. If the gas volume is divided into layers as in the RXTE PCA for instance, then X-Rays will be stopped in a single layer while high-energy particles will travel through several layers, producing a signal in each. Detection of simultaneous signals can then be used to veto events which are very likely to be particles and not X-Rays.

1.3. The Models Used:

1.3.1. Disk Blackbody Parameters with the Thin Disk Model

Any chaotic motion of gas elements about the circular streamlines gives rise to viscous forces. The physics of thin-disk accretion is driven by the transfer of angular momentum and energy via the dissipative effects of this internal "friction". The equations

$$R\frac{\partial\sigma}{\partial t} + \frac{\partial}{\partial R}(R\sigma v_R) = 0$$

$$v_R = -\frac{3}{\sigma R^{1/2}}\frac{\partial}{\partial R}(\nu\sigma R^{1/2})$$

known as the mass conservation and angular momentum equations respectively specify the dynamical structure of the disk.

α-Prescription

$$\nu \equiv \alpha c_s H$$

is known as the famous α prescription which parametrizes all the uncertainties associated with viscosity to α. Here, c_s is the characteristic sound speed in the medium and H is the height of the accretion disk. Shakura and Sunyaev(1973) developed it in early 1970s. There is no physical reason for why it should work but it is the most commonly used formulation owing to its simplicity and relevance to real systems.

Fitting the spectra with the model yields various parameters like the relative intensity of the thermal and non-thermal parts of the spectrum and the accretion disk inner temperature. The disk blackbody model that we use gives as its norm $\left(\frac{R_{in}(km)}{D(10kPc)}\right)^2 \cos\theta$. The square root of the obtained norm for the blackbody therefore gives a quantity proportional to the inner radius of the accretion disk.

1.3.2. Reflection from the Disk Blackbody with the Power Law Model

The model for reflection yields the parameters rel_refl, which is the reflection scaling factor (1 for isotropic source above disk), the redshift, various abundances for the disk, and the inclination angle of the disk to the line of sight. The power-law model yields the PhoIndex which represents the power-law index and the norm which represents the power-law intensity.

2. DATA REDUCTION

The Process

The RXTE PCA data is organized into Science Array FITS files from which spectra and lightcurves have to be extracted. The entire analysis was done using the HEASoft and caldb tools from HEASARC, NASA.

- Identification of the Standard 2 data files using the ftool **xdf**.
- Generation of a filter file containing housekeeping data using the ftool **xtefilt**.
- Creation of a GTI file containing information about good times where the data can be assumed to be free from external influences, using the ftool **maketime**.
- Extraction of the spectra from the datafiles using the tool **saextrct**.
- Estimation of the PCA response matrix using the ftool **pcarsp**.
- Using the ftool **pcabackest** to estimate the background and create a FITS file containing this 'bright source model' data.
- Fitting curves to the obtained spectra after background subtraction using **xspec**.

The Script

The script here assumes the data to be in the path $HOME/Project/data/object/$OBS_ID and creates the output files in the directory $HOME/Project/analysis/object/$OBS_ID. The background model files and the SAA history file are assumed to be in $HOME/Project/analysis/xte_files/pca_saa_history.gz

```
#!/bin/bash

for i in ~/Project/data/object/91704-03-*
do
       cd ~/Project/analysis/object/
       mkdir `basename $i`
       echo $i"/pca/"`ls FS46*` > ~/Project/analysis/object/`basename $i`/std1.list
       echo $i"/pca/"`ls FS4a*` > ~/Project/analysis/object/`basename $i`/std2.list
       xtefilt -c -a ~/Project/analysis/xte_files/appidlist -o `basename $i` -p $i/FMI
           -f ~/Project/analysis/object/`basename $i`/filter
       cd `basename $i`
       maketime $i/filter.xfl good.gti
           "(ELV.gt.10).and.(PCU2_ON.eq.1).and.(TIME_SINCE_SAA.gt.20)" anything anything
           TIME no
       saextrct @std1.list APPLY good.gti lightcurve_src ONE TIME GOOD 0.125 lightcurve
           RATE SUM INDEF INDEF INDEF INDEF INDEF INDEF INDEF
       saextrct @std2.list APPLY good.gti spectrum_src ONE TIME GOOD 16.0 spectrum RATE
           SUM INDEF INDEF INDEF INDEF INDEF INDEF INDEF
       pcabackest `cat std2.list` bkg
           ~/Project/analysis/xte_files/pca_bkgd_cmbrightvle_eMv20051128.mdl filter.xfl
           16.0 no no no no ~/Project/analysis/xte_files/pca_saa_history.gz
       saextrct bkg APPLY good.gti lightcurve_bkg ONE TIME GOOD 0.125 lightcurve RATE
           SUM INDEF INDEF INDEF INDEF INDEF INDEF INDEF
       saextrct bkg APPLY good.gti spectrum_bkg ONE TIME GOOD 16.0 spectrum RATE SUM
           INDEF INDEF INDEF INDEF INDEF INDEF INDEF
       pcarsp -f spectrum_src.pha -a NONE -l all -j y -p all -m y -n response.rsp
       cd ~/Project/analysis/object/
done
```

