Soft X-ray Study of Active Galactic Nuclei

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CERTIFICATE

This is to certify that this dissertation entitled 'Soft X-ray Study of Active Galactic Nuclei' towards the partial fulfillment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research (IISER), Pune, represents the work and study carried out by Mr Kapil Kedar Tirpude at the Inter-University Center for Astronomy and Astrophysics (IUCAA), Pune, under the supervision of Prof Gulab Chand Dewangan, Professor, IUCAA, Pune during the academic year 2016-17.

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DECLARATION

I hereby declare that the matter embodied in the report entitled 'Soft X-ray Study of Active Galactic Nuclei' is the results of the work carried out by me at the Inter-University Center for Astronomy and Astrophysics under the supervision of Prof Gulab Chand Dewangan and the same has not been submitted elsewhere for any other degree.

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ABSTRACT

This report is based on the study and work I have done in order to understand the X-ray spectral properties of MRK-110 and NGC-3998 using the data provided by the Indian X-ray observatory AstroSat. Both the objects are Seyfert type -1 Galaxies. The project work began with a thorough study of the Instrument, theory of X-ray astronomy and later extraction of useful information like image, light curve, spectrum, etc. The extraction of information was done using the High Energy Astrophysics Science and Research Centre (HEASARC) software XSELECT and the analysis of spectra; spectral fitting was done using XSPEC. Analysis of light curves was done using the ftools LCMATH and LCURVE. I wrote a C-Language code to determine the Half Power Diameter of the instrument. The report consists of computation of Half-Power Diameter, the Powerlaw photon spectral index of the spectra, the equivalent absorption column density, the flux and luminosity and the hardness ratio of the objects. Final part of the report is the discussion of the obtained results and a summary of the computations.

The computed half-power diameter (abbreviated as HPD) was about 13 arcmins. The X-ray spectra of NGC-3998 and MRK-100 was seen to have a powerlaw form with spectral index 1.9522 and 1.8852 respectively and the computed Equivalent Hydrogen absorption column density respectively was 9.820 x $10^{20} cm^{-2}$and 1.773 x 10^{20} cm^{-2}. The flux was computed to be 6.9747x10^{-12}erg/cm^2s and5.663 x 10^{-11} erg/cm^2s respectively. Errors of all the parameters were calculated with 90% confidence.

The hardness ratio for both the objects remained less than 1 suggesting that the objects have a dominance of soft x-rays over the harder ones.

Keywords: X-ray, X-ray spectrum, spectral modeling, photon index, column density, light curve, hardness ratio.

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INTRODUCTION

Active Galactic Nuclei (AGNs) are one of the most extensively studied objects in Astronomy and Astrophysics. They show remarkable properties like emission in all the domains of the Electromagnetic Spectrum, very high luminosity, emission in X-rays and Gamma rays[1], etc. While most of the questions on this topic remain unanswered, we are slowly progressing and unveiling the secrets that lie there.

Seyfert Galaxies (discovered by Carl Seyfert in 1943) are the most luminous among the known AGNs after Quasars and Blazars, with the only difference that the host galaxy isn't outshined by the Galactic Centre[2][3]. X-ray emission is a very well-known property of AGNs and comprises of a significant fraction of the total bolometric luminosity. X-rays emitting from the AGNs are believed to be formed because of the inverse Compton scattering of soft photons by the highly energetic electrons [4] in the corona and also as blackbody emission from disc, for sufficiently high disc temperatures [5]. The spectrum is observed to show a powerlaw function and hence it is important to understand the particle acceleration processes[6]. X-rays also give an idea as to what the electron temperature of the corona possibly is[5]. Similar to their well-known classification as Type 1 and 2 according to their Vis-UV spectra, they are also classified as type 1 and 2 based on the intrinsic absorption due to line of sight photons. The X-ray spectrum of typical Seyfert galaxy is dominated by powerlaw spectrum, very distinctly seen in the energy range of 2.0-8.0 keV[7]. The powerlaw spectrum below 2.0 keV also has a galactic (Milky Way) absorption component[8]. Along with the galactic absorption, a marked feature known as Soft X-ray excess is also a characteristic feature of AGNs[7].

In order to study the X-ray spectral properties, we need to have an instrument that detects the X-rays and is able to reproduce a usable data. One needs sophisticated software to 'look' and study the data. In order to extract information from the given data, I used XSELECT and XSPEC softwares from NASA's High Energy Astrophysics Science and Research Centre (abbreviated as HEASARC) software packages.

XSELECT is an ftool developed by NASA that allows us to read and extract information like the spectrum, lightcurve, image, etc. from the event file and also apply desired filters to extract relevant information from the event file.

The fitting and analysis of the spectrum is done using the software XSPEC under the HEASARC package. It is detector independent software used to study the X-ray spectral fitting and can be used to analyze the data provided by any x-ray telescope.

The Spectrum that one obtains from XSELECT consists of source photons with the background ones. And the spectrum is plotted as a function of channels. It is always desirable to plot a spectrum as a function of Energy. The relation between photon counts in a given channel v/s photon energy is of the following form[9]:

$$C(I) = \int f(E) * R(I,E) dE \quad \text{-(i)}$$

Here, C(I) is the observed Photon count as a function of Channel I, f(E) refers to the spectrum as a function of energy and R(I,E) is the response of the instrument. It is the probability of a photon of Energy E being detected in the channel I.

It is very difficult to invert equation (i) to obtain the spectrum of the source since the equation is very sensitive to very small changes in C(I) and is very unstable[8]. Inverting the response of the instrument is very difficult. Therefore, as an indirect way, we try to 'guess' the possible function that 'models' the data, $f_M(E)$, plug it in the equation and compare the computed counts with the observed one. For each $f_M(E)$, the predicted counts are calculated and compared with the observed ones till we get the 'best fitting model and parameters[8]'.

The estimate of Best Fitting values is obtained by Chi-Squared Statistics which is defined in the following way:

$$\chi^2 = \Sigma \frac{[C(I) - C_M(I)]^2}{\sigma(I)^2} \quad \text{-(ii)}$$

Here, $\sigma(I)$ is the error which is generally the square root of counts in the channel (since the distribution is Gaussian). Chi squared statistics assume that the data points are Gaussian distributed among the channels[9].

The response of the instrument, as mentioned earlier, is a continuous function of Energy and is made discrete by defining specific energy levels. The redefined response of the instrument is now

$$R = \frac{\int_{E_{J-1}}^{E_J} R(I,E)dE}{E_J - E_{J-1}} \text{-(iii)}^{[9]}$$

This R is further multiplied by an array called Ancillary/Auxillary Response File which contains information about the Quantum Efficiency of the Detector and its Effective Area. The resolution of the instrument is 2.5% at 6keV[10], which correspond to 150 eV. And the detector can detect photons in the range 0.2 to 10 keV in 1024 channels. This corresponds to an approximate energy of 9.5 eV per channel. This shows that the resolution of the instrument is much larger than the individual channel energy. It is therefore important to redefine the energy ranges in the response files (eqn iii)

In general, in order to estimate the 'best fit' parameters, one generally looks at the reduced chi-squared statistics, defined as

$$\chi_R^2 = \frac{\chi^2}{v} \text{ -(iv)}$$

Where v is the number of degrees of freedom defined as the number of PHA bins/Channels minus the number of Parameters.

The value of reduced chi-square is expected to be close to 1 for a best fit model. Any value much greater than 1 means a poor fit, while one much lesser indicates that the errors have been over-estimated.

My project is focused on understanding the Physics behind the emission of Spectrum and instrument and computation of the following entities:

- Radial Profile and Half Power Diameter:

Radial profile is a plot of brightness (number of photons per unit area) as a function of distance from the centroid of the image. Radial Profile is also a measure of the point-spread function of the instrument. (The instrument that images a point object convolutes the image with its own response, thus 'blurring' the image. This response of the instrument is called Point Spread Function-PSF)

The Half Power Diameter is the region from the centroid where 50% of the incident photons get focused. It gives a measure of focusing power of the instrument.

- Powerlaw Photon Index, Galactic Equivalent Hydrogen Absorption Column Density and Blackbody Emission:

The X-ray photons are believed to be emitted from the source because of the inverse Compton scattering of the soft photons coming from the accretion disc, by the highly energetic electrons in the corona[4] and hence are expected to follow a power-law ($N(E) \propto E^{-\alpha}$) form with photon index ranging between 1.9-2-2.[11]

The soft x-ray photons (in the range of 0.2 to 2.0) are absorbed by the galactic medium, where the amount of absorption depends upon the column density of gases along the line of sight of the source. The functional form of an Absorbed Powerlaw is[6]

$$C(E) = Ke^{-[N_H\sigma(E)]}[E(1+z)]^{-\alpha} \quad (v)$$

where K is the norm, α is the photon index and z is the redshift.

$\sigma(E) = \frac{1}{n_H}\Sigma n_i\sigma_i \quad (vi)$is the equivalent absorption cross section and n_i is the column density of various ions, and when divided with column density of Hydrogen, this gives the relative abundance of the elements. I have used the model 'wabs' to model the galactic absorption[12]and it uses the Anders and Ibihara relative abundances[13][14]. N_H is the equivalent hydrogen column density which is the Hydrogen column density that would produce the same absorption as that seen due to all the other ions/atoms. The need of intrinsic absorption of host galaxy was determined by comparing the obtained values of column density with the known standard values of galactic absorption, at the HEASARC archives. If the value is significantly larger than the known values, the intrinsic absorption of host galaxy needs to be invoked.

I have modeled the soft x-ray excess by the redshift corrected blackbody spectrum whose functional form is:

$$C(E) = 8.0525\, K \frac{[E(1+z)]^2 dE}{(1+z)(kT)^4} e^{-\left[\frac{E(1+z)}{kT} - 1\right]}; K = \frac{\Lambda}{[D(1+z)]^2} \quad - (vii)^{[12]}$$

Where K is the norm, z is the redshift and kT is the Temperature of the disc. Λ is luminosity in the units of 10^{39} ergs/s and D is distance in the unit of 10 kpc [12].

- Goodness-of-fit

Goodness of fit is a statistical tool used to check if the model actually represents the original data. Since it is statistical in nature, it uses the variance in the counting statistics as the information required to statistically determine the correctness of the model [9]. It gives the percentage number of simulations that gave a statistic value lesser than the best fit value that we have. Ideally, this number is about 50% if the model actually represents the obtained data. Since this test is purely statistical, our knowledge of the physical processes that happen, is also important.

- Hardness Ratio:

A light curve is a graph of the number of photons detected by the instrument as a function of time. Active galactic nuclei are observed to show rapid variability in the photon flux[7] and hence have a wavy light curve. Here, I have tried to plot the hardness ratio of the data using the light curve extracted from XSELECT. Various definitions of hardness ratio exist in literature. I have used the following definition:

$$HR = \frac{C_H(t)}{C_S(t)} \text{ (vii)}$$ [15]

Here, C_H (t) refers to counts in the hard X-ray (in the energy range 2-8 keV) and C_S (t) are counts in soft X-ray, at a given instant of time‘t’.

Hardness ratio gives information about the properties of the x-ray source. A hard source refers to the counts in the higher energy band being greater than the low energy band and vice versa.

The report further has been divided into Section A and B that deals with computational details and Discussions respectively.

1. ABOUT THE INSTRUMENT AND DATA PROCESSING:

1.1 AstroSat*[9]

AstroSat is an Indian space observatory launched by the Indian Space Research Organisation (ISRO) on Sept 28, 2015 from Satish Dhawan Space Centre, Sriharikota. It has a mass of about 1515kg and is set into an orbit at a height of 650km and inclination of 6 degrees. It is a multi-wavelength observatory that observes the universe in various domains like Visible Light and Ultraviolet (with the Ultra-Violet Imaging telescope – UVIT), soft X-rays (with Soft X-ray telescope – SXT) and Hard X-rays (with Large Area X-ray Proportional Counters – LAXPC and Cadmium-Zinc-Telluride Imager - CZTI). AstroSat aims at studying various phenomena such as understanding high energy processes in a binary system of stars, neutron stars and blackholes, understanding the magnetic fields around the neutron stars, etc.

1.2 The Soft X-ray Telescope (SXT)*[9]

Soft X-ray telescope of AstroSat is a focusing telescope that focuses the X-rays in the energy range of 0.3 to 8.0 keV on a Charge-Couple Device (CCD) camera assembly by reflecting them at grazing angles using a series of co-axial parabolic and hyperbolic mirrors that follow Wolter Type-I geometry. Since the X-rays emitted by the source are few in number as compared to Visible-light, Radio waves, etc, the detector detects individual photons and not the flux of photons. The telescope has a focal length of 2000mm, effective area of 22 sqcm at 6 keV and a field of view of 40'. It is calibrated by four radioactive sources, Fe-55 that emit Soft X-rays at 5.9 keV (ref Figure 1). The energy resolution is about 2.5% at 5.9 keV. The readout time of the instrument is about 2.4s. The data obtained by the SXT is stored onboard and is sent to the ground based stationonce in every orbit where it is 'cleaned' for subsequent analysis.

