Project Report

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Abstract

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Chapter 1

Acknowledgement

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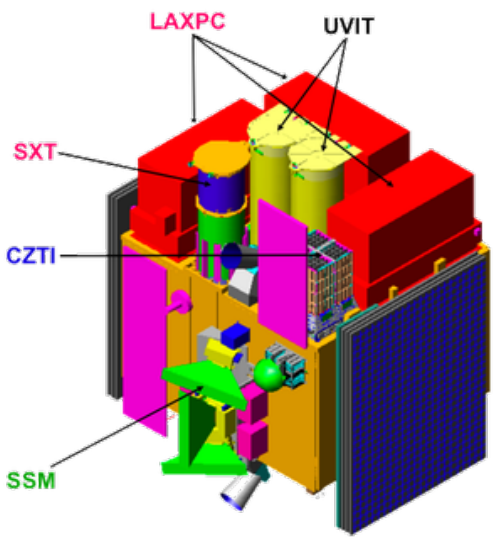
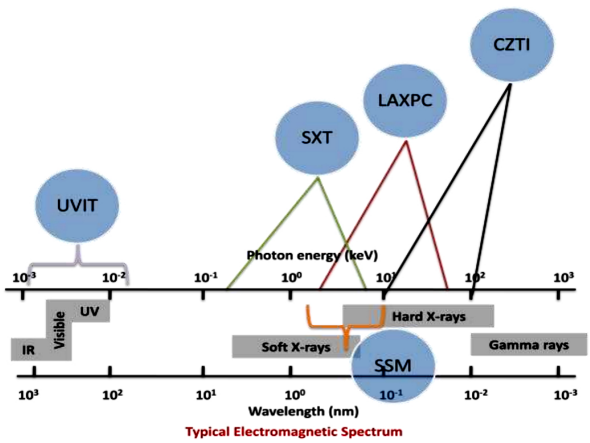
Chapter 2

Introduction to ASTROSAT

Analyzing and understanding the data one receives from X-ray satellites is something that is paramount in understanding high energy events transpiring within the cosmos. Most of the events that lead to the release of x-rays are generally very high energy events. Such extreme environments are the only regions in space where one can test the limits of physics, which, in some cases are near impossible to recreate (yet) in a "controlled" environment, not to mention the hazards associated with such experiments. This leads us to the frontiers of physics, after which everything is unknown, and exciting.



(a) Astrosat With Payloads



(b) Wavelength Sensitivity of the Instruments

Figure 2.1: The Astrosat with its payloads and their wavelength sensitivities

ASTROSAT is India's first multi-wavelength satellite dedicated to science, and aboard it are several instruments that look at different wavebands of the electromagnetic spectrum. They are:

- **Instrument 1** Soft X-ray Telescope (SXT)
- **Instrument 2** Large Area X-ray Proportional Counter (LAXPC)
- **Instrument 3** Ultra-Violet Imaging Telescope (UVIT)
- **Instrument 4** Cadmium Zinc Telluride Imager (CZTI)
- **Instrument 5** Scanning Sky Monitor (SSM)

Since the intensity of any source is a time dependent variable, simultaneous observations of such a source is very important to be able to derive much more information from a single event in various wavebands giving us a broad understanding of an event. Hence the availability of such an instrument saves the logistical difficulties one might face while gathering the same time interval data from different satellites/observatories.

Out of the five primary payloads aboard the satellite, my work focused on the first two payloads mentioned. Namely, SXT and LAXPC since they are the ones that are sensitive to the the soft (0.3 to 8 KeV) and hard (above 8 KeV) x-rays.

2.1 Introduction to the Soft X-ray Telescope

SXT, as the name suggests is sensitive to soft X-rays, that is, photons between the energy range 0.3-8.0 KeV. Wavelengths of this energy range are responsive to focusing and hence will have a higher angular resolution, allowing it to discern between different sources very close to each other. To be more precise, it will be able to resolve between two x ray sources separated by an arc min. It will be able to perform Spatially Resolved Spectroscopy, and perform several variability studies on its sources.

2.1.1 Focusing The X-Rays

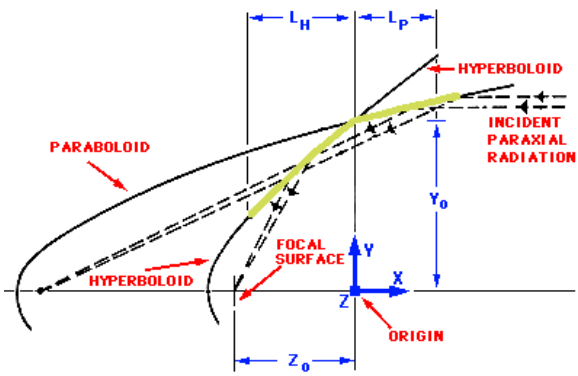


Figure 2.2: Wolter-1 Optics

The telescope consists of tubular gold foils which act as X-ray reflecting mirrors by employing the grazing incidence technique. Since the Refractive Index (R.I). of a metal, for X rays is slightly lesser than one, it is possible to get a total external reflection at a vacuum metal interface. The limiting angle for grazing incidence is a few degrees at 0.1 KeV and a few arc minutes at 10 KeV. Sections of the paraboloid surfaces can be made to focus X rays via grazing incidences. However, this arrangement violates the Abbe sine Condition and hence the images in the focal plane seriously suffer from coma. However, this can be avoided by using a second hyperboloidal surface. This arrangement is called the Wolter-1 optical arrangement and has been adopted in most of the optical telescopes flown till today.

In order to increase the collecting area, these hyperboloid mirrors are nested within each other, as shown in figure 3:

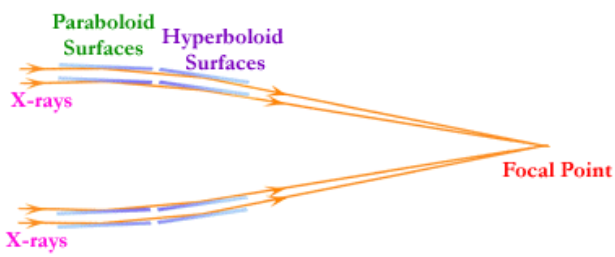


Figure 2.3: Mirror Nesting

2.1.2 Foil Optics

The Wolter-1 optics may provide some excellent image qualities, however, maintaining and making an accurate paraboloidal-hyperboloidal is very expensive and require thick, heavy mirror substrate limiting the number of mirror surfaces that can be nested together.

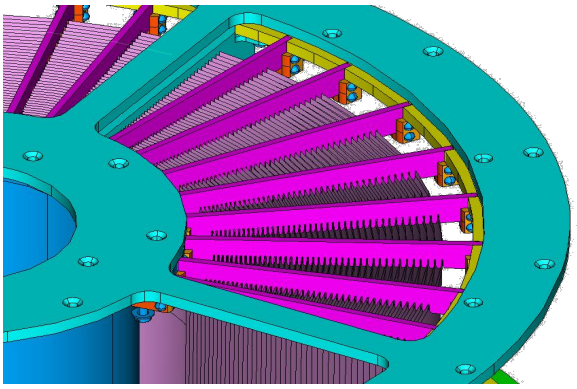
An alternative method would be to approximate the paraboloid and hyperboloid by conical surfaces tangent to them. This however sacrifices the image quality resulting in a Point Spread Function (PSF) of the order of about one arc minute. One can produce these conical surfaces by nesting thin, light weight foils in large numbers to achieve a large surface area. The SXT optics aboard ASTROSAT has adopted this design. Two mirror blocks are used, one to replace the parabolic section, namely the alpha-1 section and the other to replace the hyperbolic section caller the alpha-3 section. These blocks are then accurately aligned to form the final mirror assembly.

2.1.3 SXT Mirrors

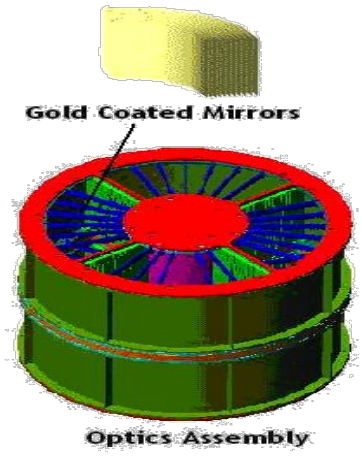
SXT mirrors are made out of 10 cm long, conically shaped 0.2 mm thick aluminum shells. Each foil is coated with 20-50 micron thick epoxy (glue) upon which a 1400 angstrom thick layer of gold is deposited. The gold acts as a reflecting surface for the X-ray.

Each shell is made up of four quadrant segments, there are 41 such nested shells in both 1-alpha and 3-alpha sections, thus requiring a total of 328 foils. Some basic parameters of the mirror assembly are as follows:

1. Focal Length : 2000 mm
2. Maximum Foil Radius : 130 mm
3. Minimum Foil Radius : 65 mm
4. Reflector Length : 100 mm
5. Minimum Reflector Spacing : 0.5 mm



(a) SXT Foil Mount



(b) SXT Optics Assembly

Figure 2.4: SXT foil mount and optics assembly

A schematic of the SXT reflector is as shown above, with the diagram of the SXT Foil Mount. The upper half consists of the 1-alpha section and the lower half consists of 3-alpha section.

2.1.4 Focal Plane Camera Assembly

The focal plane camera, the instrument responsible for collecting the data is a thermo-electrically cooled (by the Peltier effect) X-ray CCD camera, similar to the one flown in the XMM and SWIFT missions. The CCD dimensions are of 600x600 pixels each pixel being 40 square microns. It is a frame transfer device, i.e. an image transferred from image to store section can be read out while a new image is being acquired.

The CCD operates in single photon counting mode. Each X-ray photon, depending on the energy liberates about 100-1000 electron hole pairs. Preserving this total charge information for each photon will lead to the measurement of its energy, thus enabling spectroscopic studies. The energy resolution is strongly degraded by system noise. So in order to reduce the thermal noise in the CCD it is thermo-electrically cooled to an operating temperature of 193 K, which is expected to yield an energy resolution of 0.02 at 6 KeV.

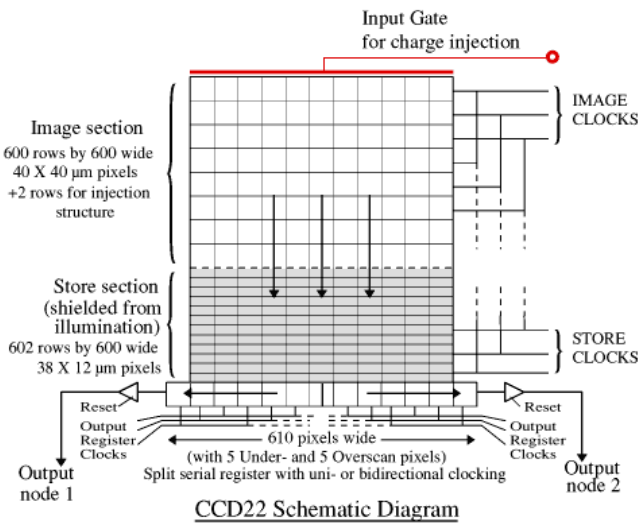


Figure 2.5

The focal plane camera assembly consists of the CCD and its cooling arrangement housed in a cryostat, which also contains Iron-55 calibration sources (at the four corners of the CCD), an optical blocking filter for the CCD and an aluminum proton shield to protect the shield from proton damage while passing through the south Atlantic anomaly region. The optical blocking filter is made of a single fixed polyamide film of 184 mm thickness, with a 48.8 mm thick aluminum coating on one side. This yields an optical transmission of about 0.0025, limiting the background light reaching the detector. The entire cryostat body is made of aluminum alloy, and gold plated for thermal insulation.

2.1.5 Data Collection Modes

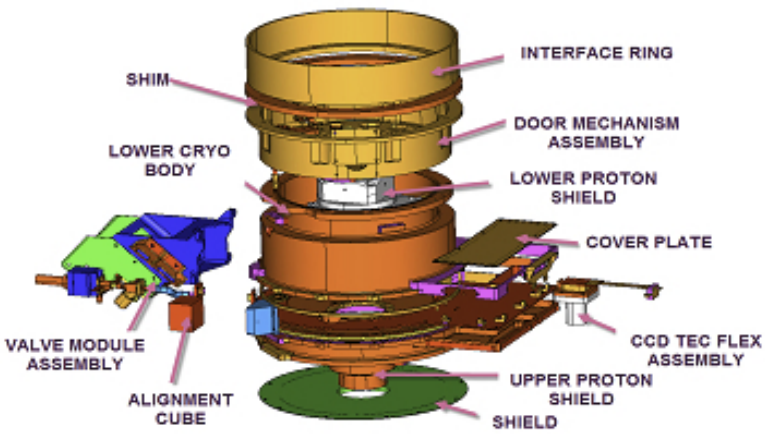


Figure 2.6: SXT CCD Module

The data from SXT CCD are stored onboard, and transferred to the ground station once each orbit (with an orbit of ≈ 97 minutes each 14 times a day). The memory quota for each orbit is 280 MB. Hence this puts serious load on the data modes and how the data is packaged. There are four data modes, and only one mode for housekeeping. In each mode, the data is packed in 2 KB segments. Hence, the SXT memory per orbit is filled with 143360 $2KB$ blocks.

The various data modes are as follows:

- **Mode 1** Photon Counting (PC)
- **Mode 2** Fast Windowed photon counting (FW)
- **Mode 3** Bias Map (BM)
- **Mode 4** Calibration Mode (CM)
- **Mode 5** Housekeeping mode (HK)

Photon Counting Mode (PC): In PC mode, data from the entire CCD is collected, provided that these are above a specified threshold energy (set by the SXT team, it can be around 100-200 eV). Currently it is about 105 eV (which is 4 sigma above the noise peak). The readout time of this mode is **2.4** s (that is, the amount of time it takes to read the data from the sensor).

Fast Windowed photon counting mode (FW): In the FW mode, a 150x150 pixel window is used at the center of the CCD. The readout time of this mode is 248 ms (hence FW mode has higher time resolution than PC mode). Data in the FW mode is also thresholded as in the PC mode.

Bias Map mode (BM): In the BM mode, the entire CCD frame is sent (again with zero threshold) with incrementally addressed 60 rows per CCD frame along with their coordinates. On the ground, each of these frames are mapped to generate an individual CCD frame. It takes 24 seconds of data to generate one fully mapped CCD frame.