3. DATA ANALYSIS

The XSPEC environment is designed for astronomical spectra fitting. We load the spectrum file in XSPEC and make a few adjustments: we ignore the spectra for 0-3 keV and 30-** keV because the interval 3-30 keV is the interval in which the PCA measurements are the best. We plot the data on a log-log scale for accurate display even at low values. A sample plot is as shown:

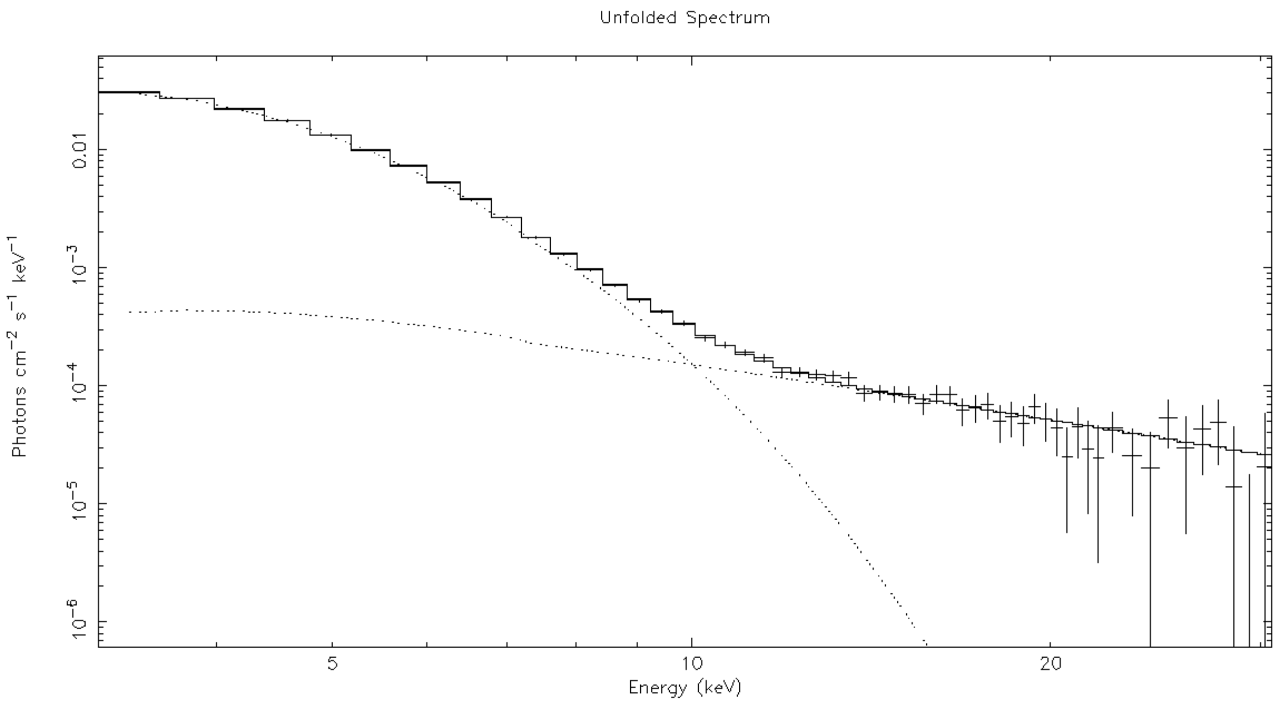

Fig. 4.—: The fit for Observation ID 91704-03-41-00

We fit the spectra with the XSPEC model wabs×(diskbb+reflect×powerlaw). The dotted lines in the figure are the individual components. The sharply falling component is the thermal component and the other component is the power-law. The fit statistic we use is the reduced chi-squared. The chi-squared is defined as:

$$\chi^2 = \sum \frac{(O-E)^2}{\sigma^2}$$

where O is the observed value of the quantity and E is the theoretically expected value. The reduced chi-squared is

$$\frac{\chi^2}{N}$$

where N is the total number of independent parameters in the model.