[* Information Summerised from the Handbook of Astrosat, Bhattacharyaya et al]

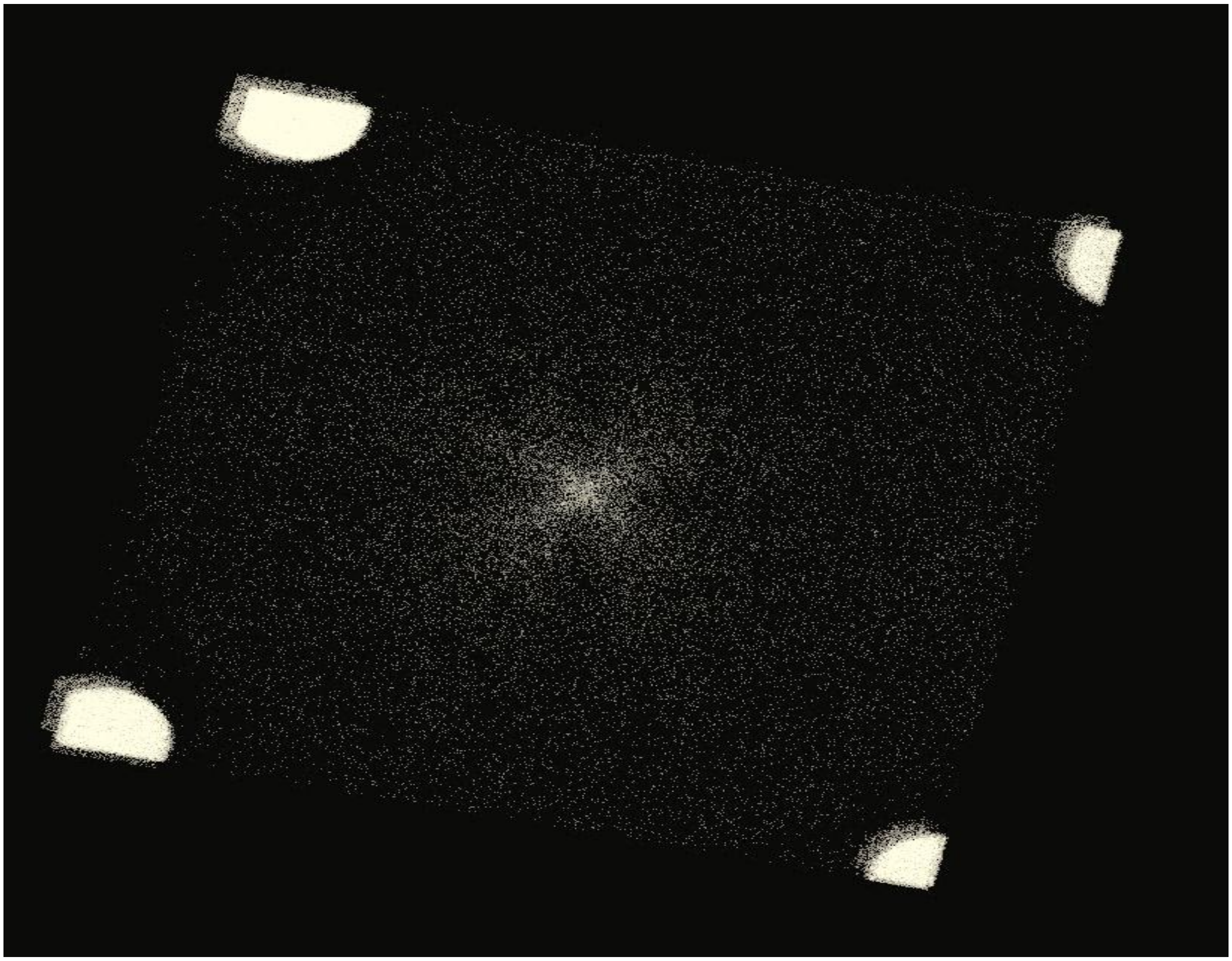


Figure 1: The AstroSat Soft X-ray image of NGC-3998 in Sky-Coordinates. At the corners, we can see the four Fe-55 calibration sources. Soft X-ray image is a representation of the events recorded, depending on where they are detected on the detector.

SECTION – A: COMPUTATION: PROCEDURES AND OUTCOMES

2. Data Reduction[10]

The data sent by the SXT to the ground based station – Mission Operation Complex (MOX), ISRO, is called the level-0 data and consists of very raw observations made by the instrument. The level 0 data is processed at the station. After making some transformations like grade filtration, removal of Pile-up effects, etc., the information is stored in a FITS (Flexible Image Transport System) file and is called the level-1 data. [10]

The level 1 data is further processed by using Pipeline Data Analysis Software and Calibration Database Files (CALDB). Various steps involved in processing the data are- Event extraction, Time-tagging events, Co-ordinate transformation from detector to satellite to Sky co-ordinate systems, flagging of bad pixels, etc. The processed level-1 data is called the level-2 data.

I was handed the level-2 data of MRK-110 and NGC-3998 collected over multiple orbits, to study. Main files to use were the event file (.evt) and for other information, I had to use the .mkf file.

The event file (.evt) generated by processing level 1 data contains vital information about the 'events' occurred on the detector. Complete descriptions of events such as the raw and detector co-ordinates of the incident photon, grade of the events, its PHA (pulse-height amplitude), PI (Pulse Invariant), etc is available in an evt file in a time ordered form. Extraction of image, spectrum, light curve, etc is done using an event file.

3. Spectral Extraction

The first thing I did with the X-ray data obtained, was to 'look' at the data in as many ways as possible. I spent some time in understanding the commands under the HEASARC package and certain tools that operated on FITS files. I began by extracting the image, calculating the location of centroid, estimating its off-ness from the already known co-ordinates, extracting light curve and the spectrum of NGC-3998 and MRK-110. Details of the extraction are given below.

Table 1: Important Figures on observations (Obtained from the event file):

Particulars	MRK-110	NGC-3998
Distance/Redshift*	153.6Mpc/0.03552[16][17]	13.7Mpc/0.003646[17][18]
Date Of Observation	Apr 16, 2016	Apr 14, 2016
Data Mode	Photon Counting	Photon Counting
Duration of Observation	5.455×10^4 sec	4.506×10^4 sec
No of Photons Detected**	177,198	163,616
Count Rate	4.367 counts/sec	2.999 counts/sec
Centroid	RA: 9:25:17:941 Dec: +52:15:00.86	RA:11:57:49:810 Dec: +55:24:23.04

*Obtained from SIMBAD.

**Consists of contribution from Source, Background and Calibration sources

3.1. Extraction of Image, Spectrum and Light Curve:

In order to extract image, spectrum, lightcurve, radial profile and derive the half power diameter of the instrument, the event file (generally labeled as ***_cl.evt) is required. The event file is generated after the Level 1 data is processed by using the SXTPIPELINE software. The event file has time ordered readings of the instrument, in the time intervals equal to the readout time of the instrument (ie 2.4 sec). I had written a C-language code that took the observations between two successive readout times and average it, such that we see a better representation of the same data. Observation of the objects by the SXT has been done in multiple orbits so that we get a richer look at the X-ray spectrum.

The counts recorded in every orbit was low, and even there, majority of the counts came from the Calibration Sources. Hence, in order to enrich the source counts, the first task I did was to merge the data from individual orbits. I used the software developed by S. Chandra and team (astrosat-ssc.iucaa.in/uploads/sxt/sxt_gti_corr_evt_merger_v02.py). This python script uses the image files (.img) from the level-2 data, looks at the data carefully and removes the overlaps between the orbits to finally produce.evt, .mkf and .lbt files that have the combined data of the object being observed, from the individual orbits. This .evt file generated is used in XSELECT to extract spectra and light curves.

The following is a brief procedure to extract the image/spectrum/lightcurve using XSELECT:

a. Open XSELECT by initializing the HEASARC software and then issuing command ‘XSELECT’.

b. Enter the name of the session, when the prompt appears

c. Issue the command ‘read event’ and enter the name and location of the event file one wishes to study, after prompted.

d. After the event file gets loaded, issue the command ‘extract all’.

e. All the vital figures from the observation (eg. Date of observation, name of the object, Total number of counts, count rate, etc.) appears after extraction is done.

f. Issue the command plot image/curve/spectrum. This plots the commanded entity on a plotting device (eg: /xw, ds9).

Given below are the images and spectra obtained from XSELECT. The colours in the images are indicative of the brightness of the image.

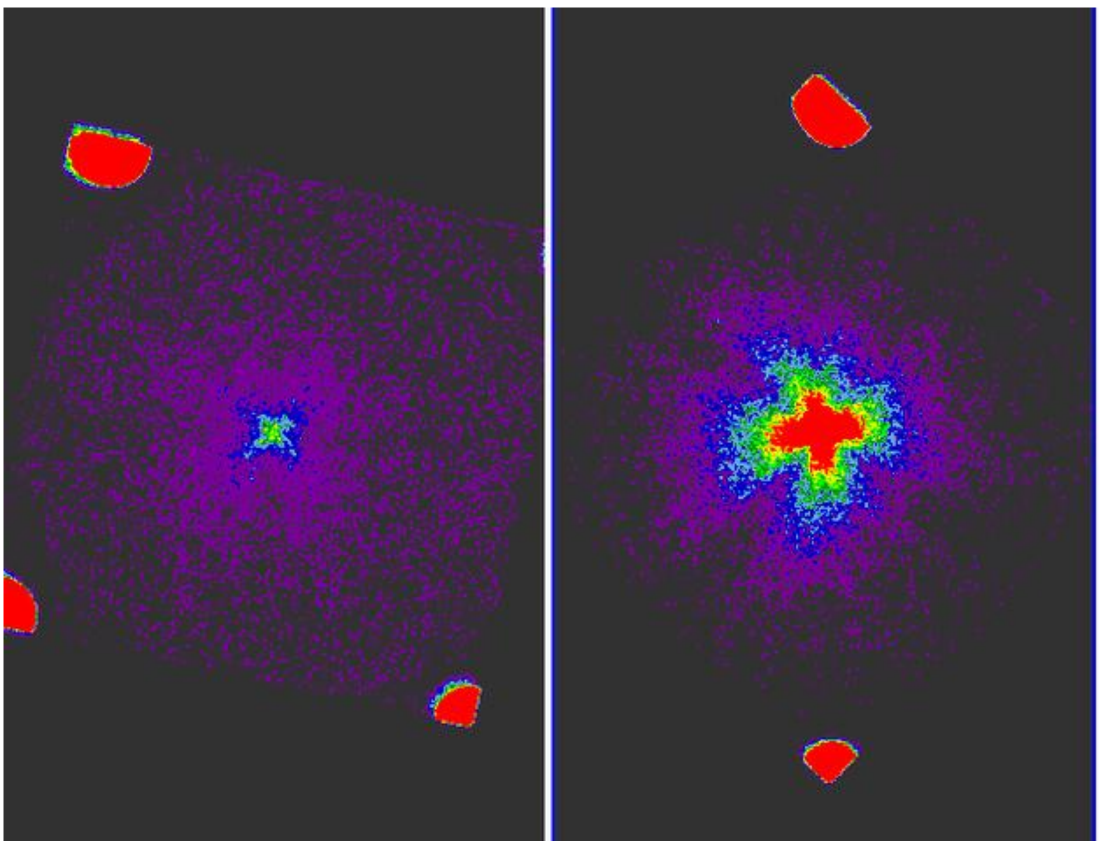


Figure 2: The False ColouredSoft X-ray Image of NGC3998 (Left) and MRK-110 (Right). The colours in the image are suggestive of relative brightness, red being brightest and violet being the least bright