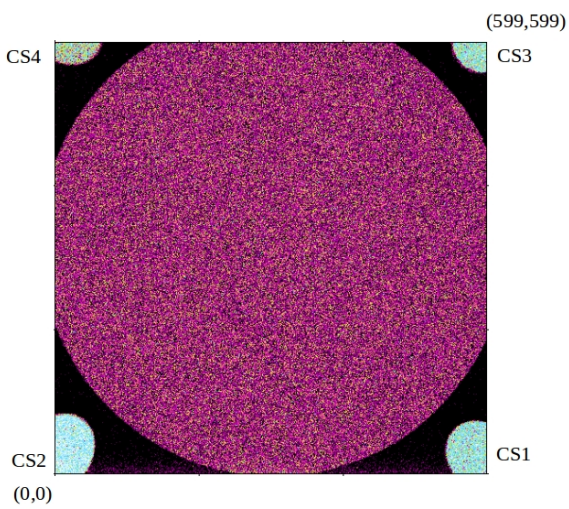


Figure 2.7: SXT Calibration Sources

Calibration Mode (CM): The calibration mode, as the name suggests, is used to check the calibration of the SXT. The readout time of the calibration mode is 2.4 s. Data from the four corner windows of the CCD with a size of 80x80 pixels and a central window with a size of 100 pixels are transmitted with zero threshold in the calibration mode.

Housekeeping mode (HK): The housekeeping mode is activated only when there is a failure of both LBT telemetry channels. When HK mode command is sent to SXT, LBT telemetry data in the form of HK data is sent in $2K$ data packages. Hence only one frame will be generated and pushed in currently operating mode data package.

Spectral information is available under all four modes. However, for this particular project I would be using only the first two modes, that is FW and PC mode for the data analysis. These are the modes that one uses to derive scientific data.

2.1.6 Data Levels of SXT

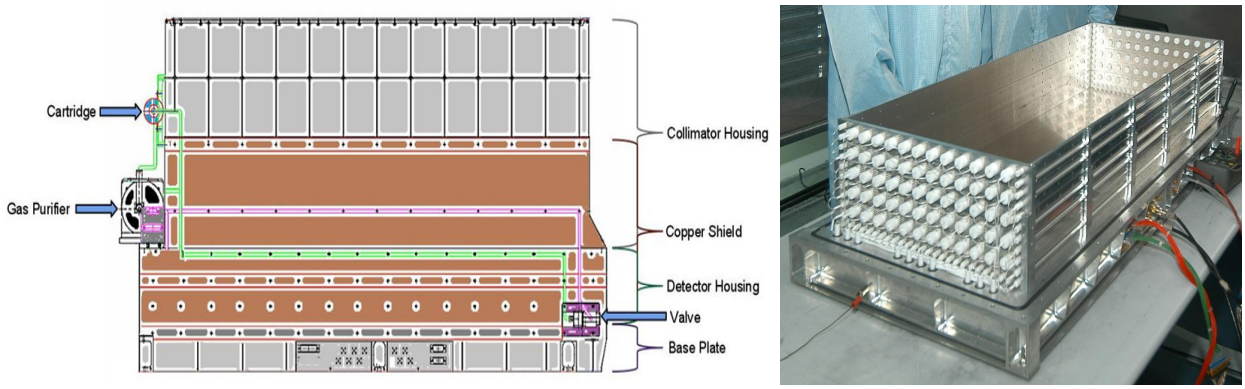
SXT has three levels of data:

- **Level** 0 **data:** These are the instrument-wise raw data in binary format, which are paired with its associated auxiliary data, which is segregated from all instrument combined raw data obtained through telemetry. This data is very mission specific and is not available for public use.
- **Level** 1 **data:** This data is obtained by applying various transformations on the level 0 data and are stored in FITS format. The data is made available for public use only after an initial lock-in period. The Principle Investigator of the data will be given access to this data at the earliest possible time after a pre-processing to level 2 and a check-out by SXT POC team. The Level-1 data directory contains science data file, time calibration file, attitude file, orbit-file, level-1 MKF file and house-keeping data file.
- **Level** 2 **data:** This data contains the standard science products obtained from processing Level 1 data for a default set of parameters and is hence available for public use. The Level 2 software offers user interface for proper selection of parameters and desired analysis of Level 1 data. One can have selections of these parameters depending on science objectives.

Once we obtain the Level 2 data, we can start with the "science" part of the project. That is discussed in detail later in the report.

2.2 Introduction to the Large Area X-ray Proportional Counter

LAXPC covers an energy range of 3-80 KeV. The three LAXPC units aboard the ASTROSAT have the largest effective area (for collecting data) and sensitivity among all the satellite missions flown so far for X-ray astronomy studies above 20 KeV, The instrument also has a fine time resolution of 10 microseconds. The collection area of the instrument is 8000 cm^2. It is well suited for timing and spectral measurements.



(a) LAXPC Schematic (b) LAXPC Anode wiring

Figure 2.8

Because of the large detection volume (with a depth of 15 cm) of LAXPC, and because they are filled with Xenon gas at 2 atm pressure, the detection efficiency is greater than 50% in 30-80 KeV band. Hence the three LAXPC units will have the largest effective area and sensitivity among all the satellite missions flown so far.

Each LAXPC detector consists of 60 anode cells with a 3 $cm \times 3$ cm cross section with a length of 100 cm arranged in 5 layers providing a 15 cm deep X-ray detection volume. Hence each anode layer has 12 anodes with a total width of 36 cm. A Veto layer made up of 46 anode cells each with cross-section of 1.5 $cm \times 1.5$ cm surrounds the main X-ray detection volume on 3 sides to reject events due to charged particles and interaction of high energy photons in the detector.

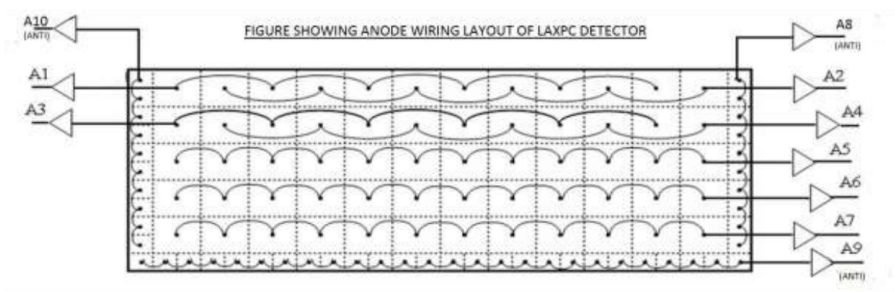


Figure 2.9: Anode wiring layout of LAXPC

The alternate anode cells of Layer 1 and 2 are linked together and thus 4 outputs are obtained from Layer 1 and Layer 2. The anode cells in each of the Layer 3, 4 and 5 are linked together to provide one output from each layer. Thus, there are 7 anode outputs that are operated in mutual anti-coincidence to reduce the non-cosmic X-ray background. The Veto layer is divided in 3 parts providing 3 Veto layer outputs. The left side and right side Veto anodes are linked together to provide one output from each one and the third Veto output is from the bottom layer Veto anodes linked together.

To suppress background from charged particles from all events, which register in multiple anodes, or those, which trigger the Veto anodes are rejected, except for the situation where one of the energies is in the K X-ray for Xenon. For X-rays with energy above the K-edge of Xe, a K-electron may be ejected and the ion can radiate a K X-ray photon in energy range 29.4 - 34.4 keV. These X-ray may escape from the detector or be absorbed in a different anode. In order to include such events the anti-coincidence logic is modified to detect this energy range. If two main anodes register an event and at least, one of them is in the energy range, of 25-35 keV, then the energy of the two anodes are added and the event is accepted. The lower (KLLD) and upper (KULD) threshold can be set through tele-command.

The detector is filled with a mixture of 90% Xenon added with 10% Methane at a pressure of 1520 *torr* (i.e. 2 *atm*). The Mylar window is supported against the gas pressure by a honeycomb shaped collimator made of square geometry aluminum cells termed as Window Support Collimator (WSC). The Field Of View Collimator (FOVC) is placed above the WSC and is aligned with the openings in the WSC. The FOVC is made of sheets of tin, copper and aluminum and is placed in a collimator housing. The total height of the collimator is about 45 *cm* giving a Field of View (FOV) of about $0.9^o \times 0.9^o$. A 1 *mm* thick tin sheet coated with copper serves as the shield for X- rays entering the detector from the sidewalls.

2.2.1 Processing Electronics

There are 7 anode outputs from the X-ray detecting cells and 3 Veto outputs from each detector that are fed to 10 Charge Sensitive Per-Amplifiers (CSPAs). High voltage is supplied to the anodes from a command controlled HV unit whose output can be varied by another command. The 7 X-ray anode and 3 Veto layer outputs forming the CSPAs are sent to the peak detectors and events satisfying the selection logic as "true X-ray events" are further processed by signal processing electronics for Broad Band Counting (BBC) and time tagging every events with its energy to an accuracy of 10 μs.

In BB counting output Anode 1 and 2 are combined as layer-L1, similarly Anode 3 and 4 are combined as layer–L2 and Anode 5, 6 and 7 are combined as layer–L3. All Anti anode A8, A9 and A10 are combined as anti-counter. All the events in each LAXPC above a lower energy threshold of 3 keV in main anodes (A1 to A7) (LLD), upper energy threshold of 80 keV in main anodes (A1 to A7) (ULD), all the three Veto layer counts are termed as Anti-counts, are recorded in separate counters.

2.2.2 Modes of operation of LAXPC

All the three payloads of LAXPC have identical operation modes. There are three different modes of operation and each instrument can be operated in more than one mode simultaneously.

The LAXPC data carries information about the cosmic X-rays detected with the instrument and it has three entries i.e. the time of detection, the energy (spectral channel) of the X-ray photons and the identity of the detecting element (detector/anode-layer) including double-identity in some cases. The signal then generated by the instrument after detecting the X-ray is processed and stored in any of the following modes:

Normal Operation mode: During this mode there are two modes running simultaneously and the data is acquired from each LAXPC.

- **Broad Band Counting Data:** This mode records the data in various energy bands with selectable time bins (all the events within a time interval selected would be replaced by an energy value representative of that interval, often being the energy value of the median time), in this case it is usually between 16 ms to 2048 ms. The default binning value is 128 ms. There are 15 counters for the broadband counting of the valid X-ray events in different energy bands covering 3-100 KeV from the three layers as mentioned above in the processing electronics section. Note that the bin time can be selected in multiples of 2, and are done so by commands.
- **Event Mode Data** In this mode, the energy and identity of each event is recorded. Also with a dead time of about 54 μs, the arrival time of each microsecond is also tagged with an accuracy of 10 μs. A total of 5 mb data is generated from each accepted and analyzed event.

Fast Counter Mode: In this mode the event rate is measured only from the top layer of the LAXPC counter in four energy channels covering 3-20 KeV band with a fixed time bin of 160 μs. The dead time in this mode is 10 μs. Each of the four counters are 8 *bit* deep and cover 3-6, 6-8, 8-12 and 12-20 KeV energy bands. This mode is used for studying rapid variabilities during short duration flares

Information on events within the PCA detectors are handled by the Experimental Data System (EDS), a microprocessor-driven on-board data system. The EDS is capable of processing upto 500,000 counts per second, and time the arrival of individual X-rays to about 1 micro second. The data can then be collected in a number of different modes simultaneously. This facilitates collection and analysis of the data appropriate to different sources.

Chapter 3

Introduction to the software

3.1 HEASARC

The High Energy Astrophysics Science Archive Research Center (HEASARC) is NASA's designated multi-mission archive for cosmic astronomy datasets for observations in cosmic, Extreme Ultra-Violet (EUV), X-ray and gamma ray wavebands as well as for Cosmic Microwave Background (CMB) datasets. These kinds of rays are mostly studied by observatories on the orbit, since these wavebands are generally absorbed by our atmosphere (our atmosphere is opaque to these wavelengths). HEASARC holds EUV, X-ray and gamma ray data for 32 observatories which have been operated over the last five decades.

3.2 HEASoft

Now in order to analyze data from the SXT and LAXPC, one needs to clean the data obtained, since this is the introduction part we wouldn't go into the details of how it is done, we would come to the process of extraction later in the report. However, once one receives the level 2 data, out of the pipeline software for a respective mission, one would need the help of certain data processing software so as to be able to extract the required light curves, spectra, image etc. from the data.

This is where software packages like HEASoft come in. HEASoft is a collection of several packages that are designed to analyze high energy data efficiently and in an user-friendly manner from HEASARC. We would be using several packages from HEASoft, to be more accurate, we would be using the packages from XANDU, which is a collection of high energy data analysis software.

The software packages we would use (for now) are Xselect and Xspec (primarily, apart from some other packages from HEASoft which we would use for plotting, listing etc.) which we would be using in order to obtain our initial calibration results.

3.2.1 Xselect

Xselect is a Command Line Interface (CLI) software responsible for the following functions:

1. Organize the input of data through the observation catalogue, and store it internally for easy use.
2. Accept intensity, phase, region, detector, grade, event file column, spectral, and timing filters, which will be applied to the event data.
3. Make good time intervals (GTI) by applying selection criteria to the Housekeeping and auxiliary filter data.
4. Extract images, light curves and spectra from the event data, using the entered filters, as well as the GTI created by the applied selections.

In our analysis, we would be using several of the above functions in order to obtain our Good Time Intervals (GTI), apply several filtering to the data etc. We would discuss the steps to obtain meaningful data later in the report. One of the salient features of Xselect is that it can be configured to support any new mission or instrument that does not require any mission specific routines, simply by editing the mission database file Xselect.mdb. This makes Xselect a great tool to obtain the preliminary files needed for spectral analysis, using the ASTROSAT data.

Now, one might wonder, what is a GTI? GTIs are a table of sorted START and STOP times in units of seconds. The GTIs give the time periods when the mission time line parameters fell within acceptable ranges. In other words, the "good times" are those times when the observation conditions were "good". Some of the principle reasons for bad observation period are 1). Bad Aspect Solution (bad RA, Dec, roll angle of the telescope versus time), i.e. when the telescope isn't tracking accurately in accordance with the change in RA and Dec while telescope slews, and 2).

High background times are when there is a surge of background events (meaning, cosmic rays or any other high energy rays, from sources other than the observed source hitting the sensor, which would generate an event that is not from the actual source being observed) and 3) When the satellite passes through the South Atlantic Anomaly (SAA), this is a region where the earth's inner Van Allen Radiation belt comes closest to the earth's surface, and hence bombards anything (in our case satellites) with higher than usual dose of charged particles, causing problems such as reduced lifetime, corrupted data etc. from the satellite. One might wish to create a more restrictive set of GTIs if one wishes to reduce the background influence on the data. Now, one might ask how does one process the data obtained from the satellite? The satellite takes in all the data, everything while it is pointed to the object, even when the object is behind earth. The GTI filtering is done during the conversion of level 0 to 1 to 2, at every step. However, even after the stringent filtration there could be some frames that are not quite right and might need further filtration during the data processing with Xselect, the process will be discussed with examples later in the report.