For this particular fit, the parameters are:

```
Parameters
========================================================================
Model wabs<1>(diskbb<2> + reflect<3>*powerlaw<4>) Source No.: 1 Active/On
   1    1   wabs      nH        10^22   7.81375     +/-  0.189697
   2    2   diskbb    Tin       keV     0.967531    +/-  6.85364E-03
   3    2   diskbb    norm              161.237     +/-  8.01071
   4    3   reflect   rel_refl          3.56687E-07 +/- -1.00000
   5    3   reflect   Redshift          0.0         frozen
   6    3   reflect   abund             1.00000     frozen
   7    3   reflect   Fe_abund          1.00000     frozen
   8    3   reflect   cosIncl           0.450000    frozen
   9    4   powerlaw  PhoIndex          1.64777     +/-  0.156458
  10    4   powerlaw  norm              7.21026E-03 +/- -1.00000
________________________________________________________________________


Fit statistic : Chi-Squared =      45.36 using 56 PHA bins.

Test statistic : Chi-Squared =      45.36 using 56 PHA bins.
 Reduced chi-squared =      0.9071 for    50 degrees of freedom
 Null hypothesis probability = 6.599811e-01
```

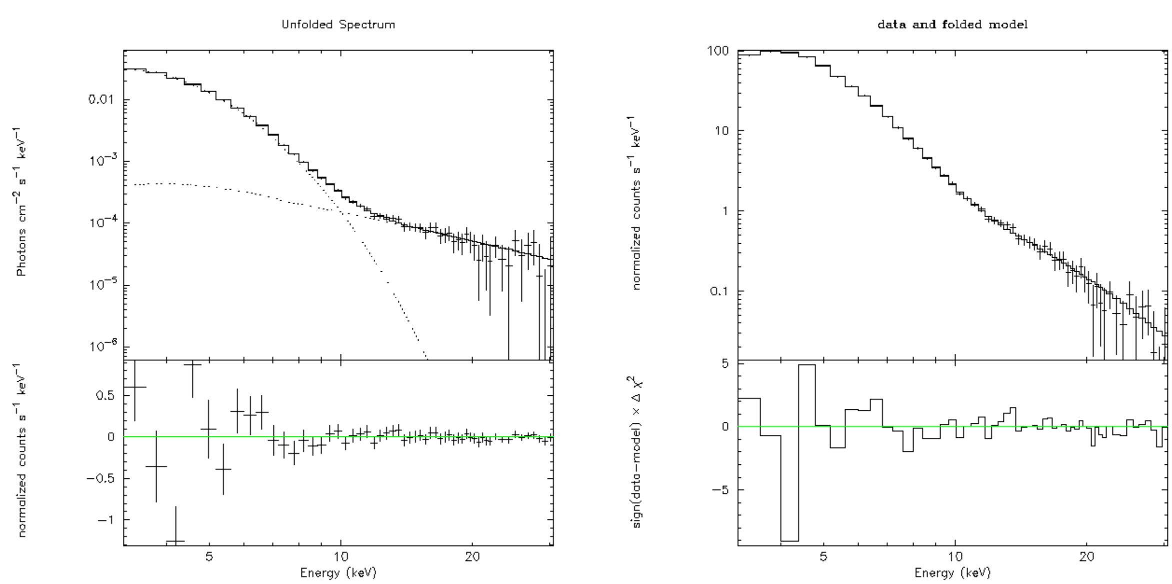

Fig. 5.—: The fit for Observation ID 91704-03-41-00, clockwise: the unfolded spectrum, the folded spectrum, the chi-squared contribution and the residue

4. RESULTS

4.1. R_{in} versus T_{in} Plot:

The internal temperature and radii of the accretion disk were plotted. The result is as follows:

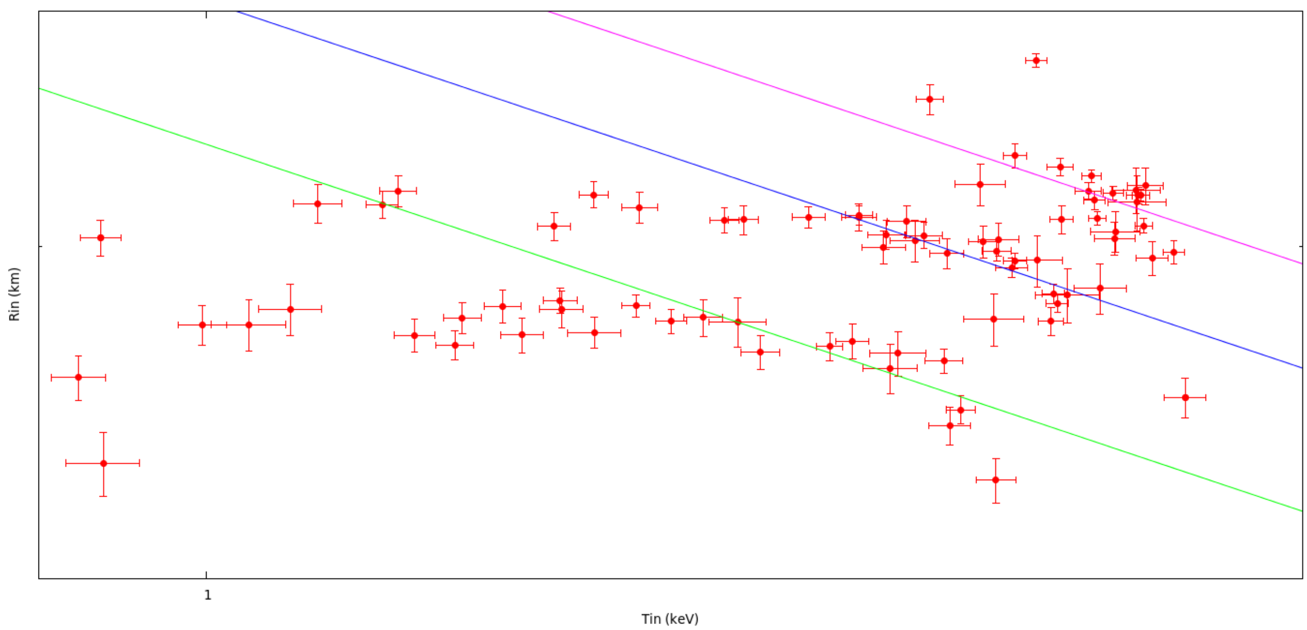

Fig. 6.—: R_{in} versus T_{in} Plot

As we can see there are three regions in the graph, and within each is an exponential relation between the R_{in} and the T_{in} of the accretion disk. The three relations are roughly given by:

$$R_{in} = 34 \times T_{in}^{-\frac{4}{3}}$$

$$R_{in} = 40.5 \times T_{in}^{-\frac{4}{3}}$$

$$R_{in} = 46 \times T_{in}^{-\frac{4}{3}}$$

in appropriate units.