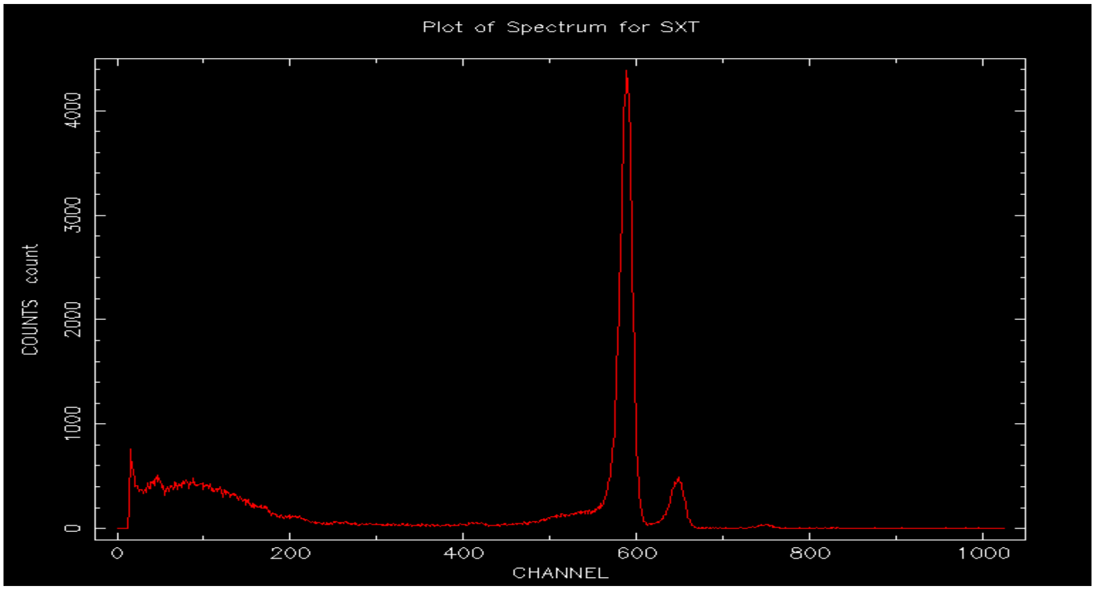


Figure 3a: Spectrum of MRK-110 obtained from XSELECT. The peaks at channel no. 585 and 640 are the calibration peaks. The spectrum is unresolved since the y axis is scaled such that the calibration peaks are clearly visible

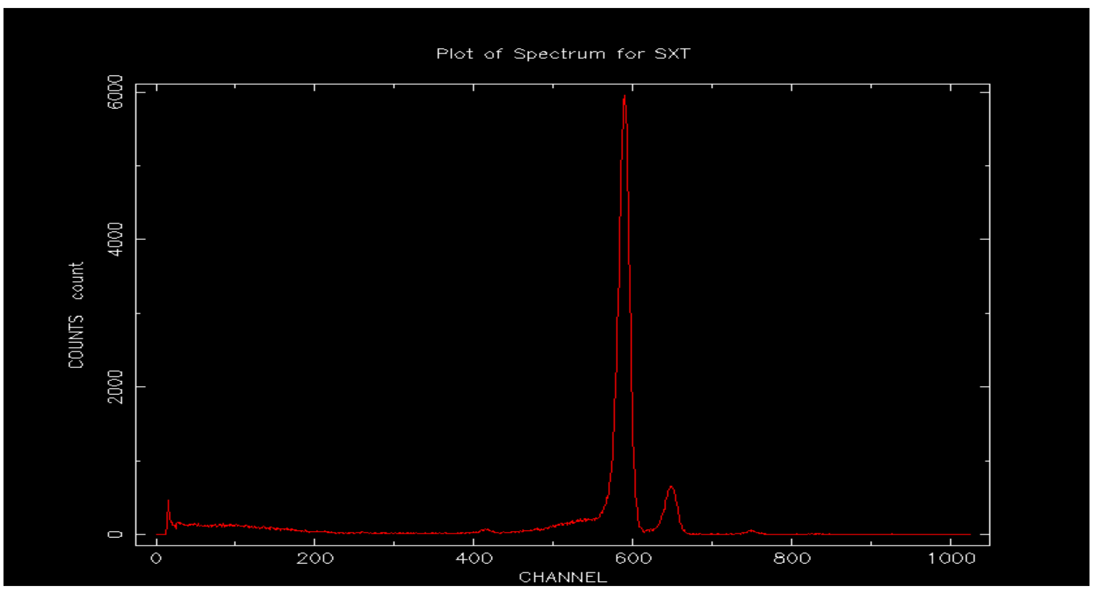


Figure 3b: Spectrum of NGC3-998 obtained from XSELECT. The peaks at channel nos 585 and 640 are the calibration peaks.The spectrum is unresolved since the y axis is scaled such that the calibration peaks are clearly visible

3.2 .Plotting the Radial Profile and determining the Half Power Diameter of the Point Spread Function:

The spectrum of the object obtained from XSELECT has the following problems:

a. The spectrum consists of huge contribution from the calibration sources.

b. The spectrum isn't pure; it is contaminated with the background noise.

c. The spectrum is labeled in terms of the channels and not the channel energy.

In order to study the source X-ray photons, it is important to eliminate the contribution coming from the calibration sources and minimize the background noise. To do that, we need to eliminate the calibration sources from the extraction region and obtain the background spectrum. This is done in the following steps:

I. Plotting the Radial Profile:

Assuming that the contribution coming from the background is uniform throughout the area of the detector, at sufficiently far away from the centroid of the image, the profile should be flat. This gives an estimate of the approximate region where source counts are focused

Brief procedure involved in extracting the radial profile is the following:

After opening the event file in ds9, I divided the image into small annular regions by choosing annulus shape from 'Region' menu. By default, the annulus consists of two annuli. I set the annulus to the centroid of the image by choosing the 'Centroid' option from 'Region' menu.

Double clicking the annuli opens the ‘Annulus’ dialog box. I set the inner radius to 0 and the outer radius to a sufficiently large distance (20-22 arcmin) such that the annulus covers most of the image and excludes the calibration sources. I divided the selected region into 150 annuli, each with the same area, as shown in Figure 4.

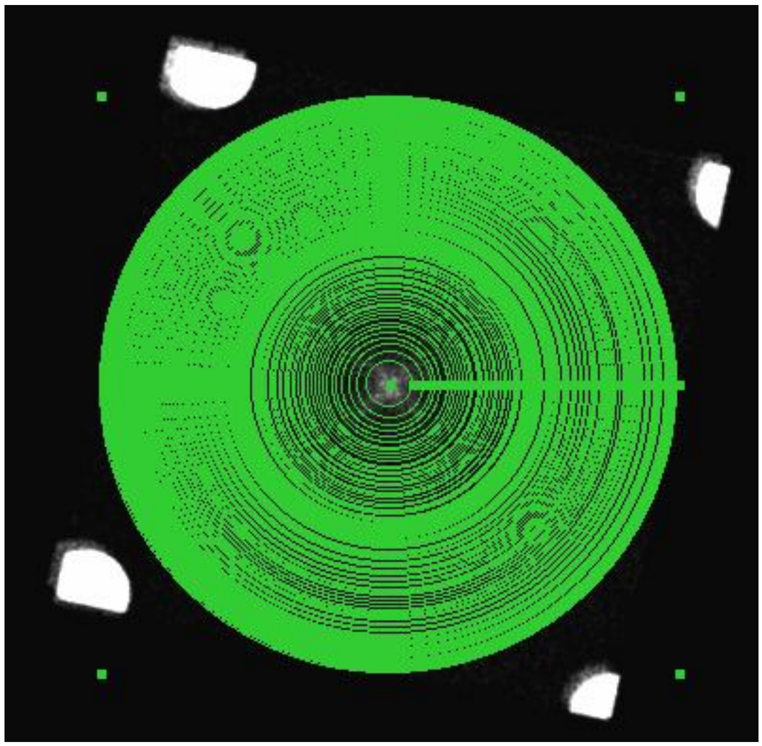


Figure 4: Image of NGC-3998 divided into 150 annuli of equal areas. The First annulus has a radius of 1.414 arcmin

From the ‘Annulus’ dialog box, selecting ‘Radial Profile’ from the ‘Analysis’ menu plots the Radial Profiles of the object. Given below are the radial profiles of NGC-3998 and MRK-110.

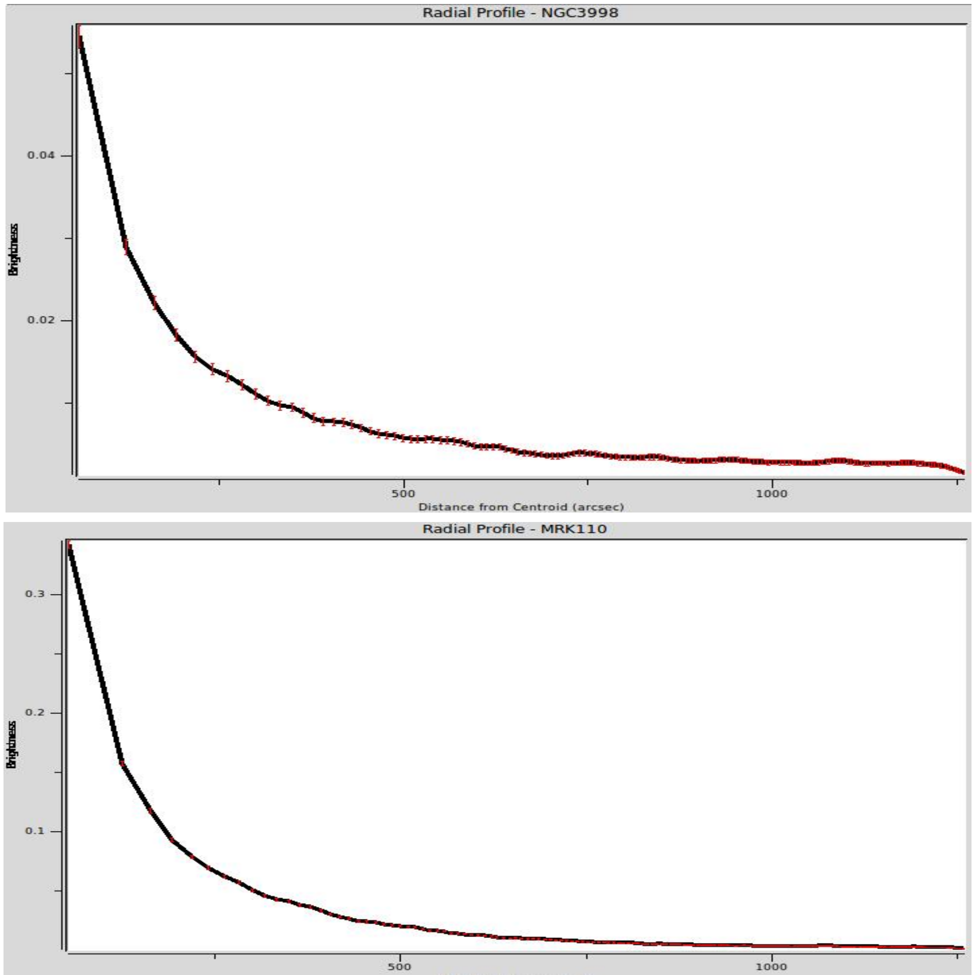


Figure 5: The Radial Profiles of NGC-3998 (top) and MRK-110 (bottom). The x-axis is the distance from centroid in arcsec and the y-axis is the Brightness

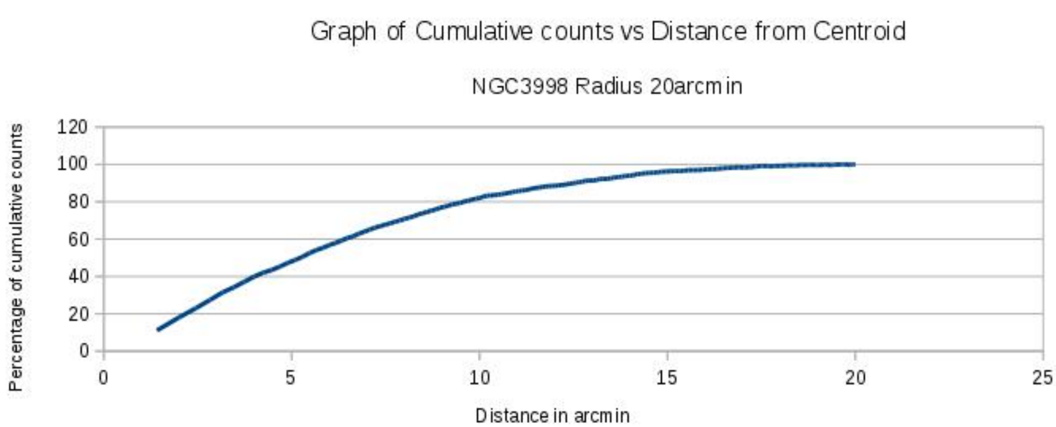
Both profiles are seen to be roughly flat after 750 arcsec (12.5 arcmin)

II. Plotting the Encircled Energy Profile (EEP)

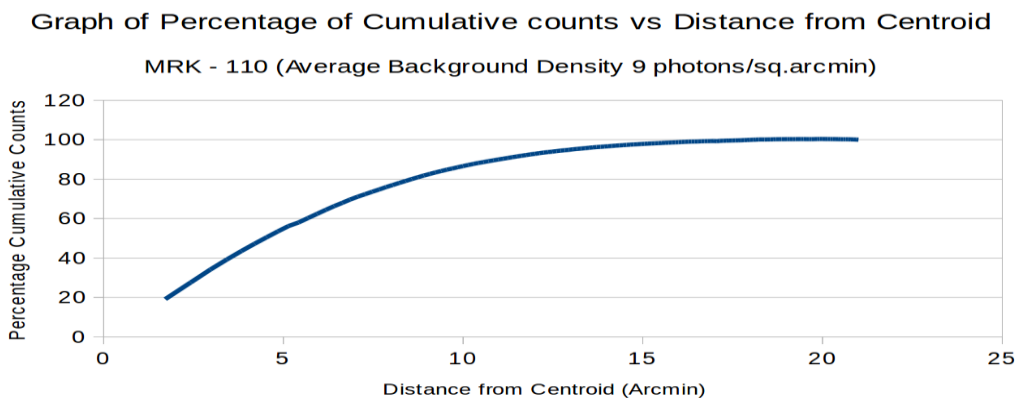
Encircled Energy Profile is a graph of cumulative counts of photons as a function of distance from the centroid. EEP enables us to estimate the half power diameter of the point spread function and also gives us an approximation to the choice of Source Region.