Now, to sum it up, we will be using Xselect, to obtain:

1. The spectral file, with an extension .pha (Pulse Height Amplitude). This file contains point based count-histogram obtained from an X-ray observation. This type of spectral file is also called the type I PHA, (type II being .pi), which complies to the Office for Guest Investigator Programs (OGIP) spectral file format. This file represents the integrated charge per pixel from an event recorded in a detector. In early electronic devices this was the size of the pulse recorded. This means, that if a high energy photon is "detected" (meaning, generates a pulse of current), this .pha file is carrying the information of the current generated by this photon, i.e. information of its energy. Note, on getting this file, one loses the timing data.

2. The Light Curve (.lc) file, which, as the name suggests, contains a map of the intensity of X-rays photons received from the source as a function of time. This helps us study the variation of the intensity of the source with respect to the time. In easier terms, light curves are graphs that show the brightness of an object over a period of time.

3. The events list, with an extension .evt . X-ray instruments record a separate signal from every individual photon they detect. This is unlike optical CCDs which need to integrate the signal from a number of photons to generate a detectable signal. As a result X-ray data is stored event by event, retaining more information allowing for greater flexibility of analysis. Every X-ray "event" (a general term for a detection, may refer to a photon or a background cosmic ray) is characterized by a pulse height that encodes the energy of the incoming photon, a time coordinate (which details when the pulse was detected), a grade (a number assigned to every event, based on the number of pixels in its immediate surrounding i.e. 3×3 pixels, which have crossed their threshold value), and typically two position coordinates (meaning, from "where" this signal was detected). One might think of the events list as a 4 dimensional array of x, y, time, energy. However, since most of the pixels are empty, an event would be a collection of non empty pixels. Also note that there are many more parameters for each photon (event) than just these 4.

4. The Image file with an extension .img . These are the images of the event files of the whole field and/or an expanded view of the central region.

Note that this just an introductory paragraph for Xselect, we would discuss the commands we use to extract meaningful (i.e. data from which we can draw scientific meaning) data later in the report.

3.2.2 Xspec

Xspec is a command driven, interactive, X-ray spectral fitting program, designed to be completely detector-independent so that it can be used for any spectrometer, the key word being "fitting". Although we use a spectrometer to measure the spectrum of the source, what we receive is not the spectrum, but the photon counts (C) within specific instrument channels (I). This observed spectrum is related to the actual spectrum of the source f(E) by (ref. *insert citation for xspec manual*):

$$C(I) = \int f(E)R(I,E)dE \tag{3.2.1}$$

Where R(I,E) is the instrument response and hence is proportional to the probability that the incoming photon will generate an event of energy E detected by the channel I. Ideally, we would think that inverting the equation would give us the f(E) for a given set of C(I), however, doing so makes f(E) get solutions that are non unique and unstable to small changes in C(I).

Another alternative would be to choose a model spectrum f(E), that can be described in terms of a few parameters and match, or "fit" it to the data obtained by the spectrometer. For each f(E), a predicted count spectrum $C_p(I)$ is calculated and compared to the observed data C(I). Then a "fit statistic" is computed from the comparison and used to judge whether the model spectrum "fits" the data obtained by the spectrometer.

The model parameters are then varied to find the parameter values that give the best fit statistic. These values are, as one might guess, are referred to as the best-fit parameters. The model spectrum, $f_b(E)$, made of the best-fit parameters is considered to be the best-fit model.

The most common statistic used to determine the "best-fit" model is χ^2, defined as follows (ref. *insert xselect manual reference here*):

$$\chi^2 = \sum \frac{(C(I) - C_p(I))^2}{(\sigma(I))^2} \tag{3.2.2}$$

where $\sigma(I)$ is the (generally) unknown error for channel I.

Now, how can we say, with the help of χ^2, that the particular model is best-fit? This is where the goodness-of-fit comes in. The χ^2 statistic provides a well-known-goodness-of-fit criterion for a given number of degrees of freedom (ν, which is calculated as the number of channels minus the number of model parameters) and for a given confidence level. If χ^2 exceeds a certain critical value one can conclude that $f_b(E)$ is not an adequate model for C(I) i.e. the observed data. As a general rule, one wants the value of reduced χ^2 (i.e. χ^2/ν) to be approximately equal to one. That is, χ^2 is approximately equal to ν. A reduced χ^2 greater than one indicates a poor fit, while a reduced χ^2 that is much less than one indicates that the errors in the data have been over estimated. Note that even if the best-fit model passes the "goodness-of-fit" test, it doesn't mean that $f_b(E)$ is the only acceptable model. For example, if the data used in the fit are not particularly good, one may be able to find many different models for which adequate fits can be found. In such a case, the choice of the correct model to fit is a matter of scientific judgment.

A point to note while choosing the model to be used Now, while choosing the appropriate model, there are many things that have an impact on the resultant data and hence would make a huge difference in what is being obtained at the end. A few things that one might do well to consider while choosing the model would be:

1. Look where the object is at, that would help you select whether you consider the galactic or photon absorption model. (do recheck)
2. (this section is under work and I will a dd new models soon)

Another point which one would have to keep in mind would be to determine the " confidence interval " for the parameter (i.e the range of values within which one can be confident the true value of the parameter lies). The confidence interval for a given parameter is calculated by varying the parameter value until χ^2 increases by a particular amount above the minimum, or best-fit value. The amount that χ^2 is allowed to increase (also referred to as the critical $\Delta\chi^2$) depends on the confidence level one requires, and on the number of parameters whose confidence space is being calculated. The critical for common cases are given in the following table (from *insert reference here* Avni, 1976) (ref. *insert xselect manual reference here*):

Confidence	Parameters		
	1	2	3
0.68	1.00	2.30	3.50
0.90	2.71	4.61	6.25
0.99	6.63	9.21	11.30

We shall discuss the implementation later in the report.

Chapter 4

Setting up the system

The software one is expected to have at their disposal in order to process the data from SXT and LAXPC are as follows;

- **HEASoft** : As mentioned previously, we would be needing packages such as Xselect and Xspec for plotting the light curves and energy spectrum of the source we would be observing. We would also (occasionally) need f tools to be able to list the good time intervals, so that we can use them for time filtering the data.
- **SAO ds**9 : It is a software that we would be using to plot the image of the source. We would be using it primarily for the SXT analysis since plotting the image for LAXPC doesn't make logical sense. Why? Because of the way both these instruments collect data. Another important function of this software would be to generate the regions file so that we can perform region filtering with Xselect. And to get the RAWX and RAWY coordinates of the center of the object in the sensor.
- **SXTEVTMERGERTOOL** : This, as the name suggests is a tool that we would be using to merge the clean event files from every orbit into one clean event file which would contain all of the data. The installation file is given in in the SXT POC website.
- **SXTMKARF** This is one of the many SXT pipeline tools that one might need install to obtain the off-axis auxiliary response files from the level 2 (offaxis) .pha files with the help of the on-axis .arf files.
- **LAXPC** Setting up the system to analyze LAXPC data requires one to run the FORTRAN codes mentioned in the downloaded software package. Note, that at the time of writing this report there were 2 major software packages for analyzing the LAXPC level 1 data. One is the base FORTRAN code written by H.M. Antia, which is available at the TIFR POC website, and the second one is the base code with a python shell, making it easier to use, and a cleaner interface. However, Dr. Antia's code is updated on December 21st and contains the recent background processing software during the time of writing this report. The method for installing the software is given in the read me files with the package.

Note that I have refrained from mentioning the installation steps of these software. I have done so because every environment has a different method of installation of the software and hence mentioning how I got them to work on my local system (which is a bash shell Ubuntu 16.04 LTS system) would be futile since the instructions which I might mention here would only work if someone has the same system as my own. However, one thing to note is that to run the sxtevtmergertool and sxtmkarf, I would recommend the installation of pip, and, using that install several python packages such as scipy etc (to keep this report short, I haven't attached a list of all the packages here). since they (i.e. sxtevtmergertool and sxtmkarf) would need those python packages as auxiliary support. Also, one might need to initialize HEASoft every-time one wishes to run those software in a new terminal.

Chapter 5

Data Processing

This section would be divided into two parts, SXT data analysis and LAXPC data analysis. Since I have done SXT analysis to begin with, I would be discussing the basic steps to obtaining the light curves and energy spectra from the level 2 data from SXT first. We would then move on to LAXPC analysis later in this section.

5.1 SXT data Processing

5.1.1 Step 1: Merging the data

In this section we would be discussing the steps to process the level 2 data obtained through the SXT pipeline. For starters, since I have done the SXT analysis till date (of writing this report) we would be discussing SXT data analysis at the start. Assuming that all the above software are installed without any errors, let us look into the basic steps towards obtaining the light curves and the energy spectrum of the given level 2 data.

Now the level 2 data that we were talking about comes in the following form (figure 5.1) and when extracted they are as figure 5.2. In order to save space the data is compressed. As mentioned above, I am using Ubuntu 16.04 LTS (And this would work on any further versions as well) and hence, the screen-shots are from the same. Once you have the data in such form, see to it that you extract it to a single file. This will be essential to create a list of the clean event files as mentioned later in the report.

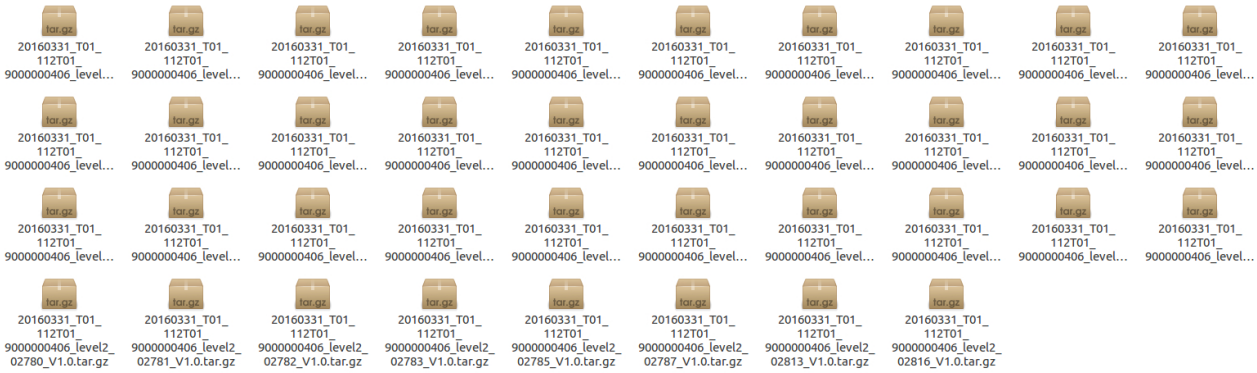


Figure 5.1: Compressed Data

Now, each of the extracted files is one orbit with their respective GTI(s). Now, as mentioned above, each of these orbits have their clean event files, which may have one or more GTIs, the reason for that could be because GTIs are those timings which are considered "good" for observation (i.e. timings when there is minimal background events, and good aspect solution), there could be several timings per orbit that would comply with those requirements and hence they will be included in the filtered file.

However, we would have to merge those clean event files into one file so that we could use it in Xselect to obtain the .pha, .im, .evt, and .lc files. For that we would have to use the python script called sxtevtmergertool, as mentioned previously. Now, in order for sxtevtmergertool to work, it needs the location of all the clean event files in one .txt file. Now, there are two ways to do it,

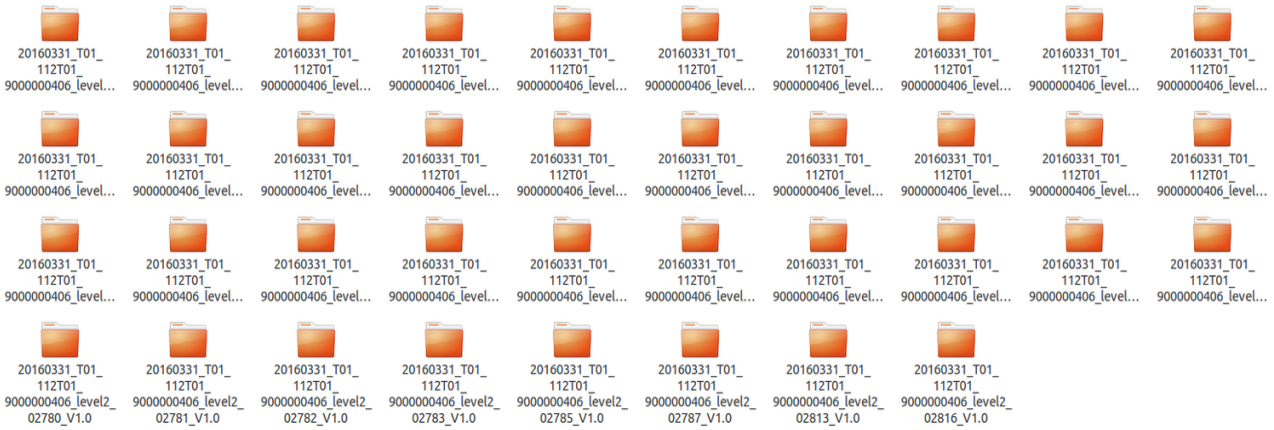


Figure 5.2: Extracted Data

1. You copy and paste the locations of each clean event files manually, or,
2. You could let linux do all the work and have it create a list for you at the location where you wish.

Now, if you're a fan of the good ol' hard work then you are free to go for the first method. However, if like me, laziness is your forte you could use the second method to get the work done for you. Now, finding the clean event file is easy,

1. Click on one of the files, eg.
2. Go to the file **sxt**
3. There should only be one file in the folder, eg. **02740**. This is the orbit ID.
4. There should be two folders and one file in it. Click on **sxt.01**.
5. You would find many files in that folder. However, the file you are interested in has **cl.evt** at the end of its name.
6. Now, to copy the location of the file, just click on the file, then **ctrl+c**, then past it in any text editor. The location would look something like this, based on where you have your data.

```
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_
        02740_V1.0/sxt/02740/sxt.01/AS1T01_112T01_9000000406sxtPC00_level2_cl.evt
```

Now, there are many aspects to the above location that changes, in every orbit, and certain aspects, such as **sxt**, **sxt.01** and **cl.evt** that remain same, (apart from the `home/ankush/Desktop/Data/Level_2_Crab/Extracted/`). Now, in order to make a list we would be using the **-ls** command. The syntax goes something like this:

```
ls /home/ankush/Desktop/Data/Level_2_Crab/Extracted/*/sxt/*/sxt.*/*_cl.evt > list_name.txt
```

Notice that we have changed certain sections of the location and replaced them with * in the argument passed to ls. This tells the system to ignore changes in those "file names" and look for files with the mentioned (without *) names within them. The ls program would then make a list of all the files (in this case, the clean event files) that comply with the above given argument and save it to list_name.txt in the directory where you are running this command. Note that sometimes the orbits have data in two different files, within the orbit folder, eg. sxt.01 and sxt.02 or more, this should be taken care for and we need those data as well, hence the * after the sxt. part, thus telling the computer to ignore the * part and take whatever files comply with the aforementioned name.