4.2. Hard Ratio versus Soft Ratio Plot:

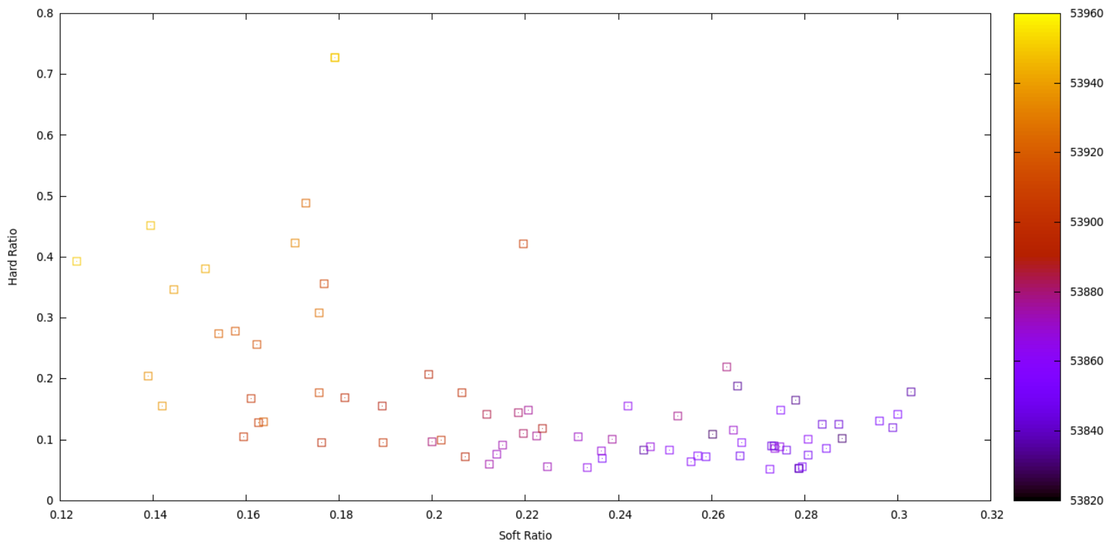

Fig. 7.—: Soft Ratio versus Hard Ratio Plot

The graph here shows a decreasing relation, implying that the soft ratio decreases as the hard ratio increases.