In order to plot the same, the number of counts of photons in each annuli is obtained from the 'Statistics' option from the 'Analysis' menu in the 'Annulus' dialog box.

I wrote a small C-Language code that took these values of counts, added them with increasing distance and plotted the EEP. The graph was expected to saturate after a region when the source contribution becomes negligible. However, it was seen that the graph is rather a straight line. This was because of a very low S/N (signal to noise) ratio. In order to check for the background counts, I estimated the average background brightness and subtracted them from the EEP and hence, a graph was obtained that saturated as the distance from centroid increased.



Graph 1: The Encircled Energy Profile of NGC-3998. 90% counts lie with 12 arcmins from the centroid.



Graph 2: The Encircled Energy Profile of MRK-110. 90% counts lie within 12 arcmins from centroid

The average background density in the case of NGC-3998 and MRK-110 was 4.3 and 9.0 per sq arcmin.

From the Encircled Energy Profile, the Half Power Diameter of the instrument is seen to be about 13 arcmins.

According to the graph, 90% of the background corrected counts lie in the region of radius 12 arcmin (approx.) from the centroid. However, in order to have a better S/N ratio, I have chosen a circular region of radius 8 arcmin from the centroid as the source region.

In order to extract the source and the background spectrum, I followed the following steps:

1. I selected a circular region with the same centroid as that of the annuli I used to derive the radial profile. In order that I have a better S/N ratio, I chose the circular region to have radius of 8arcmin. This region served as the source region.

2. An annular region from the centroid with inner and outer radii of 16 and 21 arcmins respectively was chosen as the background region (shown in Figure 5). Both these source and Background region were saved in the form of region files (.reg) that can be loaded in XSELECT.

3. In XSELECT, I loaded the event file and the region files to extract the source and the background spectrum

4. These spectra obtained were saved as a pha file for further analysis by XSPEC.

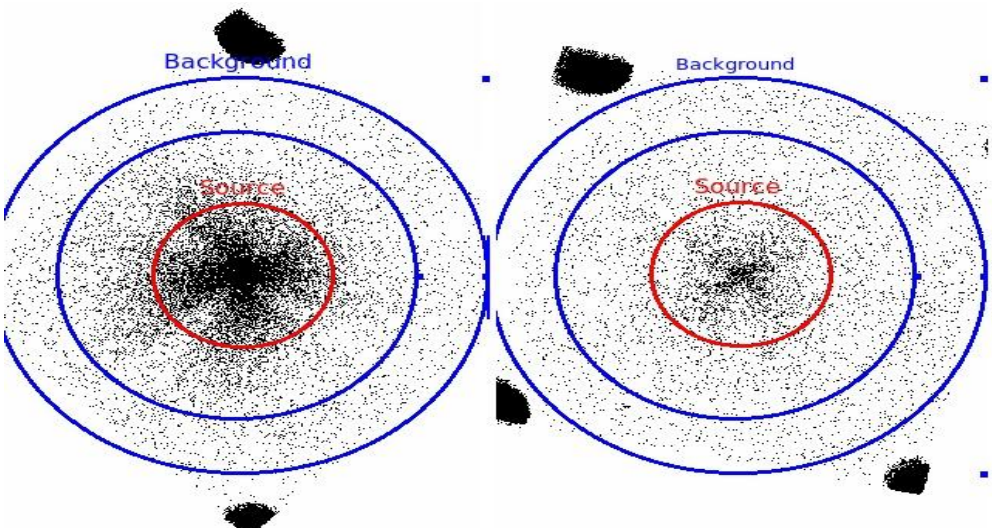


Figure 6: The Choice of Source and Background regions for MRK110 (left) and NGC3998 (right)

4. SpectralModeling and Fitting

This section discusses in brief, the methodology I followed to 'look at' the spectra, fit them and compute the values of different parameters.

4.1. Grouping the data:

Before feeding the data to XSPEC, it is important to group the data.XSPEC uses Chi-squared statistic that is applicable only when the data has Gaussian distribution. Hence the data is first processed by using software GRPPHA. GRPPHA doesn't redefine the data; it sets up a flag that is read by XSPEC. XSPEC then automatically uses the same operations on responses and background files[19]. In order that the data is classified to be Gaussian distributed, it should have min 20 counts per channel.

I followed the following procedure to group the data.

1. After initializing then HEASARC Package, issue the command 'GRPPHA'.
2. Input the Source spectrum file that was obtained as an output from XSELECT. Also, issue a name to the output file from GRPPHA.
3. The source file can be linked with the RMF, ARF and background files in GRPPHA itself. Issuing the command 'chkey RESPFILE/ANCRFILE/BACKFILE' followed by respective file names will incorporate the instrumental response and background with the source file. The background region should be scaled to the source region. I have used the ARF file corresponding to effective area of 8 arcmins and RMF file corresponding to grades 0-12 for both the spectra.
4. I grouped the spectrum in minimum 20 counts per channel. This was done by issuing the command 'group min 20'.
5. After issuing the exit command, GRPPHA creates a new file with the name provided in step 2 and this file can be used with XSPEC directly.

4.2. Spectral Fitting

This section deals with fitting the spectrum with appropriate models and computing various parameters.

4.2.1 Spectral Fitting of NGC-3998:

After having loaded the grouped spectrum of NGC-3998, one can look at how the spectrum looks as a function of energy. Issue successively, the commands ‘cpd /xw’ and ‘setp e’ and ‘ign **0.2 8.0-**’. These commands will set the plotting device, set the x-axis to energy and ignore the energy ranges below 0.2 and above 8.0 keV. Finally, pl data plots the data. Given below is the image of the spectrum of NGC-3998 and its background spectrum.

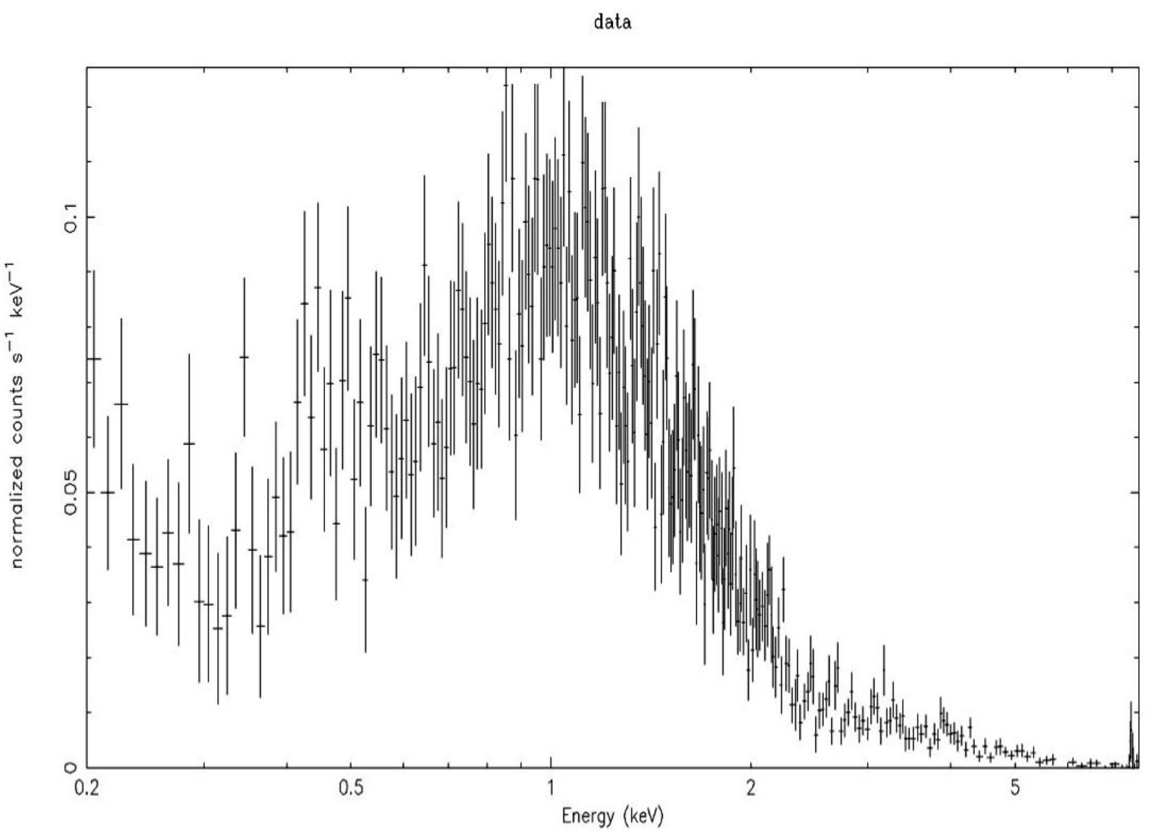


Figure 7: The background subtracted spectrum of NGC-3998. Region from 2 keV and further is suggestive of powerlaw spectrum. Region from 0.5 to 1 keV suggests galactic absorption and that below 0.5 keV is the soft excess. Peak at 8keV is due to the electronics of the instrument

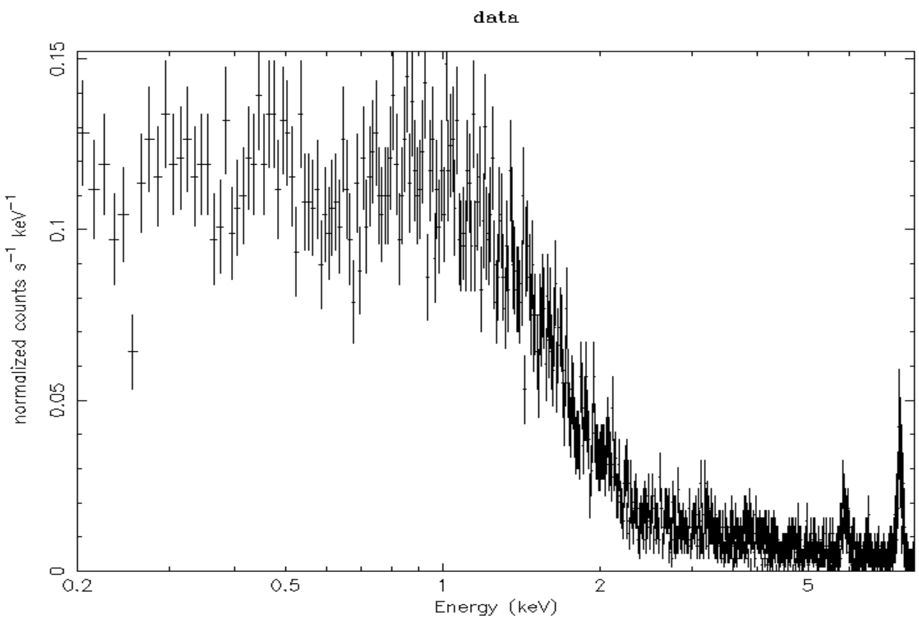


Figure 8: The Spectrum of Background of NGC-3998. The spectrum is taken from an annular region towards the periphery of the image.

As can be seen in Figure 8, the background of NGC-3998 is contaminated by the source photons, even when the selection of the background is done from the most periphery of the image. Also, it is contaminated with the noise coming from the electronic gadgets in the telescope itself (tall narrow peaks at approx. 6 and 8.5 keV). These peaks come from the copper used in the electronics of the instrument.

The spectrum is suggestive of a (redshifted) powerlaw spectrum in the range 2.0-8.0keV and an absorption dominated (redshifted) powerlaw between the range 0.2-2.0 keV.