Now we have a list of all the clean event files which should look something like this when one opens the list.txt file.

```
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02740_V1.0/sxt/02740/sxt.01/AS1T01_112T01_9000000406sxtPC00_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02741_V1.0/sxt/02741/sxt.01/AS1T01_112T01_9000000406sxtPC00_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02745_V1.0/sxt/02745/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02747_V1.0/sxt/02747/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02748_V1.0/sxt/02748/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02749_V1.0/sxt/02749/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02750_V1.0/sxt/02750/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02751_V1.0/sxt/02751/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02752_V1.0/sxt/02752/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02753_V1.0/sxt/02753/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02754_V1.0/sxt/02754/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02755_V1.0/sxt/02755/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02758_V1.0/sxt/02758/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02759_V1.0/sxt/02759/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02760_V1.0/sxt/02760/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02762_V1.0/sxt/02762/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02763_V1.0/sxt/02763/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02764_V1.0/sxt/02764/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02765_V1.0/sxt/02765/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02766_V1.0/sxt/02766/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02767_V1.0/sxt/02767/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02768_V1.0/sxt/02768/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02769_V1.0/sxt/02769/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02770_V1.0/sxt/02770/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02773_V1.0/sxt/02773/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02774_V1.0/sxt/02774/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02776_V1.0/sxt/02776/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02777_V1.0/sxt/02777/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02778_V1.0/sxt/02778/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02779_V1.0/sxt/02779/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02780_V1.0/sxt/02780/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02781_V1.0/sxt/02781/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02782_V1.0/sxt/02782/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02783_V1.0/sxt/02783/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02785_V1.0/sxt/02785/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02787_V1.0/sxt/02787/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02813_V1.0/sxt/02813/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
/home/ankush/Desktop/Data/Level_2_Crab/Extracted/20160331_T01_112T01_9000000406_level2_02816_V1.0/sxt/02816/sxt.01/AS1T01_112T01_9000000406sxtFW0E_level2_cl.evt
```

Figure 5.3: LS for all orbits

Now, looking at the list screen shot, you might have noticed that the first two clean event files have `PC00_level2_cl.evt` written towards the end of the file name. And the others have `FW0E_level2_cl.evt` as their ending. This means the ones with PC are PC mode data and the ones with FW are FW mode data. **Warning!! Do not merge PC and FW mode data together**. Create a separate file for PC and FW mode (you could name them PC.txt and FW.txt, or however you like) and copy the PC mode lines to PC.txt and FW mode lines to FW.txt.

Now we can use these (PC.txt and FW.txt) with sxtevtmergertool to create a single clean event file for each mode to be able to use it in Xselect. Assuming that we have sxtevtmergertool installed properly, (one way to check that is to open the terminal and type sxtevtmerger -h command, on doing that we should get the help window of the sxtevtmergertool) we can use the command mentioned below to merge the files.

```
ankush@GL553VD:~/Workspace_project/Crab/SXT/Clean_Events/FW$ sxtevtmerger -h
/home/ankush/auxpyscrpt/sxt_gti_corr_evt_merger_v05.py:438: SyntaxWarning: import * only allowed at module level
  def RA_DEC_to_SkyXY(RA, DEC, ra0, dec0, delta_X, delta_Y, skyX0, skyY0) :
=====================================================================

                 Running SXT GTI Coorector and Events Merger Script
                 Task: sxt_gti_corr_evt_merger_v05.py
                 Version: 0.02 Release Date: 2017-06-13

                 Developed By Sunil Chandra, TIFR, Mumbai, 09, June, 2016
                 Recently Updated on 2017-06-13

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Description: This tool merges the events files after correcting for overlapping exposures in GTIs. It also create merged mkf and lbt files.
Precautionary Remark:: Merging events files is always risky job so please use this script only if it is suited for. Never merge two events files from two different instruments.
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

---------------------------------------------------------------------

Usage: sxt_gti_corr_evt_merger_v05.py [options]

Options:
  -h, --help            show this help message and exit
  -l KEEP_LOG, --keep_log=KEEP_LOG
                        Write YES/NO flag for notifying the script about the
                        time overlap logfile
  -f FULL_PATH_FILE_LIST, --filelist=FULL_PATH_FILE_LIST
                        Input File List with full path of level2 cleaned
                        events files
  -s SOURCE, --sname=SOURCE
                        The Source Name for output files.
  -d DUP_EVT_FLAG, --dup_evt_flag=DUP_EVT_FLAG
                        The Flag for duplicate events removal.   0: NO, 1:
                        YES.
  -e HEAD_UPDT_FLAG, --head_updt_flag=HEAD_UPDT_FLAG
                        The Flag for duplicate events removal.   0: NO, 1:
                        YES.
```

Figure 5.4: sxtevtmergertool help window

Once we have confirmed that the merger tool is installed correctly, we can use the following command to get the clean event file for both PC and FW modes.

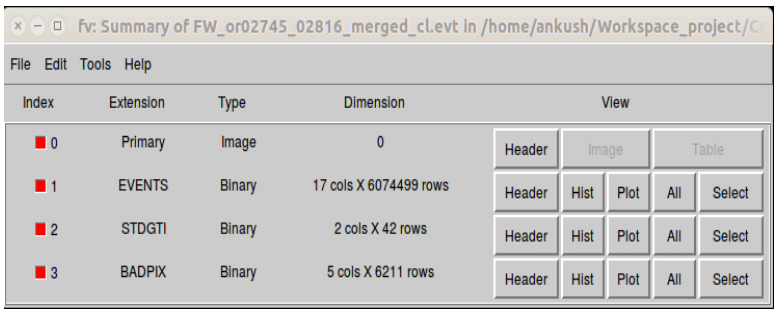
sxtevtmerger -f (location of the .txt file containing the list of all the cl.evt files) -s (name of the output cl.evt file)

5.1.2 Step 2: Creating GTI list file

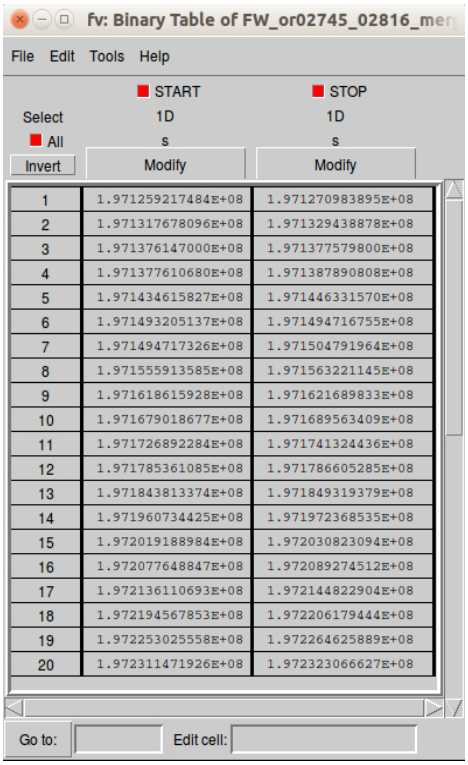
Now that we have a Clean event file we are supposed to create a GTI time list file using the final clean event file. We do this by using the FV command. We need to open a new terminal within the same working directory and type:

fv

This will open a new window where it will first prompt us to open the cl.evt file we created in the previous section. We are supposed to open it, and the following dialogue box will open (Figure 5.5a):



(a) FV Clean Event file details



(b) FV GTI

Figure 5.5

Now, in the third row, (index 2) with the extension STDGTI, we are supposed to click on the all button on the right, under the column "view". On doing that, we obtain Figure 5.5b. It is a list of all the Good time intervals in our clean event file. Notice that we had 36 orbits worth of data, we got 42 GTIs.

```
1.971785361085E+08,1.971786605285E+08
1.971843813374E+08,1.971849319379E+08
1.971960734425E+08,1.971972368535E+08
1.972019188984E+08,1.972030823094E+08
1.972077648847E+08,1.972089274512E+08
1.972136110693E+08,1.972144822904E+08
```

Figure 5.6: Time File Format

Now that we have Figure 5.5b, we need to select, under "file" (in the tool-bar), the option to export everything as text. This will save this whole list of GTIs as a .txt file. Now, for the time filtering to work, it is advisable that we remove the inverted comma's from the intervals. It should look something like as shown in figure 5.6 (Note, this is not all of the GTIs, just a small snapshot to display what format works with Xselect).

5.1.3 Intermediate Step

Instead of Filtering the file using the aforementioned method, another way of filtering would be to filter out bad orbits (and not GTIs, since each orbit might have more than one GTI intervals). The ultimate aim of this would be to make separate clean event files. There are two ways to do this.

Method 1

When you enter Xselect, select the clean event file, filter using the command **filter time file** (given in the following section), and extract the event using the command (Xselect is given in the next section):

extract event

One can use **ext event** as well. Once executing the command Xselect would extract an event file, and you can then use that event to proceed with this file for further analysis (don't forget to save the event file!). This was one way of extracting the event. Another way (And the reason why this step is given here) would be to use the event merger tool to merge different orbits, without using xselect.

Now, the previous method does a similar thing since it creates separate clean event files for every GTI interval. What we would be doing in the second method would be to isolate the orbits in groups and use the merger tool on them, to get separate clean event files for every orbit group. How does one do that?

Method 2

From the initial orbit list file, the one that we made using the ls command in the previous section. Make equal groups of orbits each i.e. if you have a total of 40 orbits, make groups of roughly 5 orbits each (you can go more or less, since the main intention here is to make separate groups of more than one orbit). What do I mean by "make groups"? Well, create a new text file, and from the initial file (let us call that **file 1**), copy the first five (or whatever group size you have decided) lines, (note that each line is the location of one orbit, and sxtevtmergertool reads this, collects the files and merges them into one clean event file) and paste them in a new text file. Once done, select those text files and use sxt event merger tool on them to obtain clean event files for every bunch of orbits.

Now, do this for both PC and FW mode. What you could expect to see is that in all of the, the image might be slightly off centered, or completely off centered. It will be more evident in the FW mode data than the PC mode data (However, you might see the skewed effect in the combined image Ref. Figure 5.9). Now, once you have all the merged clean event files, plot them using Xselect, and look for offaxis, skewed images, etc. and eliminate those from your observation, i.e. never use them. Alongside the image, look for outliers in the light curve as well (the image and the light curves are extracted using the commands mentioned in the following section). Remember, if your image looks "good", but the light curve has outliers, those orbits cannot be used to proceed further.

Now, the above step is crucial, and needs to be done repeatedly unless one has atleast five or so orbits that are:

1. In continuity, no time gaps between them.
2. Has no outliers in the light curves
3. The central bright spot would be at the center, without any skew.

Once done, the clean event file that you have will only need region filtering before you can extract the .pha, .lc, .evt, .im files, and whatever other file you need from the data. Further details given in the following section.

5.1.4 Step 3: Xselect

Now that we have separate clean event files for both FW and PC mode and we have the GTI list file, we can move ahead with Xselect. The steps of analysis for both PC and FW modes are the same, only with minor differences which I would mention as the need arises. Now, it is always advisable to use xselect and xspec in separate directories so as to avoid confusion, since both these software generate a lot of files that might create a cluster of files in the directory where you are working, However, that is just my approach, and is subject to debate. Remember to initialize HEASoft before using Xselect.

```
ankush@GL553VD:~/Workspace_project/Crab/SXT/LaTeX_op$ heainit
ankush@GL553VD:~/Workspace_project/Crab/SXT/LaTeX_op$ xselect

                        **  XSELECT V2.4d  **

> Enter session name >[PCP3_Parti] Session_trial_1
Session_trial_1:SUZAKU >
```

Figure 5.7: Step 1

Once the Xselect terminal is open, Xselect will prompt you to enter the session name. This is just the name of the session and is up-to the user to decide the session name. In my case it was `Session_trial_1`. Remember space doesn't work and hence _ is advisable.

Now let us start by selecting the clean even file we made, for FW mode or for PC mode. The way we do that is to first use the command:

read event

Xselect will then prompt us for the directory of the clean event file, here we are supposed to enter the directory location of the clean event file, and not the file itself, after which Xselect will prompt us again for the file name, which we are supposed to enter then. After which Xselect will prompt us to change the mission we are working on, to which we would answer "yes" and get the following output:

```
ankush@GL553VD:~/Workspace_project/Crab/SXT/LaTeX_op$ heainit
ankush@GL553VD:~/Workspace_project/Crab/SXT/LaTeX_op$ xselect

                        **  XSELECT V2.4d  **

> Enter session name >[PCP3_Parti] Session_trial_1
Session_trial_1:SUZAKU > read event
> Enter the Event file dir >[/home/ankush/Workspace_project/Crab/SXT/Clean_Events/PC/] /home/ankush/Workspace_project/Crab/SXT/Clean_Events/FW/
> Enter Event file list >[PC_or02740_02741_merged_cl.evt] FW_or02745_02816_merged_cl.evt
Got new mission: ASTROSAT
> Reset the mission ? >[yes]

 Notes: XSELECT set up for      ASTROSAT
 Time keyword is TIME       in units of s
 Default timing binsize =   5.0000

Setting...
 Image  keywords   = X          Y           with binning =    1
 WMAP   keywords   = X          Y           with binning =    1
 Energy keyword   = PI                     with binning =    1

Getting Min and Max for Energy Column...
Got min and max for PI:     0   1023

Got the minimum time resolution of the read data:  0.28149
MJDREF =  5.5197000000000E+04 with TIMESYS = UTC
 Number of files read in:           1

******************** Observation Catalogue ********************

Data Directory is: /home/ankush/Workspace_project/Crab/SXT/Clean_Events/FW/
HK Directory is: /home/ankush/Workspace_project/Crab/SXT/Clean_Events/FW/


        TELESCOP    INSTRUME    DATAMODE    DATE-OBS    DATE-END    OBJECT      OBS_ID
      1 ASTROSAT    SXT         FW          2016-03-31  2016-04-03  Crab        T01_112T01_9000000406

Session_trial_1:ASTROSAT-SXT >
```