4.3. Total Flux versus Time:

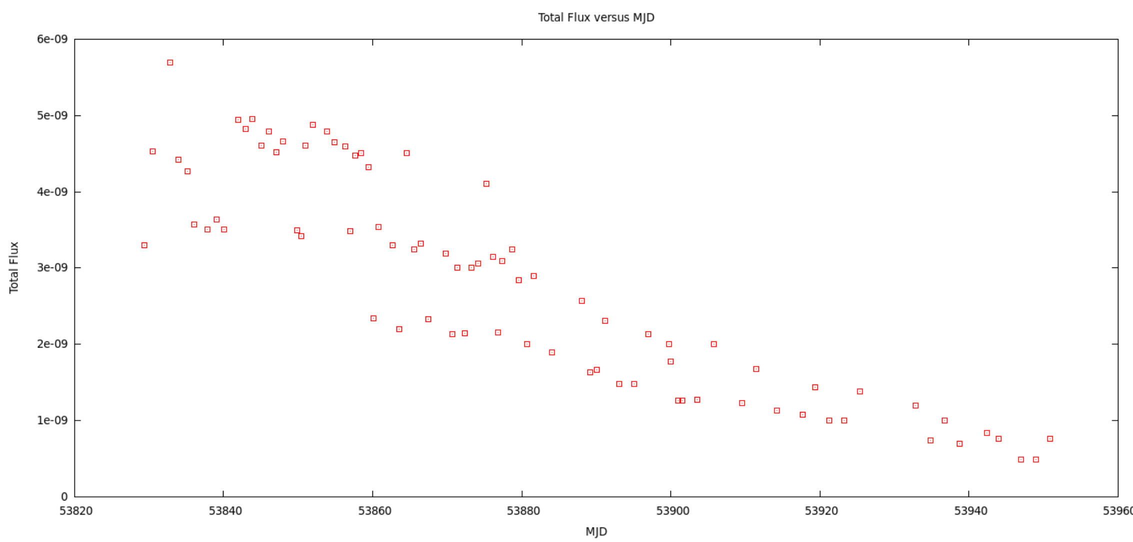

Fig. 8.—: Total Flux versus Time Plot

4.4. R_{in} versus Time Plot:

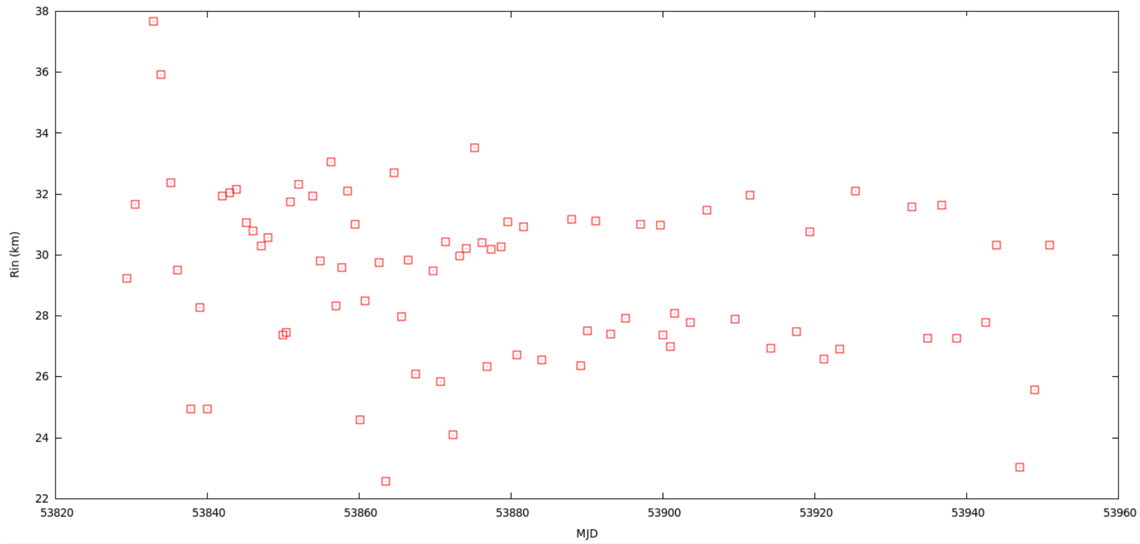

Fig. 9.—: R_{in} versus Time Plot

4.5. T_{in} versus Time Plot:

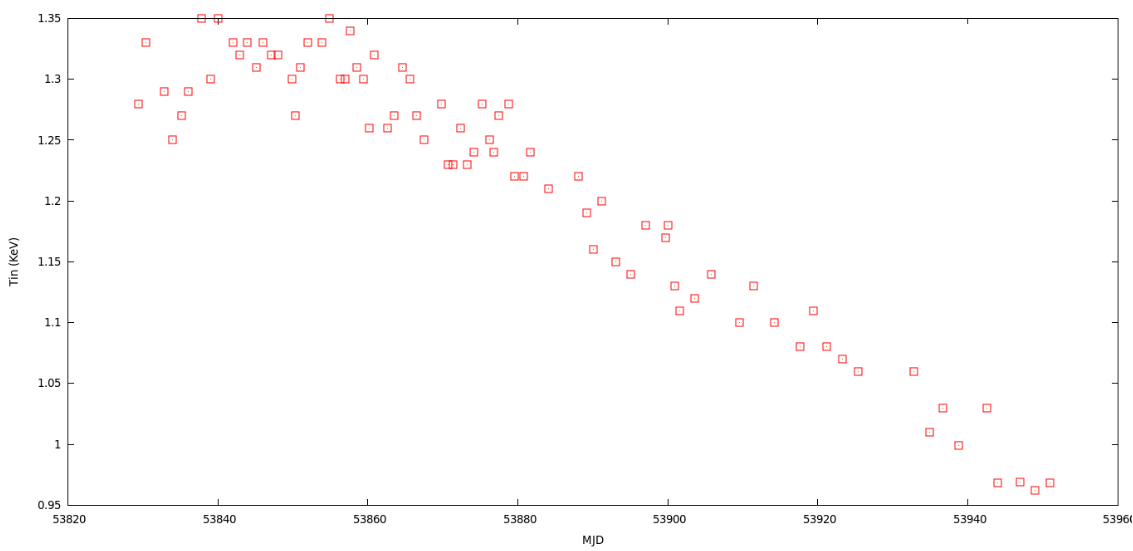

Fig. 10.—: R_{in} versus Time Plot

4.6. Soft Ratio versus Total Flux Plot:

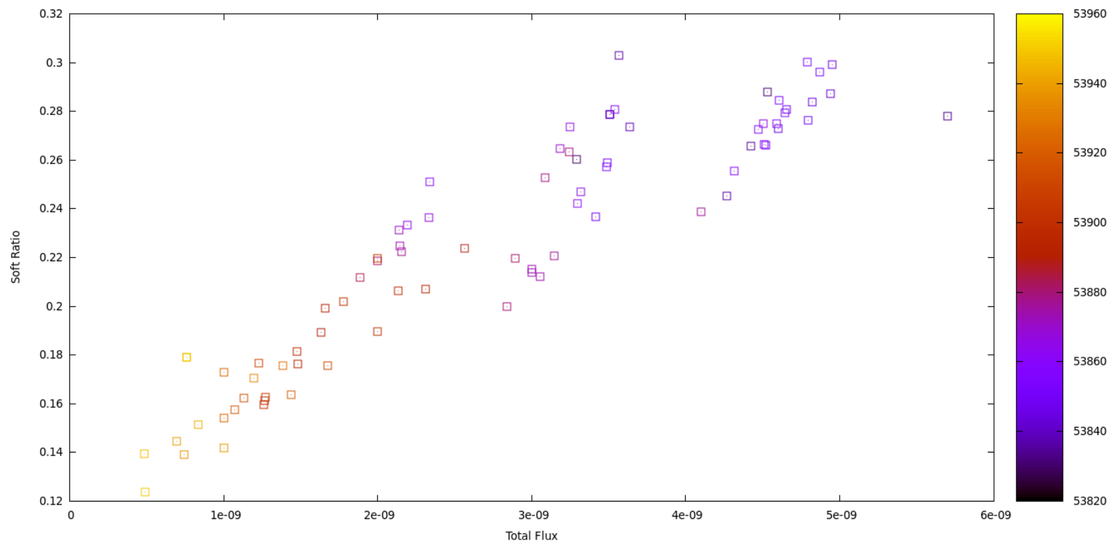

Fig. 11.—: Soft Ratio versus Total Flux Plot

4.7. Hard Ratio versus Total Flux Plot:

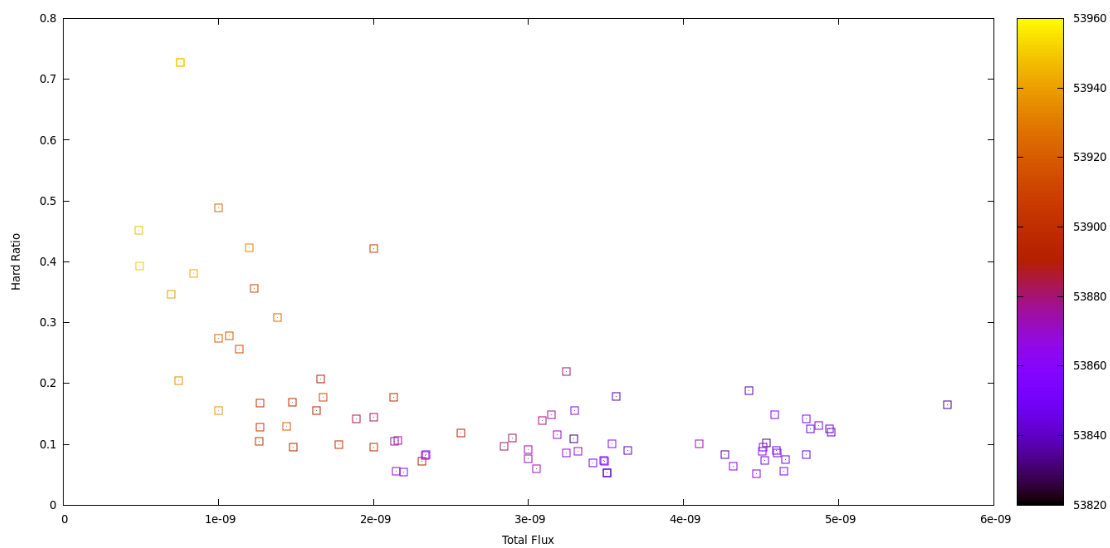

Fig. 12.—: Hard Ratio versus Total Flux Plot

4.8. Total Flux versus T_{in} Plot:

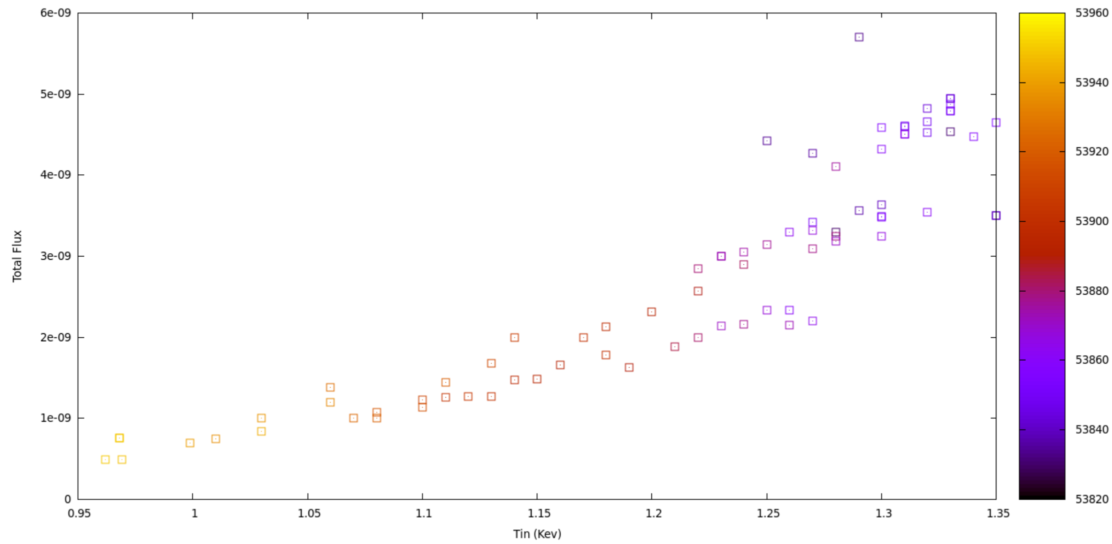

Fig. 13.—: Total Flux versus T_{in} Plot