The procedure to fit powerlaw spectrum is the following:

1. Issue the command ‘model zpowerlw’. The photon index and norm may be skipped.
2. Issue the ‘fit’ command. XSPEC automatically runs the fitting algorithm to find the best fitting value of powerlaw index and the norm.

The fitting value of the index and norm in this first step was computed to be 2.13577 and 2.00797×10^{-3}. The Chisq value of the fit was 124.05 using 92 PHA bins and the reduced Chisq was 1.3783 for 90 Degrees of Freedom.

Shown below (Figure 9) is the unfolded powerlaw fit to the energy range 2.0-8.0 keV and its extrapolation to lower energy. The upper panel shows the model spectrum and the actual data points while the lower panel is a representation of the off-ness of the actual values from the model predicted values.

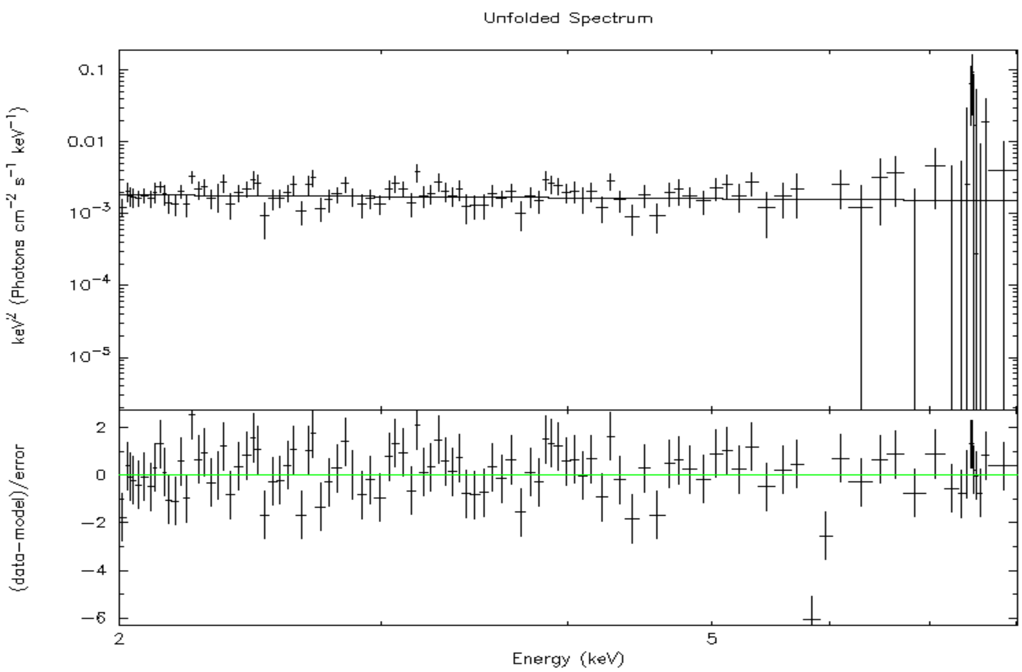


Figure 9: Powerlaw fit to the Energy band 2.0-8.0 keV – NGC-3998. The tails at towards the higher energy region are just large error bars, seen since the scale is logarithmic. The horizontal bar on the upper panel is the representation of the powerlaw model

The spectrum of extrapolated powerlaw to lower energies clearly shows the signature of absorbance due to galactic medium (Figure 10). In order to account for this absorption, I used the model 'wabs'. Wabs is a model that estimates the photo-electric absorption of x-rays using Wisconsin Cross-Sections[18][19][20]. Wabs is a multiplicative model, one that represents the modification a medium brings in the spectrum emitted by the source[18].

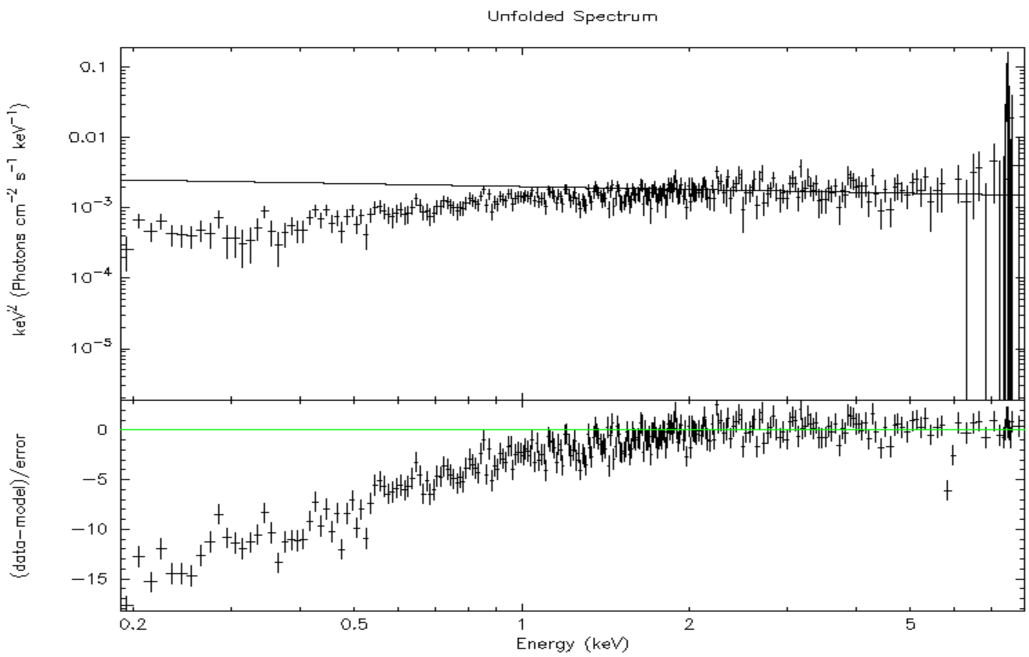


Figure 10: NGC-3998: Extrapolation of powerlaw to lower energies is an indication to include the galactic absorption in the modeling of the spectrum

Procedure to fit the absorbance is as follows:

1. Issue the command ‘addcomp 1 wabs’. This includes the galactic absorption component to the Powerlaw model.
2. Skip the equivalent column density and issue ‘fit’ command.

The best fitting values after including the Galactic Absorption component are tabulated below:

Table 2: Summary of Best fit Parameters for Spectrum of NGC-3998

Parameter	Value of Parameter	Error (upto 90% confidance)
Redshift	0.0036	-
Powerlaw Index	1.9522	+0.0846 / -0.0805
Powerlaw Norm	1.6488×10^{-3}	+/- 0.0001
Absorption Column Density	$9.82 \times 10^{20} cm^{-2}$	+0.0181 / -0.0167 cm^{-2}

The best fit chi squared value was 300.25 using 281 PHA bins and reduced Chisq value was 1.0800 for 278 Degrees of Freedom. Inclusion of Intrinsic Absorption due to host galaxy (zwabs) didn't improve the fit statistic significantly (1.0610 for 280 PHA bins). The 'Goodness' command gave 58.00% realizations being less than the best fit statistic.

The final Spectrum with the best fitting parameters is shown in Figure 11.

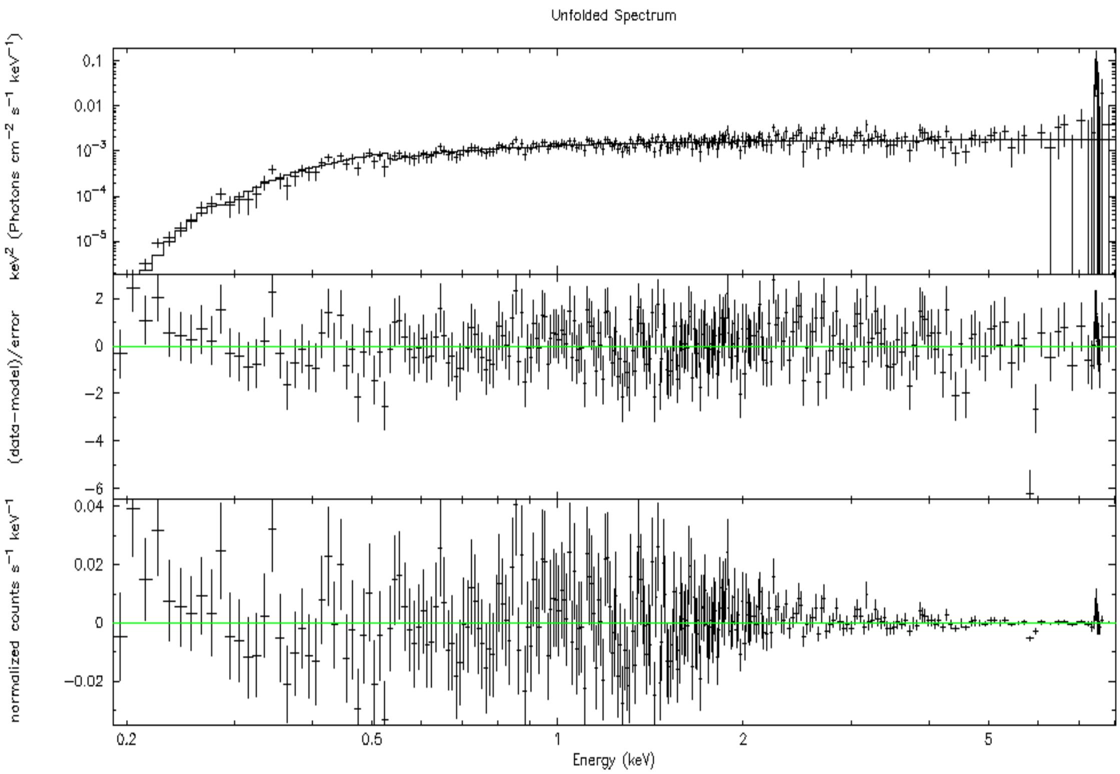


Figure 11: Final best fit Spectra – NGC 3998.

The first panel in Figure 11 shows the model spectrum and the observed distribution of data points. The second panel shows the measure of off-ness of the data values from the predicted values, normalized by the standard error, the third panel shows the plot of residuals, which is a plot of data minus the folded spectrum. An Unfolded Spectrum is a plot that shows the counts as a function of energy, taking into consideration the instrumental Quantum efficiency, ie, how many photons would have possibly be incident.

Having gotten the best fit models, I computed the flux of X-ray radiation coming from the source. Flux in the energy range 0.2 to 8.0 keV can be computed by issuing ‘flux 0.2 8.0’ command. It was found to be in $6.9747 x 10^{-12}$ erg/cm^2s with 68% confidence in the range $6.826 x 10^{-12}$ to $7.146 x 10^{-12} erg/cm^2s$. The estimated luminosity of the source approximately is $1.5663 x 10^{41}$ erg/s.

4.2.2. Spectral Fitting of MRK-110

Procedure similar to that of NGC-3998 was also followed for modeling MRK-110 data. The spectrum of source and background is given below:

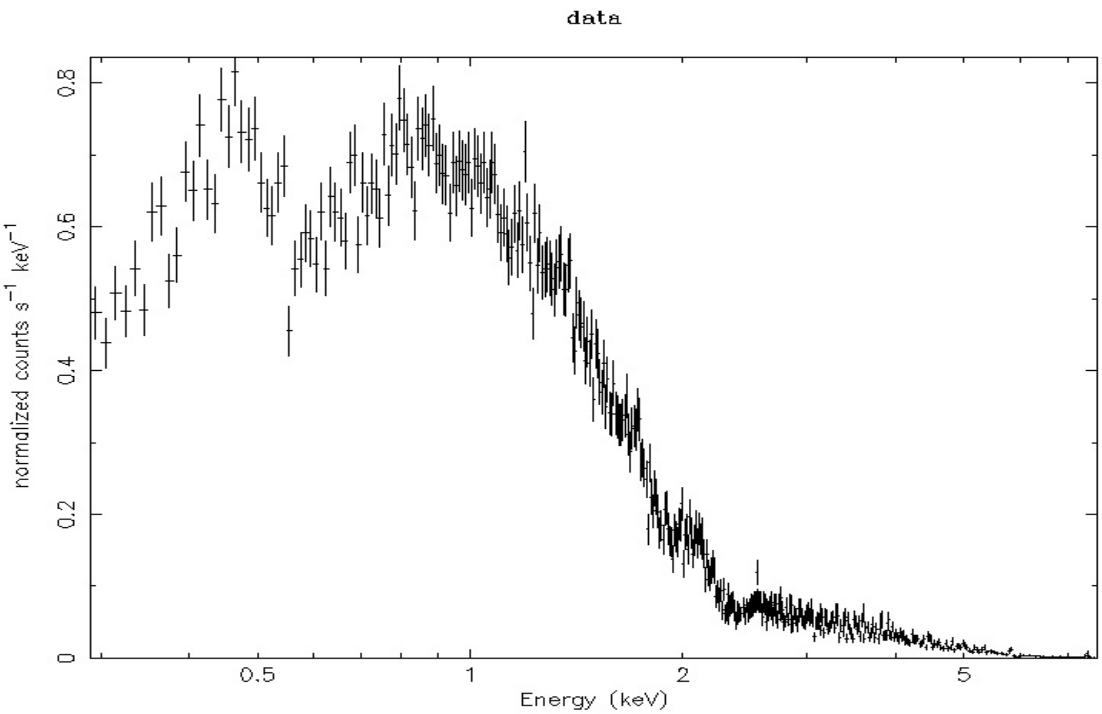


Figure 12: Source Spectrum (Background Subtracted) of MRK-110. Region from 2 keV and further is suggestive of powerlaw spectrum. Region from 0.5 to 1 keV suggests galactic absorption and that below 0.7keV is the soft excess.