Figure 5.8: Step 2

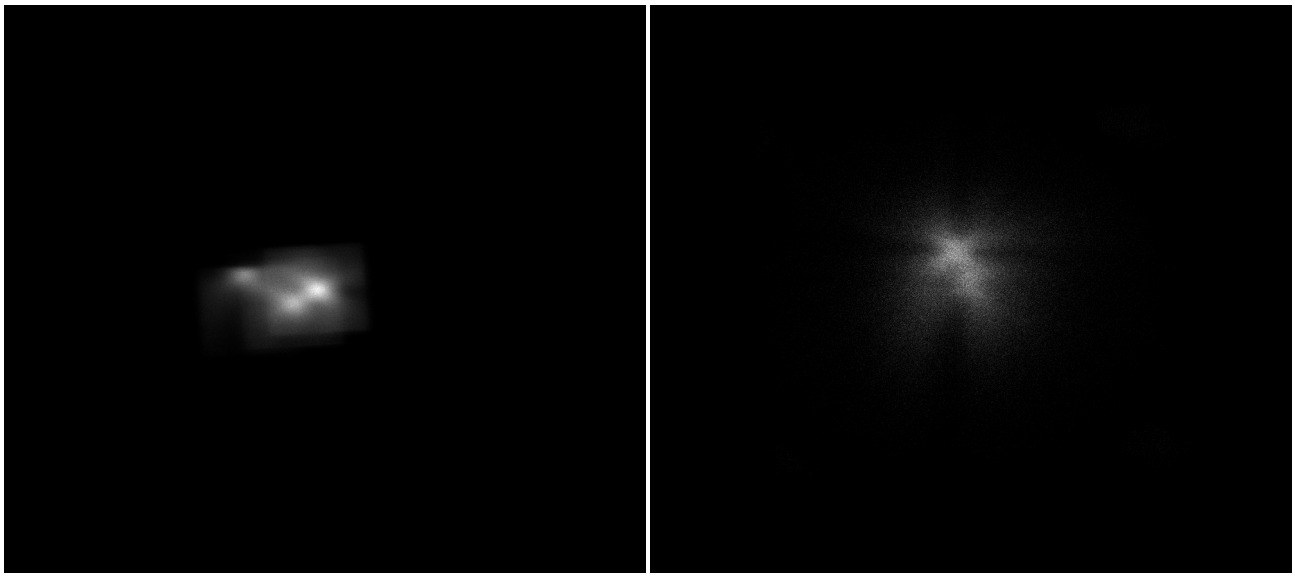
Now, we are ready to analyze PC/FW mode data. Up until now the steps are the same for both modes. First we would start off by extracting the data from the clean event files, data includes everything, i.e. img, evt, lc, pha, etc. files as we had discussed previously. The command to do that would be:

ext all

This stands for extract all. The commands of HEASoft can be written in short form as well, as long as they are not ambiguous. So, extract all becomes ext all. Now, the first thing we need to check is whether the data is proper or not, we would do that by plotting the image using the command:

pl im

Which means, Plot Image. This command would open a window of SAO ds9 and display the fits image there. The images one might get for starters might look something like this:



(a) FW mode without time filter (b) PC mode without time filter

Figure 5.9

Now, it is quite prominent by looking at the images that the data we have is skewed (some of the GTIs have bad aspect solution, hence they aren't, in essence "Good" time intervals, based on the definition of aspect solution we discussed prior to this). i.e. There are certain GTIs in the list that are when the telescope wasn't pointing towards the source, or, when the telescope hadn't completed the slew to the object. However, we also see that there are certain GTIs that have the object at the center. We will be needing those GTIs. This is where it could get a bit tricky, since now, we are supposed to eliminate the bad GTIs. There are many ways of doing the said task. We could isolate different sets of GTIs by opening the time list file we got from fv, and select different sets of GTIs (first five GTIs become one set, the second five become the second set, so on and so forth), and save them in different .txt files. We do the same for both PC and FW modes. (note that it is not mandatory that we select GTIs in the sets of 5 only, we could take sets of 2, 3, 4 etc. depending on the number of GTIs we have) A rule of thumb would be that since it is the initial stages of the observation that the telescope hasn't slewed properly to the object, the initial GTIs have a higher chance of being skewed (however, it is not compulsory).Once we have the time files, we use the following command to filter out (filter every other GTIs out other than the ones mentioned in the list) the time interval:

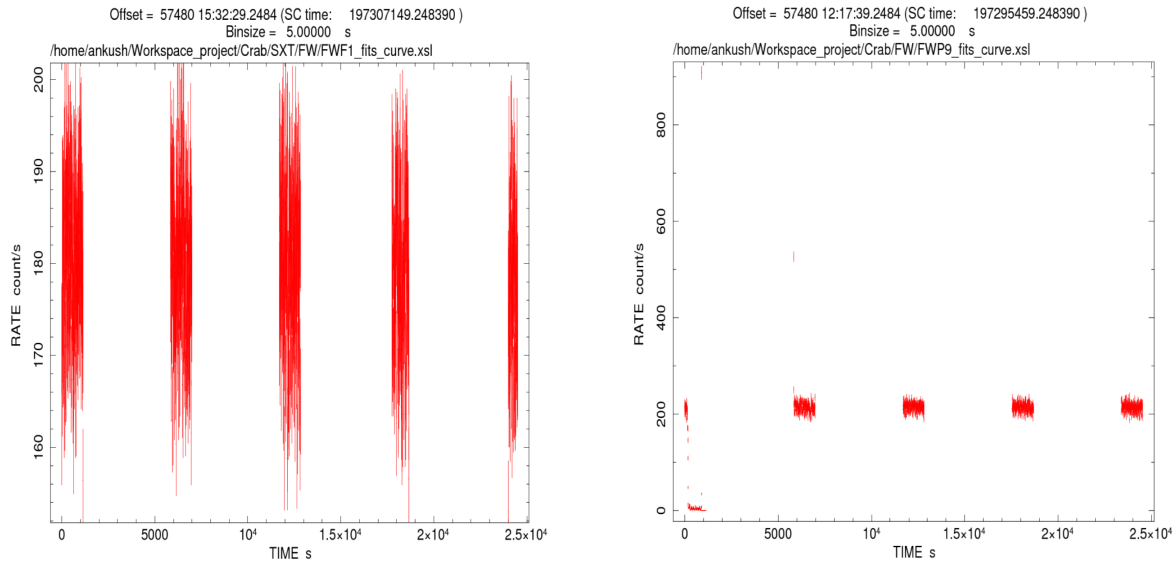
filter time file (file name with path)

Note that if you have followed the auxiliary step, section 4.1.3, and have your own GTI filtered clean event file, then you need not further filter time using the above command (i.e. filter time). You can bypass this step, and move on to region filtering directly.

Now, all the while we are filtering, we need to check the light curve as well, for the GTI set we are plotting. We plot the Light curve using the following command:

pl curve

The light curve, as mentioned previously, is a plot of intensity with time. If there are any intensity peaks in the light curve, it would suggest that the GTI where this peak occurs is a bad GTI. A good time interval from a bad time interval can be differentiated as follows:



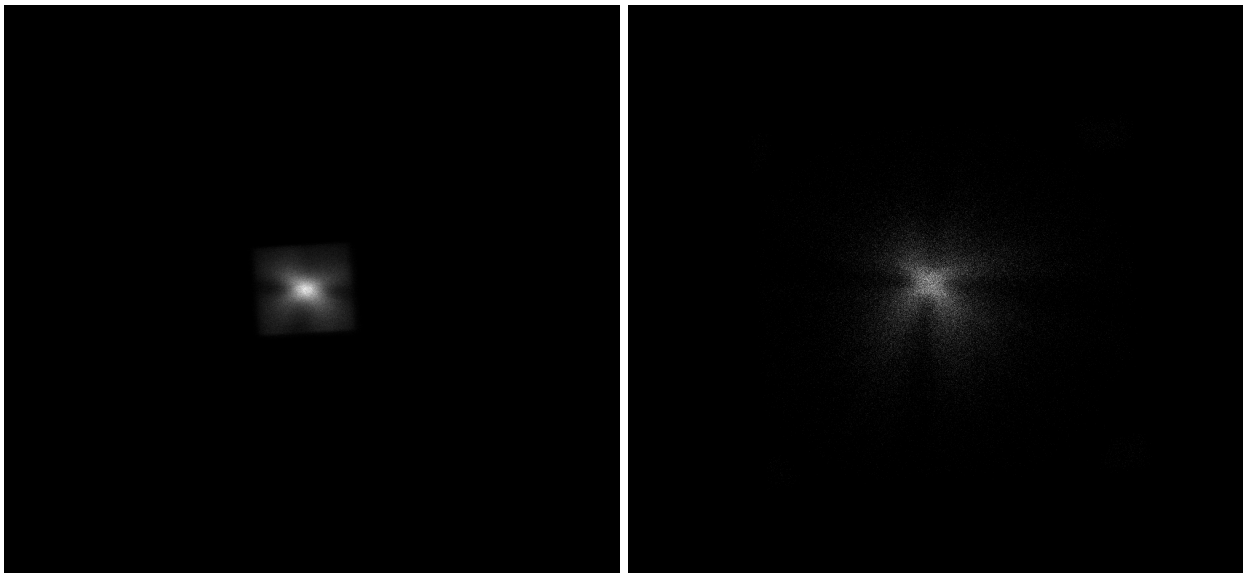
(a) Good GTI Set

(b) Bad GTI Set

Figure 5.10: The above is for FW mode data, as mentioned in the image itself

After performing the GTI filter, we should now have a set of GTIs that are 1). Not Skewed, and 2). Do not have unnatural peaks in intensity (something that isn't supposed to be there, however, the details are debatable, and beyond the scope of this report, for now).

After applying the necessary time filters, extracting everything and plotting the images again, should give us the following output;



(a) FW mode with time filter (b) PC mode with time filter

Figure 5.11

Now that we are done with time filtering we need to apply region filters to the above before the output becomes usable for Xspec. In order to perform region filtering we first need the regions file. A region file (with an extension .reg) is a two dimensional filter that can be used to include or exclude data from a given file. They are read and created using SAO ds9. In order to create regions file, we need to plot the image, click on edit, in the section where none is selected by default, select region, then in the same tool bar, click on region, a menu drops down, click on shape, and select annulus, i.e. a region of the shape of a ring, once done left-click on the image, and we should see a green (by default) color ring appear where we had clicked. Click on that ring, and now you can adjust the radius of both, the inner and outer circle of the ring. Once you have selected the ring, on the quick access panel, click on the region section, within which click on the information button. We would then see a small window pop up, which would give me the radius of the inner and outer circle in degrees. Click on the "degrees" button and select arcmin to display the radius in arc minutes (am).

Note: Another thing that one has to take care about is that when selecting regions for PC mode, since you are selecting the regions manually, the centroid might not be the centroid of the image. In order to know the exact centroid coordinates (which will be used later in the SXTMKARF part), we need to click on the information button on the tool bar, which would open another window, with the x,y coordinates of the center, along with the radius values. Once done, click on the region drop down menu again, and select centroid. Ds9 will automatically try to detect the centroid of the image, since it is like a PSF, and hence would move the region's center to that location. Note down the centroid coordinates, and save the region. Keep doing this for every regions to get the best possible results.

Now, this is where we have different ways of selecting the regions.

For FW mode, the regions have to be with;

1. 5 *am* outer circle radius and no exclusion from the center (using a circular region instead of an annulus) and,
2. 5 *am* outer circle radius with 1 *am* central exclusion. Meaning, the outer radius of the annulus is 5 *am* and the inner radius of the annulus is 1 *am*.

For PC mode, the regions have to be with;

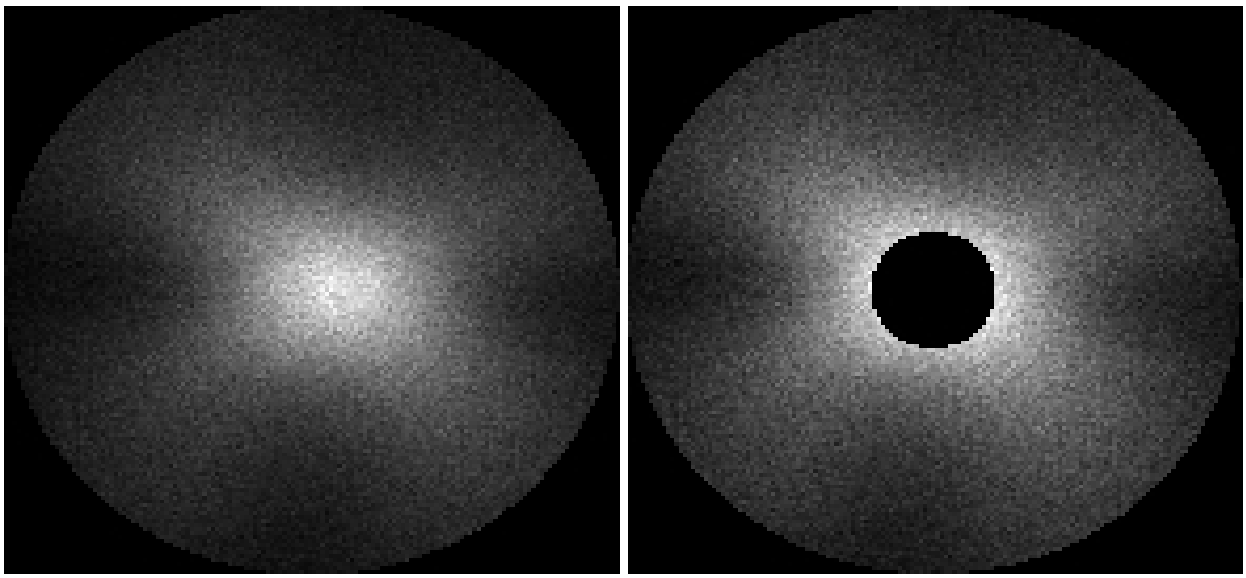
1. 16 *am* outer circle radius and 1 *am* inner circle radius.
2. 16 *am* outer circle radius and 2 *am* inner circle radius.
3. 16 *am* outer circle radius and 3 *am* inner circle radius.

Once generated, we need to save them with names discernible among other region files. Now, we would have to apply these region filters using the command:

filter region (file name of the region file with .reg extension)

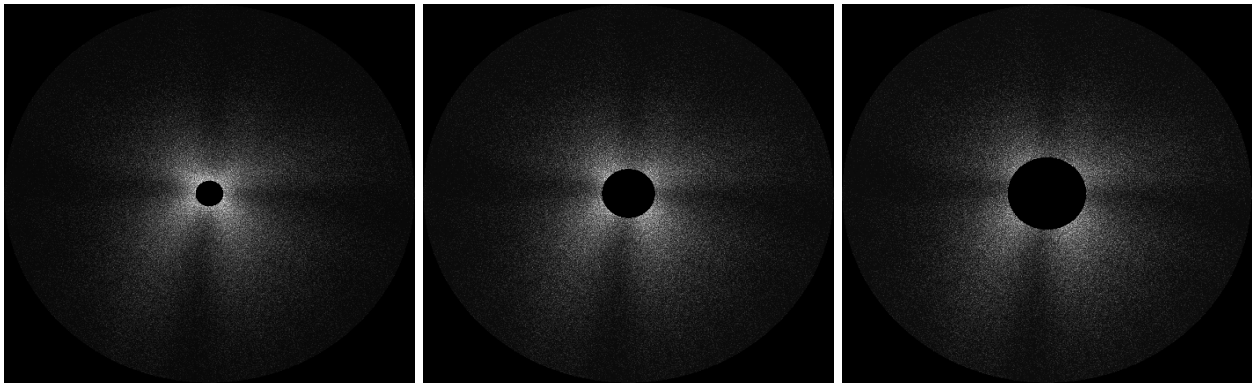
Note; to avoid bugs in the output files, it is advisable to apply one region filter, save the output (discussed later), quit, open xselect again, open the clean event file, use the time filter that was selected previously as the Good GTI filter, then apply the second filter, save, rinse and repeat for all the regions (2 for FW and 3 for PC mode).