4.9. Blackbody Flux versus Power-Law Flux:

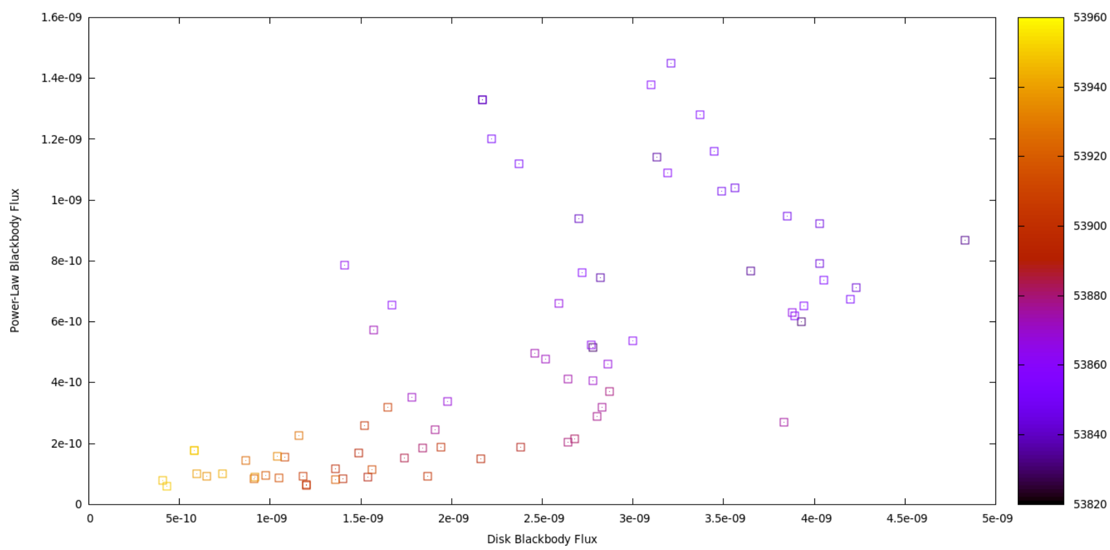

Fig. 14.—: Blackbody Flux versus Power-Law Flux

4.10. Conclusions:

Here, every graph is split into three regions and the object evolves from one region to another in the course of time. Since there is a clear demarcation between these three regions, they **might** be three separate spectral states. These states change on the timescale of the entire observation. The separation of any of these graphs into three clear regions can be attributed to the evolution of the source from one state to another.

However on looking at the time variability of the various parameters in the time plots, we discover a consistent variability on the timescale of a day. We do not know the reason for this variability. A possible reason for this could be oscillations of the system in the given spectral state itself, but that will have to be worked upon.

Acknowledgments

We are thankful to the Homi Bhabha Center for Science Education and Tata Institute of Fundamental Research for organizing the Astronomy Nurture Camp under which this project was undertaken. We would like to thank Dr. Manojendu Choudhury for guiding us throughout the project. We have made use of NASA's Astrophysics Data System, and we would like to thank the maintainers of the RXTE GOF Archives.

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6. *http://heasarc.nasa.gov/lheasoft/* The HEASoft Page