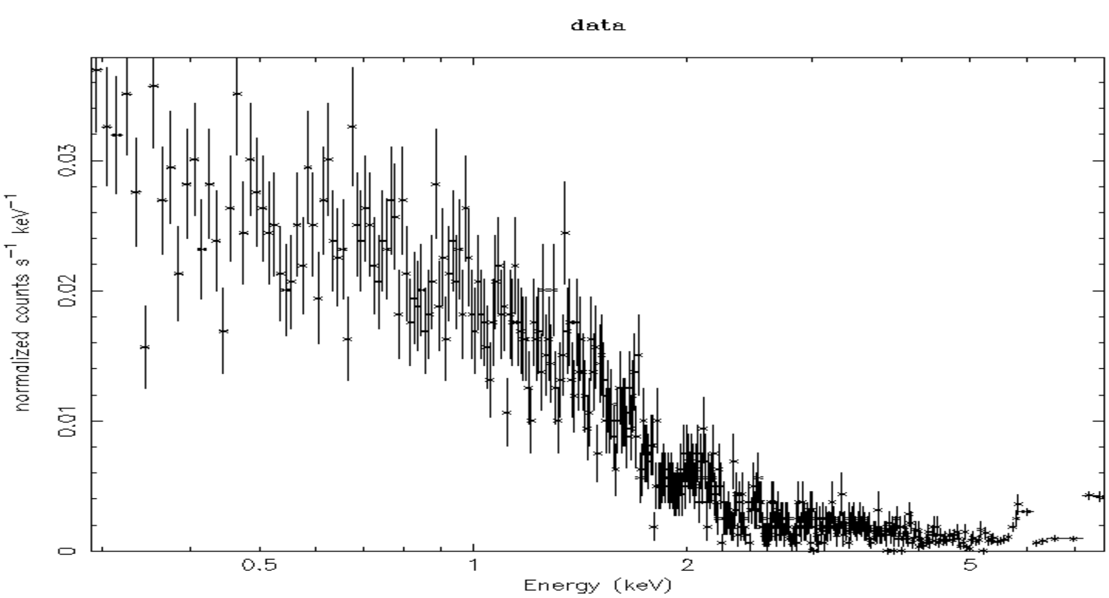


Figure 13: Background Spectrum of MRK-110

While a (redshifted) powerlaw fit to the range 2.0 to 8.0 gave the reduced chi squared value =1.0754 for 223 degrees of freedom (chi sq value of 239.81 using 225 PHA bins) with a goodness statistic of 57% realizations being less than this best fit value, extrapolation of this to the lower energy and including the galactic as well as intrinsic absorption gave worse values of reduced chi square. I further included the galactic absorption component, wabs.

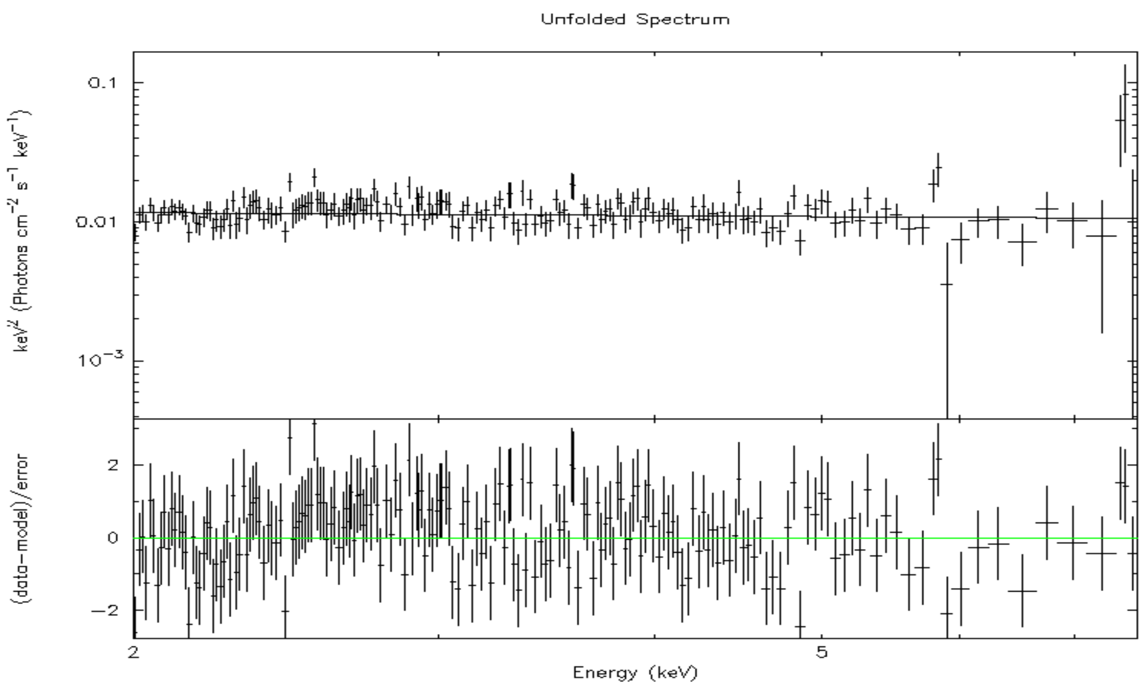


Image 14: Powerlaw fit – MRK-110 data. An appreciable peak is observed around 5.9 keV

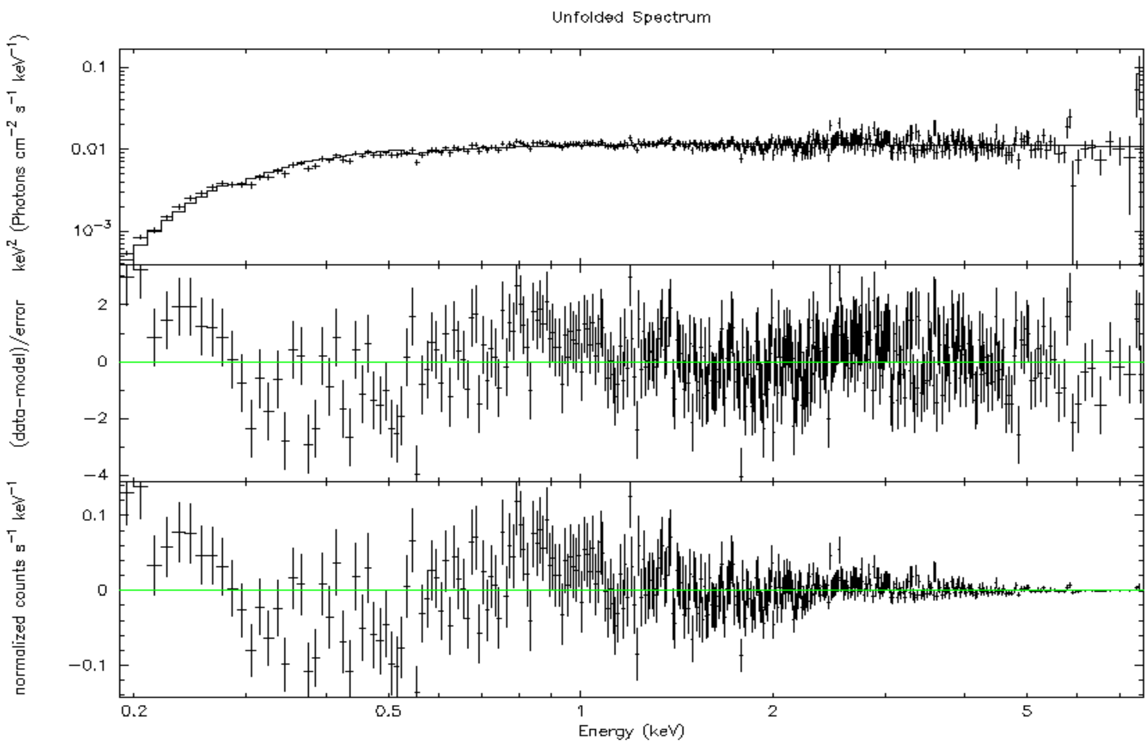


Figure 15: Fit model (zpo*wabs) on the data of MRK-110. The middle panel is the offset of data from the model; lower panel is the plot of residuals. Plots are suggestive of Soft excess at lower energies.

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The best-fit value obtained here is as follows:

Chi-Squared value was 528.73 using 406 PHA bins. Reduced Chi-Square value was 1.3120 for 403 degrees of freedom. Goodness-of-fit gave 90% realizations being less than the best fit statistics.

In order to model the soft excess seen between 0.2 keV and 0.3 keV, I used the Redshift corrected blackbody model 'zbb'. This is an additive model and represents the source property.

After including the blackbody model, the final best fit statistics were as follows:

Obtained Chi Squared Value was 480.63 in 406PHA bins. Reduced Chi-squared value was 1.1986 for 401 degrees of freedom. The f-test gave the probability of 1.3441 x 10^{-8}. Goodness-of-fit gave 70% realizations < Best fit statistic of 480.63.

The final Best Fit Parameters with their errors are tabulated below:

Table 3: Best Fit Parameters for Spectrum of MRK-110

Parameter	Computed Value	Computed Error (90% Confidence range)
Powerlaw Photon Index	1.8852	+0.0509 / -0.0503
Powerlaw Norm	0.0102	+0.0006 / -0.0006
Redshift	0.03552	-
Equivalent-Hydrogen Absorbing Column Density	1.7738 x 10^{20} cm^{-2}	+0.5110x10^{20} / -0.5366x$10^{20}$$cm^{-2}$
Blackbody Temperature (kT)	0.2543	0.01664 / -0.01593
Blackbody Norm	7.1102 x 10^{-5} (10^{39} ergs s^{-1} kpc^{-2})	(+1.5411 / -1.5894) x 10^{-5}(10^{39} ergs s^{-1} kpc^{-2})

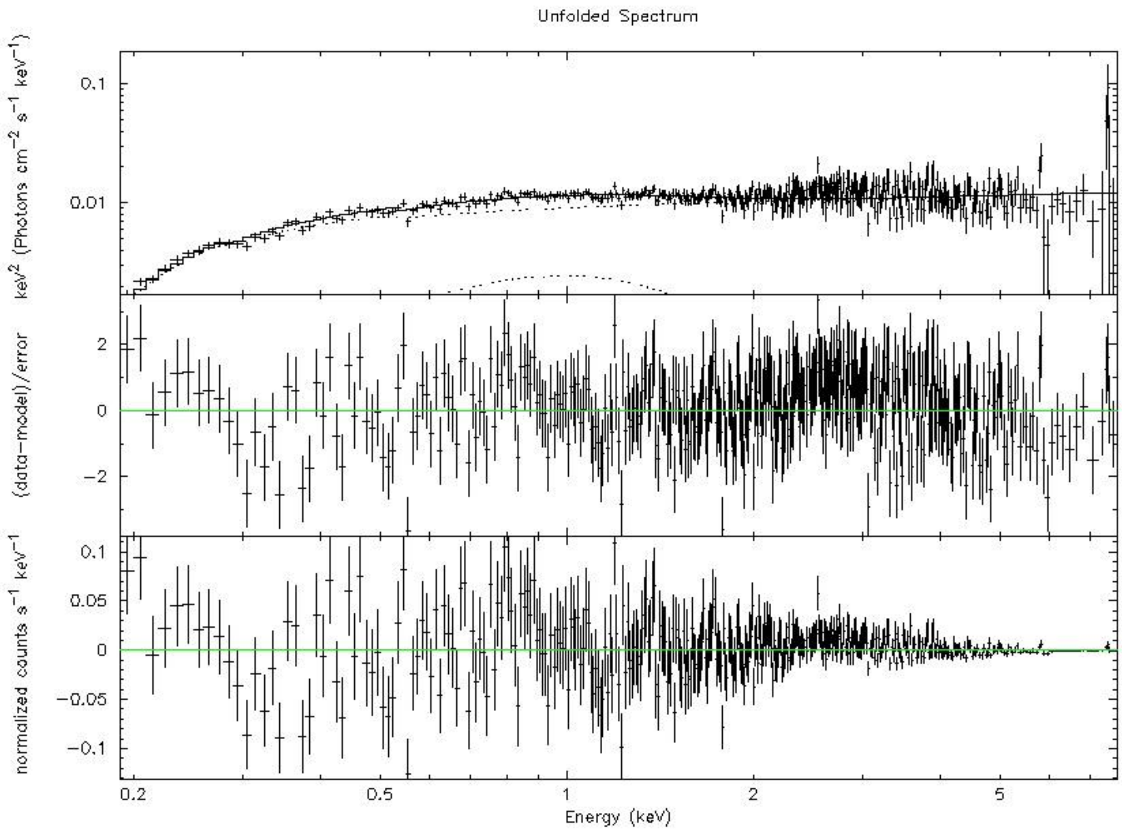

Figure 16: Final Best Fit Model to MRK-110 data.The functional form is (zpo+zbb)*wabs. The soft excess seems to be modeled well, but still shows its existence, suggesting some other mechanisms contributing to its formation.