The output of the above operations would be as follows:



(a) FW mode no central exclusion (b) FW mode with 1 *am* central exclusion

Figure 5.12: FW Mode outputs



(a) PC mode with 1 *am* exclusion (b) PC mode with 2 *am* exclusion (c) PC mode with 3 *am* exclusion

Figure 5.13: PC Mode outputs

Once the region filtering is done, and we have obtained the images as mentioned above, we are supposed to save each outputs with the command:

save all

The above command will save the light curve as a .lc file, the image as a .img file, the spectrum as a .pha file and the event as a .evt file.

Note that on region filtering and then plotting the image we might not exactly get the same output as shown above, what I have shown in Figure 5.12 and 5.13 are what you would see on opening the spectrum file (i.e. the .pha file) in ds9.

At this point, the work of Xselect is pretty much done. We would now move on to Xspec.

5.1.5 Step 4: SXTMKARF

When the telescope is collecting data, there is a finite probability that the data that we receive might be off-axis, when compared to the telescope axis, meaning, the peak intensity wont be at the center of the sensor. Now, recall that the effective area, and the quantum efficiency is multiplied together to obtain the Auxiliary Response File (arf). Now, since the quantum efficiency depends on the aspect solution (which in turn means how well the telescope is pointing towards the object and how well it is able to track the object over time), any off centered object (i.e. poor/bad aspect solution) would cause changes in the ultimate result. Hence a tool such as sxtmkarf is used to generate an OGIP style arf which would have its center as the object's center and not the telescope's axis. In FW mode this shouldn't make much difference, however, in PC mode this would make a considerable difference.

Now in order to perform the necessary corrections we use the following inputs:

1. Spectrum file
2. ARF
3. RMF
4. The RAWX and RAWY coordinates of the center of the object.

We have all the data by this point other than the RAWX and RAWY coordinates. In order to obtain that we need to use Xselect and plot the image (with the time filters and without region filters). Once done, the following instruction is used to set the coordinates to RAWX and RAWY coordinates.

set xyname rawx rawy

Then we need to extract and plot the image. Upon which we would see that on hovering the mouse over the object, instead of seeing its wcs coordinates, we would see the pixel coordinates. Now, in order to get the centroid coordinates, select a circular region, and place it at the center of the object, roughly. Once done, the information window (the one we used to see the dimensions of the region while region filtering) would show you the centroid coordinates. However, it is crucial that one does not use these centroid coordinates yet. In order to obtain the correct (or close to correct) centroid we would have to click on the region drop down menu from the tool bar and keep clicking on the centroid button, upon doing so, you would observe the region moving. Keep clicking unless the region stops to move. Once done, we now would have a region that is very close to the centroid. Note down the centroid coordinates from the information window. The first coordinate is rawx and the second is rawy.

Once we have this last bit of information, we can proceed with generating an off-axis arf using the SXTMKARF tool.

In order to run this tool, we need the file sxtmkarf.sh, which comes with the software package. In order to run this we first need to "tell" the system to accept and run the python script as a command with access to change files in the working directory. We do that by using the command:

chmod 755 sxtmkarf.sh

After which we use the command:

./sxtmkarf.sh

To compile and run the python script. This instruction then goes into the sxtmkarf.sh text file and based on the parameters mentioned within the file executes the sxtmkarf command with the mentioned parameters as arguments. The text with arguments (in bold) will look something like this:

$sxtmkarf$
$phafile = (your\ spectral\ file).pha$
$outfile = (output\ file\ name).arf$
$rmffile = (the\ default\ response\ file).rmf$
$inarffile = (the\ default\ arf\ file).arf$
$expofile = NONE$
$psfflag = N$
$vigfile = CALDB$
$srcx = -1$
$srcy = -1$
$chatter = 4$
$clobber = Y$
$history = Y$
$cphead\ (the\ default\ arf\ file).arf + 1\ (output\ file\ name).arf + 1$

Note that the user is supposed to copy and paste the names of their respective files in place of the files I have mentioned above as arguments. The last line is crucial as well since this is the instruction that is responsible for copying the headers from the old arf to the new arf, so that xspec is able to recognize the new off-axis arf as a valid input.

Once the user enters all the above, and saves the contents of the file and then runs the execution command, the program should ask for the rawx and rawy coordinates of the centroid, once entered, the program should give you the output with the entered name, besides $outfile$. * Don't forget to initialize heasoft first *

Once done, the user should have the required off-axis arf files to work with on the spectrum file which will be explained in the following section.

5.1.6 Step 5: Xspec

Now that we have extracted the spectrum files we can move on to spectral analysis using Xspec. There are in particular four files we need as inputs for Xspec.

1. The Spectral file i.e. the pha file
2. The Background pha file
3. The Response file, i.e. the rmf file, and
4. The Auxiliary response file, i.e. arf file.

The **Spectral File**, as discussed previously, contains the point based count histogram obtained from an X ray observation, representing the integrated charge per pixel from an event.

Similarly, the **Background File** contains the background counts observed by the satellite, and looks something like the image shown in figure 5.14. Other than the occasional background flares, the background soft cosmic x-rays and cosmic ray induced events are relatively constant and do not change much over time (meaning, their behavior is quite predictable), the background pha file doesn't really need any change.

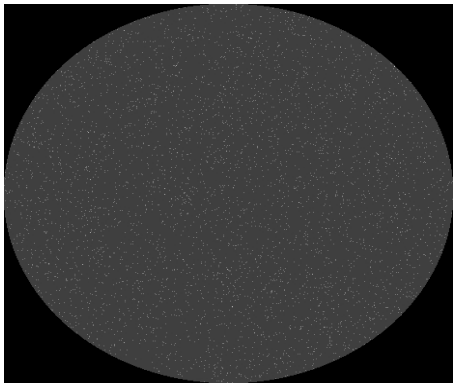


Figure 5.14: Detector Background

The **Redistribution Matrix File** (rmf) contains the probability map of all the pixels to detect an event when a X ray photon is incident on the sensor. This is sensor dependent and hence remains the same for a particular sensor. In other words, rmf maps the energy space into detector pulse height (or position) space. An ARF (Auxiliary Response File) is needed with an RMF to produce the input energy spectrum weighted by telescope area and detector efficiencies. (**)

The **Auxiliary Response File** (or arf) contains the combined telescope/detector/filter effective areas (because of reflectivity and vignetting and other such effects, the geometric area of the telescope is reduced to an effective area), and the quantum efficiency of the detector as a function of energy averaged over time (and therefore over aspect solution). This means that a bad aspect solution data would give skewed values. Hence it is necessary for us to use tools like SXTMKARF in order to correct for this error, by generating arf files which are off-axis (to match up with the bad aspect data) using the pha files from the data we extracted from Xselect.

Based on the aforementioned discussion on the types of files needed for Xspec to work; Xspec uses those files as follows:

1. Choose a parameterized model which is thought to represent the actual spectrum of the source.
2. Choose values for the model parameters.
3. Based on the parameter values given, predict the count spectrum that would be detected by the spectrometer in a given channel for such a model.
4. Compare the predicted spectrum to the spectrum actually obtained by the instrument.
5. Manipulate the values of the parameters of the model until the best fit between the theoretical model and the observed data is found.
6. Then calculate the "goodness" of the fit to determine how well the model explains the observed data, and calculate the confidence intervals for the model's parameters.

C(I): The Observed Spectrum In order to generate an observed spectrum, Xspec uses two files, The input pha file (or in better terms the data file) containing D(I), and the background file containing B(I), both being a function of the energy channel I. The data file tells Xspec how many data counts was detected by the instrument in a given channel and the background file tells the same for background photons in a given channel. Xspec then uses the back file to obtain a set of background subtracted spectra C(I) in units of counts per second. The background subtracted count rate (for each spectrum) is given by (ref. Xselect manual);

$$C(I) = \frac{D(I)}{a_{D(I)}t_D} - \frac{b_{D(I)}}{b_{B(I)}}\frac{B(I)}{a_{b(i)}t_B} \tag{5.1.1}$$

where D(I) and B(I) are counts in data and background files, t_D and t_B are exposure times in the data and background files, $b_{D(I)}$ and $b_{B(I)}$ are background scaling values from data and background files and $a_{D(I)}$ and $a_{B(I)}$ are area scaling values from data and background files, which together refer the background flux to the same area of the observation as necessary. When this is done, Xspec has an observed spectrum to which the model spectrum can be fit.

R(I,E): The Instrumental Response Before Xspec can perform any prediction, Xspec must know the specific characteristics of the instrument. This information is known as the detector response. Recall that for each spectrum the response R(I, E) is proportional to the probability that an incoming photon of energy E will be detected in channel I. As such, the response is a continuous function of E. This continuous function is converted to a discrete function by creating a response matrix which defines the energy ranges E_j such that (ref. Xselect manual):

$$R_D(I,J) = \frac{\int_{E_{J-1}}^{E_J} R(I,E)dE}{E_J - E_{J-1}} \tag{5.1.2}$$

Xspec reads both energy ranges E_J and the response matrix $R_D(I,J)$ from a response file in a compressed format that only stores non zero elements.

XSPEC also includes an option to use an auxiliary response file, which contains an array $A_D(J)$ that is multiplied into $R_D(I,J)$ as follows (ref. Xselect manual *Insert Xselect manual reference here*):

$$R_D(I,J) \rightarrow R_D(I,J) \times A_D(J) \tag{5.1.3}$$

This array is designed to represent the efficiency of the detector with the response file representing a normalized Redistribution Matrix Function, or RMF. Conventionally, the response is in units of cm^2.

M(E): The Model Spectrum The model spectrum, M(E), is calculated within XSPEC using the energy ranges defined by the response file (ref. Xselect manual):

$$M_D(J) = \int_{E_{J-1}}^{E_J} M(E)dE \tag{5.1.4}$$

and is in units of photons/cm^2 /s. XSpec allows the construction of composite models consisting of additive components representing X-ray sources (e.g.,power-laws, blackbodies, and so forth), multiplicative components, which modify additive components by an energy-dependent factor (e.g., photoelectric absorption, edges, ...). Convolution and mixing models can then perform sophisticated operations on the result. Models are defined in algebraic notation.

Fits and Confidence Intervals Once data has been read in and a model defined, XSpec uses a fitting algorithm to find the best-fit values of the model parameter. At the end of a fit, XSpec will write out the best-fit parameter values, along with estimated confidence intervals. These are one sigma confidence intervals and are calculated from the second derivatives of the fit statistic w.r.t. the model parameters at the best-fit. These are however unreliable. XSpec has a separate command (error or uncertain) to derive confidence intervals for one interesting parameter, which it does by fixing the parameter of interest at a particular value and fitting for all the other parameters. New values of the parameter of interest are chosen until the appropriate delta-statistic value is obtained. XSpec uses a bracketing algorithm followed by an iterative cubic interpolation to find the parameter value at each end of the confidence interval.

Now that we have had a basic idea as to what XSpec does with the data, let us see how the operations are realized in practice using commands.

We first start by initializing HEASoft (as we do for Xselect) and then we initialize XSpec. Once done, we should see the XSpec prompt like this:

XSPEC12>

We then enter the following commands in sequence to initialize XSpec with the data.

XSPEC12> data (data file name with location and extension)
XSPEC12> back (back file name with location and extension)
XSPEC12> resp (rmf file name with location and extension)
XSPEC12> arf (arf file name with location and extension)

To check whether the data is initialized correctly, we type the following command:

XSPEC12> show data

If we get an output as follows; then we know that the data has been accepted by Xspec.

```
XSPEC12>show data

1 file 1 spectrum
Spectrum 1  Spectral Data File: file:///home/ankush/Workspace_project/Crab/SXT/Final/Fw/spec/FWP9_5am.pha
Net count rate (cts/s) for Spectrum:1  1.801e+02 +/- 1.917e-01 (100.0 % total)
 Assigned to Data Group 1 and Plot Group 1
  Noticed Channels:  1-1024
  Telescope: ASTROSAT Instrument: SXT  Channel Type: PI
  Exposure Time: 4904 sec
 Using fit statistic: chi
 Using test statistic: chi
 Using Background File               file:///home/ankush/Workspace_project/Crab/SXT/Final/Fw/back_rmf/SkyBkg_comb_EL3p5_Cl_Rd16p0_v01.pha
  Background Exposure Time: 2.447e+05 sec
 Using Response (RMF) File           file:///home/ankush/Workspace_project/Crab/SXT/Final/Fw/back_rmf/sxt_pc_mat_g0to12.rmf for Source 1
 Using Auxiliary Response (ARF) File  file:///home/ankush/Workspace_project/Crab/SXT/Final/Fw/arf_offaxis/FWP9_5am_1am_v02.arf

XSPEC12>
```

Figure 5.15: Xspec show data output

We now need to set the plot to an energy scale so that we get the normalized count (i.e. counts compared to the reference level set by the rmf and arf files) with energy in KeV. This is done by using the command:

XSPEC12> setplot energy

Now, since the energy sensitivity range of SXT is 0.3 to 8.0 KeV, anything other than that would be meaningless data. However, the signal to noise ratio towards the ends of the energy range is high, hence it is advisable that we consider only the central region of the spectrum (Note that you can use this command to ignore channels as well, just don't enter the channel limits in float, because for this command, float=energy in KeV, and integer=channel number). We do the above using the following command:

XSPEC12> ig **-0.7 7.0-**

Here, ig is a short form for ignore. The above command tells xspec to ignore all the energies below 0.7 KeV and above 7.0 KeV. One thing that helps us mediate the binning issues is **grppha** to bin the data, which would help reduce the impact due to noise, among several other things (ref. *insert xspec manual reference here*) on the model fit and hence it's impact on the reduced χ^2 value.

Now, we are ready to introduce a simulation model into xspec. As mentioned above, we do that by using the model (or mo, in short) command as follows;

XSPEC12> model tbabs*(powerlaw)
1:TBabs:nH> 0.21
2:powerlaw:PhoIndex> 2.14
3:powerlaw:norm> 10.4

We can also enter the command mo tbabs*(po) in place of the above since both mean the same. Now, as it is mentioned above, we need to take care about the object's location, and basic optical signatures as well in order to conclude what would be a good model for it. Now, in this case since crab nebula is near the galactic arm, the light coming for there would face extinction due to the ISM in the galactic arm. This model calculates the cross section for X-ray absorption by the ISM as the sum of the cross sections for X-ray absorption due to the gas-phase ISM, the grain-phase ISM, and the molecules in the ISM (ref.). The parameters entered is the best fit parameters that were found out for the ideal case, which is obtained from different sources.

Now, if you wish to change the value of any of the parameters, you do it by using the following command (in this example we are setting the first parameter):

XSPEC12> newpar 1

Now, the format for changing any parameter is as follows (*review this*):

(Value of new parameter) (step value) (minimum limit) (minimum value) (maximum value) (maximum limit)

Once we do that, Xspec asks us for parameter values for nH, phoIndex and Norm, however, for now let us exit the terminal using /*. Once done, we now command xspec to fit the predicted model to the data received, using the command;

XSPEC12> fit

Once done, Xspec fits the model spectrum to the data spectrum. And Xspec writes down the best fit parameter values. Now, we would have to plot the spectrum with our plotting tool. The one I used was xw. To load the tool we need to type the following command;

XSPEC12> cpd /xw
XSPEC12> pl ldata ratio

The above command plots the logarithmic data on both axes. It also plots the variations in the data when compared to our model in a graph below the plot. The output is as follows;

The next thing we would have to do after we plot is to adjust the gain of the model. This is done using the command;

XSPEC12> gain fit
slope> 1 -1
offset>
XSPEC12> fit

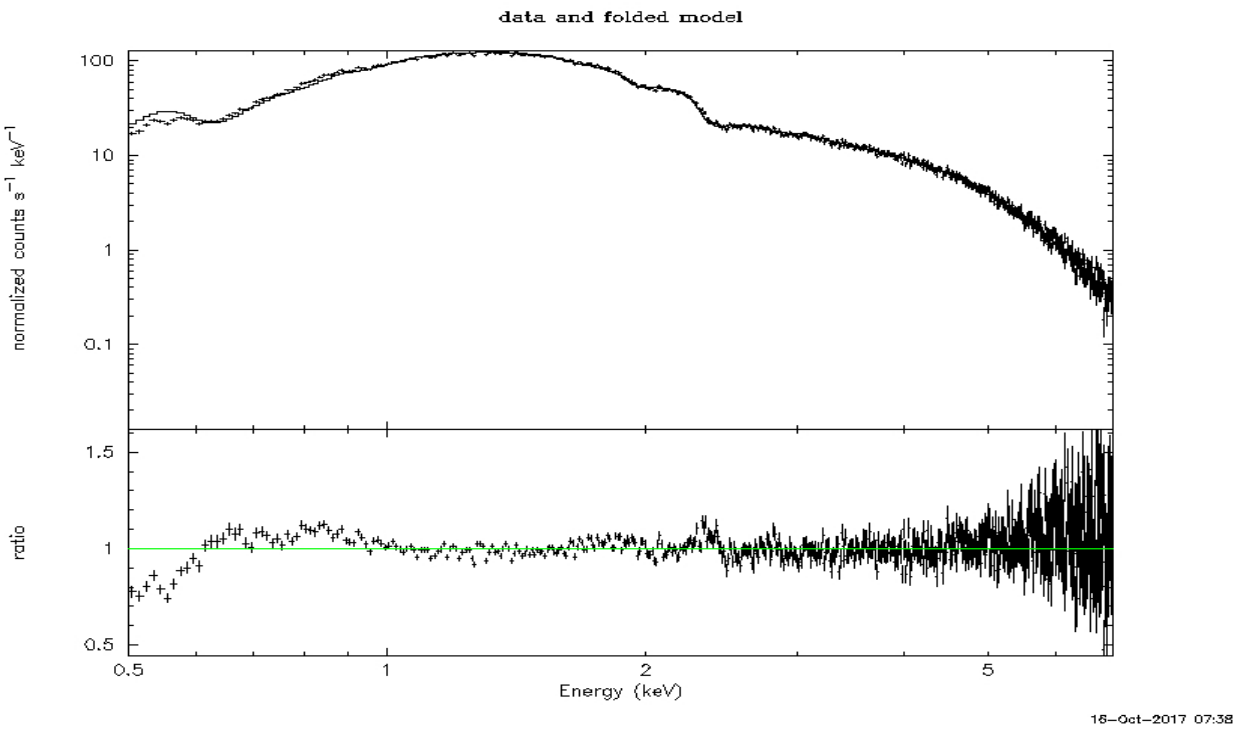


Figure 5.16: log data plot

This would adjust the gain so that we have a slope frozen to 1 and an offset calculated by the system, to have the best fit. We then fit the above and use the command **pl** again to obtain the above plot (Figure 5.16).

Now, we can see that the low energy region shows a significant amount of deviation. This can be further corrected using several commands, one of them being setting the solar abundances using the command, abund. As a rule of thumb, it is our intention that the normalization be the lowest possible. And, the χ^2 value be close to one. Now, there are several tables used for plasma emission and photoelectric absorption models. We could set different abundances, however, the table "wilm" seems to give us the least norm and χ^2 value closest to one. So we would follow this abundance model for now. We do that by using the following command:

XSPEC12> abund wilm
XSPEC12> fit

After that we get the following curve:

However, it is not mandatory that we stick to one model since it depends on the source as to what solar abundance ratio table is appropriate for it, hence, we might do well to check other abundance models as well. I say this because different elements form by different processes. Some of the elements are formed by type II supernovae (light metals i.e. Mg, C, O etc. Note that anything heavier than Hydrogen and Helium is considered a metal) and some are formed by type Ia supernovae (i.e. the "Iron peak" elements i.e. Fe, Ni, Zn, Co, Mn, Cr). Type II supernovae are mostly because of massive stars (meaning, stars with low life time, since they are burning fuel, faster) and type Ia supernovae are because of white dwarf stars exploding in a binary system when they go over the Chandrasekhar limit, maybe due to in-falling matter from the companion star (in short they are from stars that have had a long life span, i.e. low to intermediate mass star). Since these stars go "boom" at different times, the elements formed by these explosions are incorporated into new stars at different epochs during the star formation history of the galaxy. This could mean, that finding a correct (that gives $\chi^2 \approx 1$ meaning an ideal fit of our model with the data) solar abundance model (comparison of log of element to element ratio in the observed object to that of the same element to element ratio in the sun) could give us an idea as to what that source is made up of. However, this hypothesis is up for debate because of my lack of knowledge, as of now. Also, looking at the abundance ratio of different stars can give us strong clues as to what their age might be.

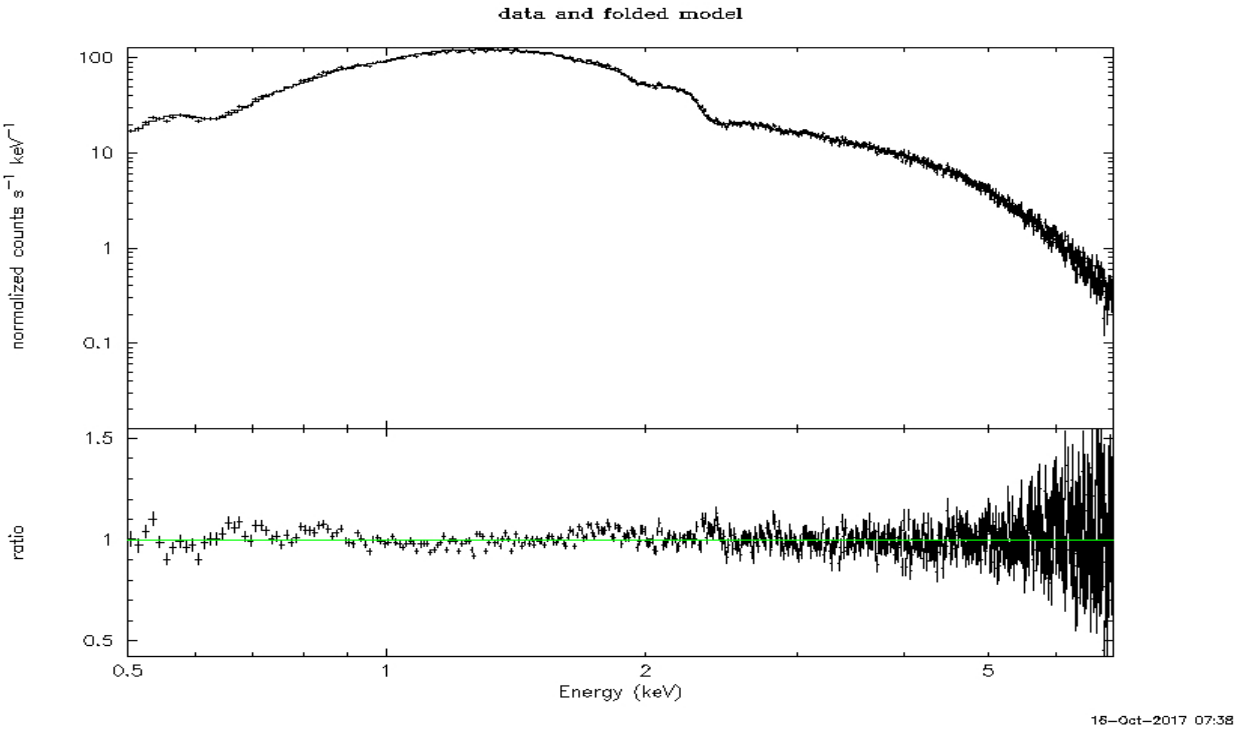


Figure 5.17: log data plot with abundance set with wilm table

Since the object we are observing also happens to be an emission nebula, there are certain photoionisation effects that could impact our data since the model we are using is an absorption model. We do that by using the command, xsect. Now, there are three options in this case;

1. obcm (from Balucinska-Church and McCammon with old Helium crossection),
2. bcmc (from Balucinska-Church and McCammon with new Helium crossection), and,
3. vern (from Verneret. et. al.)

For now, we will be using bcmc. We do that as follows:

XSPEC12> xsect bcmc
XSPEC12> fit

The last thing that we need to define is the systematic error in the model we used. We do that with the help of the command systematic. Systematic errors are the errors that might be introduced into the final result due to flaws in the equipment or in the design of the experiment. Unlike random errors, systematic errors cannot be reduced by merely repeating the experiments with the same equipments, and hence may lead to an overall alteration of the final result. Hence there is a need to introduce a model dependent systematic term to the variance. We set a systematic error of 2 percent by using the following command.

XSPEC12> systematic 0.02
XSPEC12> fit

Once we reach this step, we now have the results of the object in que stion which we need to analyze. We also have the final plot of the en[-ergyp] spectrum by now. Note that since the properties of every object are different, the above method (which was for the crab nebula data that I had) will vary. A significant variation will be with the model we would use, which, as mentioned above is completely based on the object we are observing and it's property. In case of this being an unknown source, we are supposed to take educated guesses

as to what the object might be like, hypothesize, accordingly select the model, look at the reduced χ^2 value and judge whether the model we used to fit is the correct model explaining the source. If not, then rinse and repeat unless we find the best fit model. As mentioned in the previous sections, we check for the goodness of the output by using two commands;

XSPEC12> goodness

XSPEC12> error 1 2 3

These commands help us determine whether the variation in values we got for the three parameters (if we use one model to fit), i.e. nH, phoIndex and norm, has the accepted values of those parameters within their variation range. If not, then we are making some mistake somewhere.

5.2 LAXPC data processing

Now, once the software is set up, which is mentioned in the previous section, we will perform the following steps to obtain the data required to plot the light curves and spectra. Now, since it is mentioned that there are two software for LAXPC data processing, we would stick to one software package for analyzing the data. Now, another thing to note is that the pipeline from IUCAA, had some problems with processing the background files, at the time of writing this report, I am not sure whether this is resolved yet, however, because of this, we would be sticking to the code by Dr. H. M. Antia, with the new background software (released in December 2017). Also, since I mentioned that the IUCAA code is just with a python shell around the FORTRAN code by Dr. Antia, I would focus on how to use the code from Dr. Antia, for now.

Unlike the SXT analysis, the number of steps needed to analyze the LAXPC data is comparatively less since most of the work is done by a black box pipeline software (reason being I myself am not sure how the software works =]exactly). Things such as the GTI filtration is done by the software and we need not bother with explicitly removing the GTI like we did during SXT analysis. Now, one of the primary differences in a proportional counter design and a telescope design is the fact that telescope focuses the photons, and the proportional counter counts the energy of the photons based on how far they go within the Xenon-methane gas, i.e. based on what anode layer depth they go.

Now, why is LAXPC used? Other than the fact that the energy range is broad (at the time of writing this report, LAXPC has the largest sensitivity range possible for any X-ray Proportional Counter, which is 3-80 KeV energy range), one of the many uses being the data generated is perfect for power spectrum analysis, i.e. plotting the power spectrum using the data, because the Nyquist frequency achievable using the data obtained goes upto 4000 hz and above (*reconfirm that*). This helps us detect QPOs, thermonuclear bursts (not sure if they would show up in frequency powspec), and other such signatures.

Now, the software is responsible to convert the level one data into level two. This is unlike the data that is processed in SXT since the data we work with is level 2 data. The LAXPC software corrects for the GTI (poor aspect solution, high background e.t.c.), and other such effects. Once done, the software generates the light curve and the background light curve out of this data which is then used with the software such as lcurve (to obtain light curve) or powsepc (to obtain the power spectrum) out of the data.

5.2.1 Processing steps

Once the data is obtained, it should be in the following format.

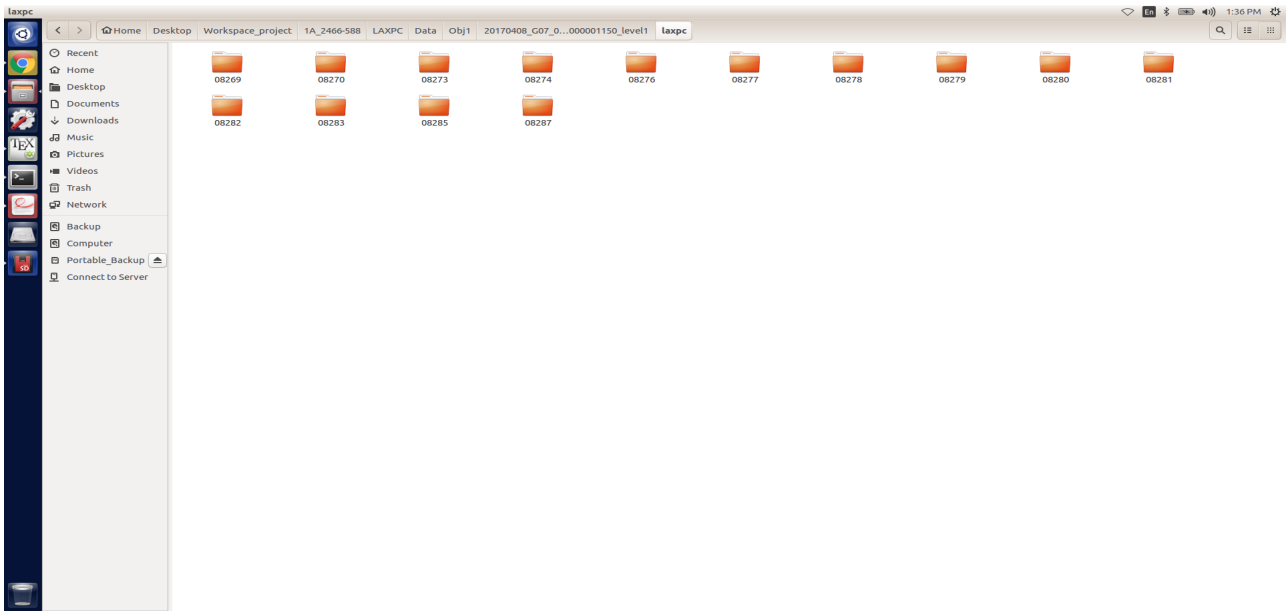


Figure 5.18: LAXPC data sample

Now, in the above image, each file represents one orbit, where the GTI isn't filtered. Now, the data wouldn't always be in the same format as shown, since it depends on how the data was obtained. Now, the main intension of the user would be to obtain the data in the form as shown above, i.e. all the orbits in the same directory as shown. One way to do that would be to use the copy command from linux to copy all of them in one directory.