The flux value in the energy range 0.2 to 8 keV hence computed was 5.7231 x 10^{-11} erg/cm^{2}s with 68% confidence range of (5.6630 – 5.7650) x 10^{-11}erg/cm^{2}s. The luminosity of the source hence computed is 1.6879 x 10^{44} erg/s.

5 Analysis of Light Curve – Determining the Hardness ratio

This section briefly describes the methodology of extraction of light curves and removing background counts from it. Finally it describes the procedure to plot light curve and its outcome.

5.1. Extraction of Light-Curves:

In order to plot the hardness ratio, one needs to have background count corrected light curves. I extracted the light curves of the background and the Source in the following way.

1. Load the event file in XSELECT
2. Filter the source region in XSELECT by issuing the 'filter region ***.reg' file.
3. Filter the Energy Range by issuing 'filter pha_cutoff [min channel] [max channel]'. The channel corresponding to the required energy range can be obtained from XSPEC.
4. Extract the light curve for energy range 0.3 to 2.0 keV by issuing the 'extract curve' command. Here, the corresponding channel numbers are 30 and 200 respectively. Save the light curve by issuing 'save curve'.
5. Now, in order to extract the light curve of hard X-ray spectrum, one needs to first clear the initially applied channel filter. This is done by issuing 'clear pha_cutoff'. After clearing the channels, redefine the filter as per given in step 3. The energies 2.0 to 8.0 keV correspond to channel nos. 200 and 800 resp.
6. Clear all the filters first and then repeat the same procedure to extract the background lightcurve.

5.2 Subtraction of Background Counts:

The ftool 'lcmath' is used to subtract the background from the source light curve. This software uses the light curve files obtained as an output from XSELECT.

I followed the following procedure to subtract the Background from the Source light curve:

1. Open the ftool ‘lcmath’ by issuing ‘lcmath’ command.
2. Load first the Source light curve when prompted.
3. Load the background light curve when prompted.
4. Final set the ‘Add instead of Subtract’ to ‘No’.

This generates a background subtracted source light curve file (.lc) that can be further used with ‘lcurve’ to generate hardness ratio. The procedure to do the same is the following:

1. Open the ftool lcurve by issuing ‘lcurve’ command.
2. Set the number of files to 2 (for hard and soft X-ray lightcurves)
3. Enter the Light-curve file corresponding to Soft X-ray in ‘Ser 1’
4. Enter the light curve corresponding to Hard X-ray in ‘Ser 2’

After this, lcurve gives vital information about the light curve such as the time of observation, newbin time, etc. Lcurve now prompts for the required newbin.Newbins refer to the time interval one sets per bin. Here the observations are roughly 14 hours long, hence I have used a time interval of 1000 sec per bin.

I. Hardness Ratio Plot of NGC-3998

Table 4: Statistics of Light Curve of NGC-3998

Parameter	Value
Start time	5:17:17:279 (h:mm:ss.sss) on Apr 14, 2016
End Time	3: 21:02:799 (h:mm:ss.sss) on Apr 15, 2016
Newbin Time	1000 s
Number of Intervals	166
Minimum value of counts in Soft X-rays	0.0314/sec
Maximum Value of Counts in Soft X-rays	0.1477/sec
Minimum value of Counts in Hard X-rays	0.0140/sec
Maximum value of Counts in Hard X-rays	0.0870/sec

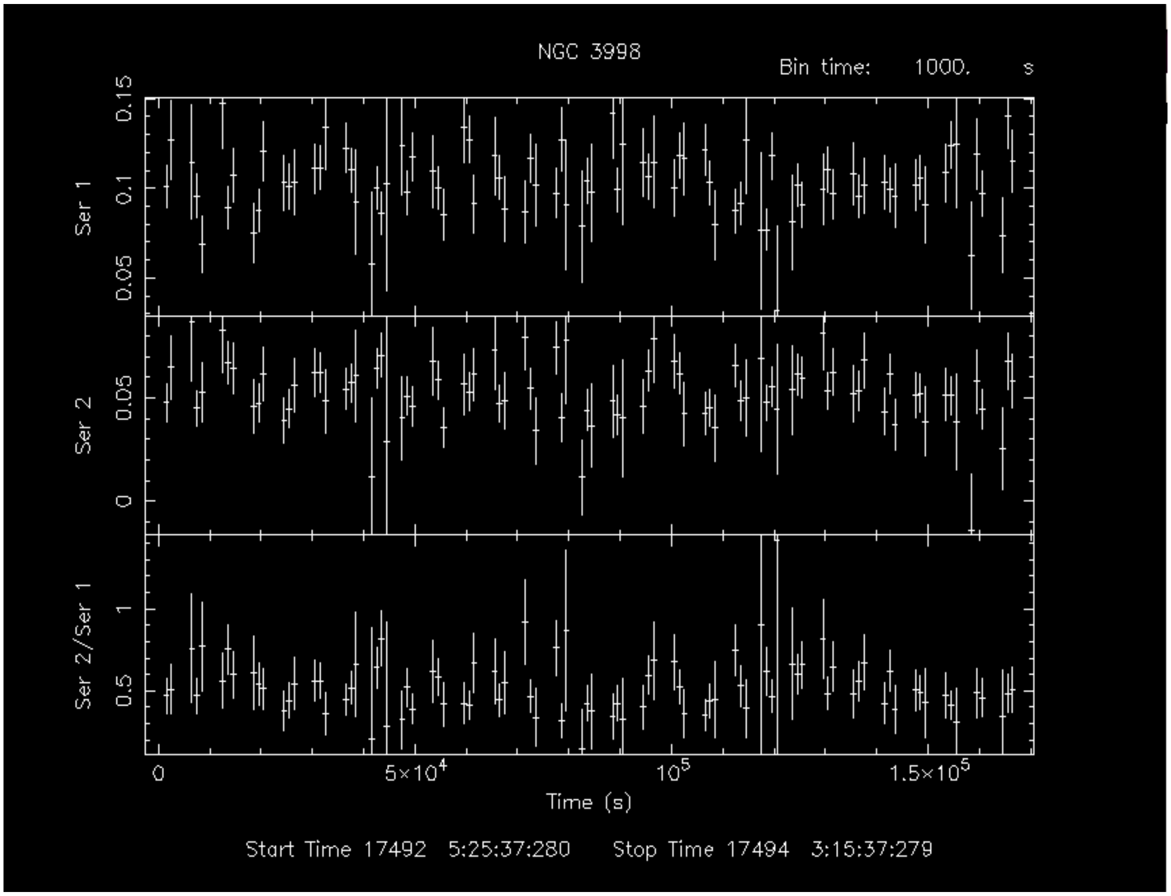

Figure 17: Background Corrected Light Curves of Soft (Ser1) and Hard X-rays (Ser 2) coming from NGC-3998. Here the y axis is the number of counts. Ser 2/Ser1 is the Hardness Ratio.

II. Hardness Ratio plot of MRK-110:

Table 5: Statistics of Light Curve of MRK-110

Parameter	Value
Start time	4:23:25:132 (h:mm:ss.sss) on Apr 16, 2016
End Time	18: 16:07:567 (h:mm:ss.sss) on Apr 16, 2016
Newbin Time	1000 s
Number of Intervals	137
Minimum value of counts in Soft X-rays	0.5063/sec
Maximum Value of Counts in Soft X-rays	0.7995/sec
Minimum value of Counts in Hard X-rays	0.2373/sec
Maximum value of Counts in Hard X-rays	0.3538/sec

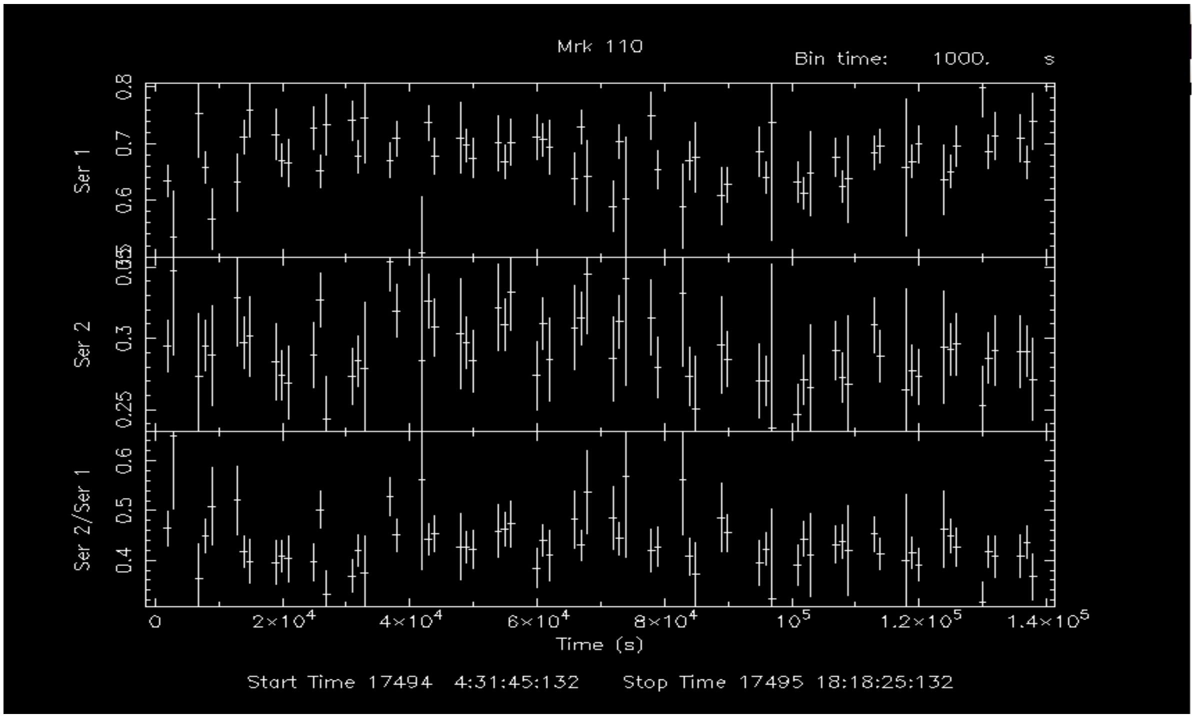

Figure 18: Background Subtracted light curves of Soft (Ser1) and Hard (ser2) X-rays coming from MRK-110. Y-axis is number of counts. Ser2/Ser 1 is the hardness ratio plot

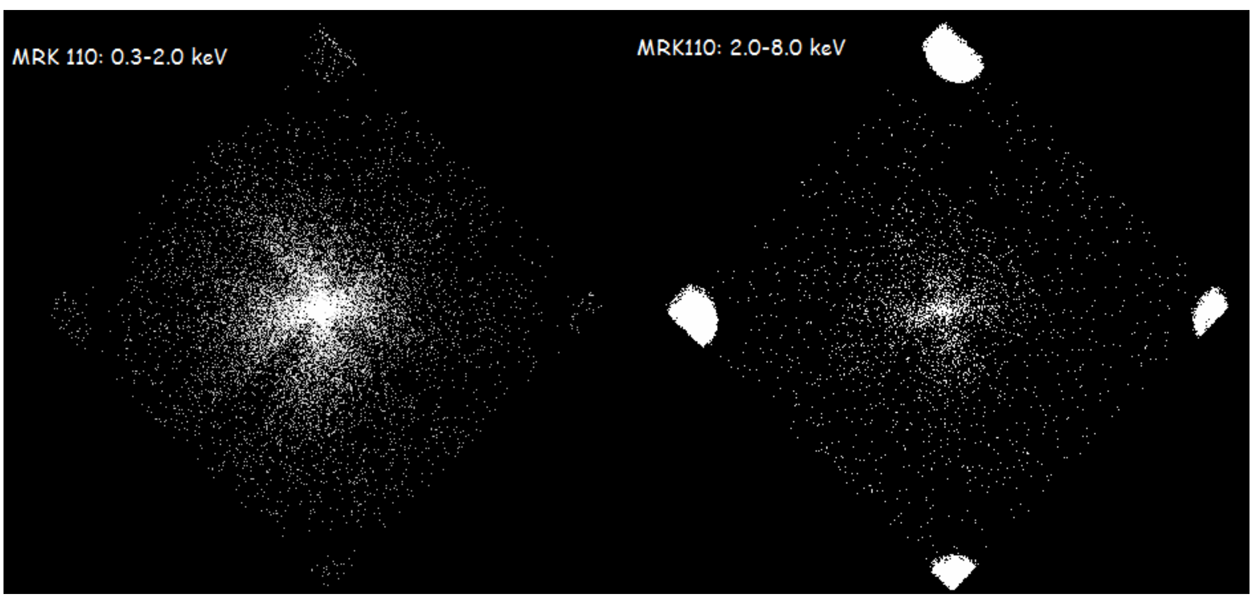

Figure 19: Images of MRK-110 in the soft (left panel) and hard (right panel) bands.

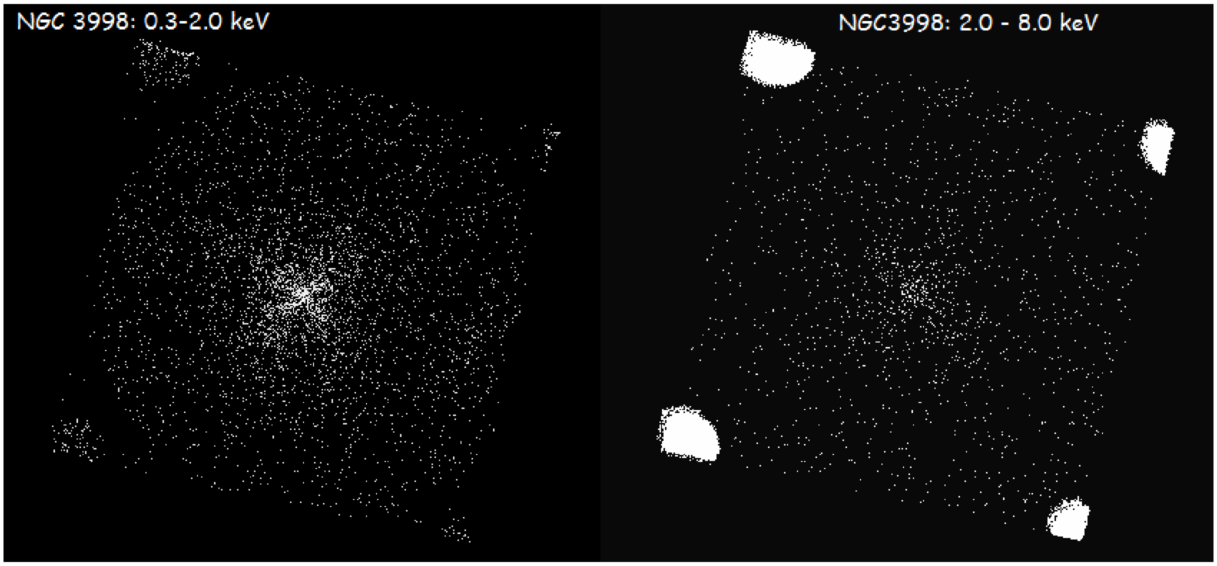

Figure 20: Images of NGC-3998 in Soft (Left) and Hard (Right) bands. This figure also demonstrates the dependence of effective area on energy. Most of the high energy photons are concentrated at the center in a small area while the soft photons are distributed throughout the image.

SECTION – B: DISCUSSION

6 .Computation on the Spectral Fitting:

The Half Power Diameter of the point spread function of AstroSat SXT was determined to be 13 arcmin. This is also the angular resolution of the instrument. Although the results I have obtained show the power of AstroSat as a potential observatory in the Soft Xray domain, it may not be effectively used in a studying the X-ray properties of Galactic Clusters that host numerous Xray sources at angular proximity to each other

Powerlaw equation (eqn v) suggests the number of photons emitted by source is greater at lower energies, while Figure 10 and Figure 13 shows that galactic absorption is greater as we go towards lower energy. This is evidence of the fact that the absorption cross-section (the probability that the incident photon ionizes the atom it is incident on) decreases rapidly as one goes to higher frequencies. The values obtained for the powerlaw photon index have been in very good agreement with what has been observed and established about AGNs.

Seyfert Type 1 galaxies are the ones whose galactic plane is perpendicular to the line of sight, hence the signatures of intrinsic absorption are seen negligibly. In the case of the objects studied here, the galactic absorption computed is seen to be in a good agreement with the known values at HEASARC archives (1.22 x $10^{20}cm^{-2}$ for NGC 3998 and 1.47 x 10^{20} cm^{-2} for MRK 110). The offset of the values is probably due to issues with the instrument. Also, higher values of absorption in NGC 3998 as compared to MRK 110 also suggest that the X-rays are probably intercepting the periphery of the torus.

After inclusion of galactic absorption, the spectra of both the galaxies show signatures of excess emission below 0.4keV. Soft X-ray excess is a very typical signature of AGNs. It isn’t very prominently seen in the spectrum of NGC-3998, but shows itself appreciably in the spectrum of MRK-110 (Figures 11 and 14), which might possibly be because of higher number of counts. The presence of soft excess is still an issue of debate and various theories have tried to explain it [7]. The issue is still unresolved.

My primary guess was to include the redshift corrected blackbody emission. The addition of this model although did not significantly improve the fit, but very low probability of f-test (a test that uses F-statistics and gives the estimate of correctness of a new additive component in the model. Low value of f-test probability corresponds to greater chances that the model is true)[12]value suggested that it is a very good model that fits the observed data. While, after inclusion of blackbody model, the fitting seemed to improve (figure 16), the soft excess still retains its form. The norm of the equation is scaled as shown in equation 7 and is measured in 10^{39} ergs s^{-1} kpc^{-2}.

There is a dip observed in the spectrum of NGC-3998 between energies 5-6 keV. This may be an absorption edge. An emission feature is also seen between 5-6 keV in the spectrum of MRK-110, which may be the Iron K-alpha fluorescent emission line, which originates from the accretion disc, and is a very typical feature of AGN Soft X-ray spectrum.

The luminosity of the sun over the entire energy range is 3.83 x 10^{33} erg/s[20]. Comparing this with the computed X-ray luminosity, MRK-110 and NGC-3998 are about 4.1 billion and 40 million times respectively. This luminosity comes from a very small region at the centre of the host galaxy. Such high luminosities are very typical features of Active Galactic Nuclei.

Goodness-of fit:

While the goodness of fit for the energy range 2.0-8.0 keV is appreciable enough, its value worsened when the lower energy spectrum was modeled only for Galactic Absorption. Since there is a signature of Soft Excess Emission at lower energies that, even after modeling with blackbody emission, still contributes to higher reduced chi square value. And hence, it is off from 50% mark with a significant margin.

Hardness ratio

The hardness plots of both the AGNs do not seem to be greater than 1 anywhere (except for one interval in NGC-3998). The maximum value reached is seen to be 1.5 (+/- 0.1) and 0.63 (+/- 0.05) in the case of NGC-3998 and MRK-110. The sources remain soft for most of the observation time. However, there exists a limit to the values of this hardness ratio. Most of the soft x-rays get absorbed by the intervening galactic medium, while the graphs I have computed are based on the photons that the detector observed. Hence practically, this is just a figurative approach to see the spectral hardening. The Figures 19 and 20 of these objects in the soft and hard band show that most of the hard x-rays are concentrated near the centroid of the image.

7. Results And Conclusion

I studied the X-ray spectral properties and the physics of x-ray detectors in this project and have been able to derive the x-ray images, spectrum, light curves, radial profiles, encircled energy profiles and have determined the values of the photon index of powerlaw form, the equivalent hydrogen column density, the Half Power Diameter of the instrument, the hardness ratio.

The photon index for NGC-3998 and MRK-110 was computed to be 1.9522 (+0.0846 / -0.0805) and 1.8852 (+0.0503 / -0.0508) respectively with 90% confidence in the error intervals. The Equivalent Hydrogen Column Density was 9.8200 (+ 0.0181 / -0.0167) x 10^{20} cm^{-2} and 1.7738 (+0.0051 / -0.053) x 10^{20} cm^{-2} respectively.

Flux of X-ray in the range 0.2-8.0 keV was hence computed to be in 6.9747×10^{-12} erg/cm^2s with 68% confidence in the range 6.826×10^{-12} to $7.146 \times 10^{-12} erg/cm^2s$ and 5.7231 x 10^{-11} erg/cm^2s in the range (5.663 to 5.675) x $10^{-11} erg/cm^2s$.

The soft X-ray excess was seen to show a good fit with the blackbody emission model with computed disc temperature of 0.2543 (+0.0167 / -0.0159; 90% confidence) keV. Both the sources were seen to have the softer part of spectra dominant over the harder one.

Overall, the study AGNs was done and parameters computed were seen to be in good agreement to the already known values.

<u>References</u>:

[1] Dr V. Beckmann, Dr C. Shrader, 'Active Galactic Nuclei', Chapter 1 (Wiley VCH, 2012).

[2]Seyfert Carl, 'Nuclear Emission in Spiral Nebulae', Astrophysical Journal, vol. 97, p.28 doi: 10.1086/144488

[3] Dr V Beckmann Dr C Shrader 'Active Galactic Nuclei', Chapter 4, (Wiley VCH, 2012).

[4] Haardt, F. and Maraschi, L. (1993) 'X-ray spectra from two-phase accretion disks', Astrophysical Journal, 413, 507–517, doi:10.1086/173020

[5] R Svensson, 'X-rays and Gamma Rays from Active Galactic Nuclei', Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas, Proceedings of IAU Symposium #195, held at Montana State University -- Bozeman, 6-10 July 1999. Published by Astronomical Society of the Pacific, San Francisco, p. 143.

[6] Malcolm S Longair, High Energy Astrophysics, Edition 3, Chapter 17 (Combridge University Press, 2011)

[7] Dr V. Beckmann Dr C. Shrader 'Active Galactic Nuclei',Chapter 5 (Wiley VCH, 2012).

[8] Malcolm S Longair, High Energy Astrophysics, Edition 3, Chapter 9 (Combridge University Press, 2011).

[9] Aneta Aiemiginowska, 'Handbook of X-ray Astronomy', Chapter 7 (Cambridge Universtiy Press, 2011).

[10] Bhattacharyay D. et al, Handbook of AstroSat, 'AstroSat INDIA'S FIRST MULTIWAVELENGTH ASTRONOMY SATELLITE A simultaneous view of the Universe in UV and X-rays', Space Science Programme Office, ISRO Headquarters.

[11] Haardt, F. and Maraschi, L. (1991) A two-phase model for the X-ray emission from Seyfert galaxies. Astrophysical Journal. Lett., 380, L51–L54, doi:10.1086/186171.

[12] Keith Arnaud, Graig Gordon and Ben Dorman, 'Handbook of Xpec, 'XSPEC – An X-ray spectral fitting package', HEASARC, Astrophysics Science Division, NASA/GSFC.

[13] Morrison R., McCammon D., 'Interstellar Photo-electric cross sections, 0.03 – 10 keV', Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 270, July 1, 1983, p. 119-122, doi: 10.1086/161102

[14] 1982, Geochimica et Cosmochimica Acta 46, 2363.

[15] Park et al, 'Bayesian Estimation of Hardness Ratios: Modeling and Computation', Astrophysical Journal 652:610-628, 2006, doi: 10.1086/507406

[16] Koss M et al, 'Host galaxy properties of the Swift BAT ultra-hard X-ray selected active galactic nuclei',Astrophysical. J., 739, 57 (2011) - 20.09.11 20.07.15 October(I) 2011 2011-10-01

[17] Data obtained from SIMBAD, http://simbad.u-strasbg.fr.

[18] Cappellari M et al, 'A volume-limited sample of 260 nearby early-type galaxies: science goals and selection criteria', Mon. Not. R. Astron. Soc., 413, 813-836 (2011) - 10.05.11 14.11.16 May(II) 2011

[19] Rehana Yusuf and Ian George, Manual of GRPPHA, HEASARC, NASA.

[20] Factsheet of Sun, NASA, https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html