Now, once done, we are ready to work with the data. We now have to make a list of four particular files within each orbit. It is in a format as shown below:

$$20170408_G07_065T02_9000001150_level1/laxpc/08269/AS1G07_065T02_9000001150lxp_level1.mkf$$
$$laxpc/08269/aux/AS1G07_065T02_9000001150lxp_level1.tct$$
$$laxpc/08269/lxp1/modeBB/AS1G07_065T02_9000001150lxp1BB_level1.fits$$
$$laxpc/08269/lxp1/modeEA/AS1G07_065T02_9000001150lxp1EA_level1.fits$$

The main goal now is to make a list of these files, i.e. the two .fits, one mkf and one .tct file from every orbit into one list file having the locations of the said files. laxpcl1, i.e. the fortran executable file requires these files to run. There is a script written to perform this function, with the name **findfile**. One would have to change the arguments in this file and run this file. You would have to change the location within the file for it to work. It is just a script that finds files within any directory and procedurally copies the locations of these files into one file. The output file would be called ls1 (the name can also be changed within the find file script).

Another thing to note is that for laxpcl1 to work, one would need a gti interval as well. This is not present by default, and hence each time you wish to run the laxpcl1 script, it would look for the good time interval file, and hence would give an error prompt if it does not find the file. Hence one would have to first create a file **gti.inp** and in the first line put 0. This is done so that the software can detect a blank file which it will later change and put in the correct gti intervals.

Once these things are done, one can run the laxpcl1 script. In the first line it would ask you for the pcu number, i.e. out of the 3 LAXPC pcu, which one would you like to use. Note that at the time of writing this report, the 3rd pcu is not operational, since there is some kind of leakage in the chamber, because of which the pressure in the pcu isn't exactly 2 atmospheres, and hence it's composition is different from the other pcus, hence rending the data un-reliable.

However the next thing which the program will ask for is the time bin needed. This is where you define the time bin needed by you. Note that this is also important since this decides the Nyquist frequency (half of max sampling frequency, needed in power spectrum). For example, if you would want to detect some event that you hypothesize to give a peak frequency of 300 hz, then you need to have a time bin of less than 0.006 seconds. This would translate to the maximum possible frequency of 300 Hz, (insert van der klis paper reference). After that we mention the anode layers we need, **0** for all the layers, **1** for the top layer (A1+A2), **3** for Second layer (A3+A4), **2, 4 to 10** for the respective anode layers. For example, to get the laxpc pcu 1 data, for a time bin of 0.00025 seconds (Nyquist frequency of 2000) and the data from all the pcu levels, we enter the following;

1 0.00025 0

Then, the software will prompt for the channel numbers needed, i.e. the lower channel limit and the upper channel limit, the signal within which will be considered. The rest of the signal, outside these channel numbers will be ignored. Now, in order to find out the channel number, and their corresponding energy ranges, we need to open the response file for the particular pcu at the time of the observation. This is done using the software called backshiftv2 which is generated along with laxpcl1 (but using a different FORTRAN code). Now, once you execute the executable file, (similar to laxpcl1), it will ask for the pcu number and the and the anode level, the anode labeling is same as the one used for ./laxpcl1 in the previous paragraph. Then once you press enter it should ask for the time bin, lower limit channel number, upper limit channel number, and nul flag, which is a flag to fit low energy background. set it to -2 for using fit to layer 1 background for channels 0-200 (¡ about 20 keV). Now, since you do not have any output from ./laxpcl1 yet, you will not have the file it asks for next, which is the background file generated from ./laxpcl1. However, keep the section blank and just press enter. Upon doing so, the software would give you an error and would prompt you to enter the date of the observation, upon doing so, and pressing enter, look for a line that says, "**use —- response file**", note down the name of that response file. Now, assuming you have downloaded the latest response files from the website, you would have to find the response file within that folder containing responses for every consecutive dates, and

once found, open that response file with fits viewer (part of heasoft package, hence you would have to initialize heasoft first, and then enter fv followed by the fits file name). Once open, look for the **EBOUNDS** row, and under the view column, click on 'All', this will display the energy bounds for the respective channels. Write down the channel numbers for the respective energy bounds. This is what enter as the lower and upper channel limit.

Once done, the software will ask for the number of channels to be used in the spectrum. The response files are made with 512 channels for LAXPC PCU 1 and 3, and 256 channels for LAXPC PCU 2. This could also be seen when one opens the response files for each pcu (found out using the backshiftv2, for each pcu).

Once done, the software should ask for earth occultation correction, this is done because, as mentioned in the previous section, ASTROSAT takes data throughout the orbit, even while it is behind earth when facing the object, LAXPC has a provision of correcting this, hence this step. For starters, unless mentioned, we will consider skip this step with `*/`, and press enter.

5.2.2 Products

After doing that, the software will process and finally through out the following data:

1. **lxpilevel2.event:** Summary of frames read from level 1 EA mode, the 'i' in the file name stands for ith pcu. So, for LAXPC1, it would be lxp1level2.event
2. **lxpilevel2.evn:** This is the FITS giving data for each "valid" event. The quotations around valid is to emphasize when a GTI interval is considered, i.e. refer the part where we discussed what makes a GTI.
3. **lxpilevel2.evn1:** This the ASCII file containing the event data.
4. **lxpilevel2.lc:** This is the ASCII file for the light curve. The following are the column value (ref. the manual attached within the laxpc folder):
   (a) **col-1:** Instrument time (sec from switch on of STBG)
   (b) **col-2:** UTC time (sec from 1 Jan 2010)
   (c) **col-3:** counts in the specified time bin (**not count rate**)
   (d) **col-4,5:** RA, Dec of pointing direction (in deg)
   (e) **col-6-8:** Longitude, latitude (in deg) and altitude (km) of satellite
   (f) **col-9:** Elevation of source above the Earth's limb (in deg)
   (g) **col-10:** ULD count rate (per sec)
   (h) **col-11:** CPM counts
   (i) **col-12:** Fitted background count rate (per sec)
   (j) **col-13:** Rate of rejected events (per sec)
   (k) **col-14:** Total count rate in all anodes and channels corrected for dead-time.

   There are other entries in the file as well in the last line of the document, they are (from left):

   (a) ObsID of the last file processed along with source and observer names
   (b) lxpi: giving the detector used
   (c) frbk: A factor by which the fitted background in the 12th column of the file needs to be multiplied if range of anodes or channels is restricted.
   (d) Efficiency of observations, i.e., fraction of GTI during the entire observation
   (e) fbk: A factor by which the average background spectrum is multiplied, depending on the latitude and longitude range covered during observation
   (f) fraction of time in data gap (excluding SAA)
   (g) Total exposure time for observation in sec as obtained from GTI
   (h) Fraction of frames lost, i.e., missing or marked bad or eliminated
5. **lxpilevel2.lcurv:** FITS file giving the light curve. This shows only the time covered by GTI and shows count rate per sec. The count rate is for the specified anode and channel range and is corrected for the dead-time.

6. **lxpilevel2.lcbk:** FITS file giving the light curve for fitted background model. This shows the time covered by GTI and the count rate per second. The cont rate is for a specified anode and channel range and is corrected for the dead time.

7. **lxpilevel2.pha:** ASCII file giving the spectrum. It contains count rate per sec averaged over all time specified by GTI. The number of channels is taken from the input value for NCA. First column is channel number, the next 10 columns are count rate in anodes A1-10 and last column is the total count rate in A1-7. Irrespective of value of input parameter IAN all anodes are included. The spectrum is corrected for the dead-time.

8. **lxpilevel2.spec:** FITS file giving the spectrum for the specified anode averaged over all time specified by GTI. The number of channels is taken from the input value for NCA. The spectrum is corrected for the dead-time.

9. **lxpilevel2back.pha:** ASCII file giving the modelled spectrum for the background averaged over the same duration as the source spectrum. For NUL=0 the background model based on ULD counts is used, while for NUL=-1 background model based on fit to latitude and longitude is used. For NUL=-3 fit in 3D is used, but this is not very good. The format is the same as that for source spectrum.

10. **lxpilevel2back.spec:** FITS file for background spectra for the specified anode. The format is the same as that for source spectrum.

11. **lxpilevel2.gti:** ASCII file giving the GTI generated from the observed light curve. The first line is no. of entries and the subsequent lines specify the time range. First two columns specify the Instrument time which are used by the program, the next two columns are in UTC. This file can be edited and moved to gti.inp and the program has to be run second time to use the GTI input. To generate GTI file it is advisable to run the program with a time bin of about 1 sec and full range of anodes and channels. Once the gti.inp file is prepared the program can be run for required time bin, anodes and channels.

12. **lxpilevel2.four:** The Fourier transform of the entire light curve. If there are too many entries then time range may be truncated. This may not be very useful as it would cover the Earth occultation and SAA passage also, with gaps set to 0.

13. **lxpilevel2.mkf:** Summary of .mkf file read. It could be used to check the time range covered by each file or to check if all files are read.

14. **lxpilevel2.uld:** ASCII file giving the ULD counts as read from the level-1 BBC file.

15. **lxpilevel2.gap:** The first several lines are same as the .lc file but covering those period when there is a gap in data. The gaps due to SAA passage are excluded. This can be used to identify where data are missing. The last few lines give the range of Instrument time for the gaps and the last line gives the total time lost.

16. **lxpilevel2.frame:** Summary of frames read from level1 fits files grep Frame lxp?level2.frame will give the summary of frame lost in each orbit one per line giving lxpi, obsID, orbit no., total No. of frames, bad frame, total frames eliminated.

As one might notice, the above points have been quoted directly from the read me files provided with the software. One would do good to refer to those if one would like to get an in-depth understanding of the software.

Now that the above is done, we can do several things with the fits files that are provided to us, such as plotting the light curve, and hence obtaining the power spectrum of the same. Now, there are several ways of doing the above, one could use the ASCII files to obtain obtain the plots, I personally used python to plot the data and perform normalizations (Leahy with Poisson noise level = 2, Fractional rms squared normalization with Poisson noise level = $2/meanrate$ and Absolute rms squared normalization with Poisson noise level = $2 \times meanrate$). However, at the time of writing this email, I am also working on recreating those plots on IDL and read from the event file, if that would make any difference.

5.2.3 Power Spectrum

The importance of plotting the power spectrum is something of a necessity since knowing what periodicities we have in the signal is something that would tell us a lot of things. Depending on what you are observing, it could be anything, orbit of the satellite around earth, if the object has a companion, then their orbit around each other, if the star is accreting, then the rotation of the disc, so on and so forth. Now, if one wishes to

quickly see whether there is anything in the data or not, (which would include red noise and QPOs, etc.) one can simply use the lxpilevel2.four file, which is, as mentioned above, the Fourier transformed power spectrum, i.e. the ASCII file for the power spectrum (since you need FFT to obtain the power spectrum from the light curve). One can simply use tools of their choice to plot the power spectrum, i.e. gnuplot, or fplot (which is a part of the heasoft package), or simply python, which would give you a rough idea if there is anything in the data to spend more time into and look at later.

Now, if the object looks interesting, then one can proceed further to use tools such as powspec, or python to further perform normalizations and hence obtain the plots needed.

If one wishes to perform normalizations using python, one can search for the stingray package for python, and how to use it. One can easily obtain the said normalizations, and other things such as the dynamic spectrum, etc. using the software.

However, since the standard software used to plot power spectrum is called **Powspec**, I would focus on how can one use it to perform normalizations. Note that powspec, at the time of writing this report just had two normalizations available, i.e. Leahy normalization and RMS squared normalization. Now, when you are using POWSPEC you need to remember that it works with arguments, and hence depends heavily on what parameters you pass it while you execute the "powspec" command. A detailed description of the powspec commands could be found on the powspec.txt available on-line. However, lets say someone wishes to use it, one would need the following:

1. The light curve fits file.
2. The window file (one can use - i.e. the default window file, or generate custom window using xronwin task)

Once done, you enter the following in your terminal, (preferably within your working directory):

powspec norm=.....

In place of the dots (.....) you can have the following options based on what kind of normalizations you need: (ref. powspec.txt found in the ftools page)

1. **0** = power spectra is normalized by dividing by the number of good newbins per interval.
2. **1 or -1** = (d/f); power spectra are normalized such that the (white) noise level expected from the data errors corresponds to a power of 2 (note that correcting the data errors for instrument dead time might be necessary to bring the expected noise level to 2) The minus sign is to be put when one needs to subtract the white noise level from the powerspectrum and then display it. **(Leahy Normalization)**
3. **2 or -2** = power spectra are normalized such that their integral gives the squared rms fractional variability (therefore the power spectrum is in units of (rms)**2/Hz). The expected (white) noise level must be subtracted to obtain the rms fractional variability of the series. The minus sign has a similar significance as in the previous case. (RMS squared normalization)

Note: Now, one might find it appealing to write their own code in IDL in order to find their own normalizations, since powspec is limited in that sense. I do recommend the same. As mentioned above, one can always use tools such as python and/or IDL in order to achieve the task, which would give endless flexibility to the user to perform tweaks to the code. However, it is advisable that one compares the results using powspec or any other tools as well and try and reproduce the results in all the cases so as to be absolutely sure that the code that they wrote works and gives valid results.

Coming back to the task at hand, once the user has entered the default window file, the user would be prompted to enter the new bin value. Now, this is a very important step since this is where you change the two parameters that help you determine whether or not you would observe a particular signal or not.

Now, I would briefly take a break and explain, in brief what this, and another parameter you would enter in the following section is, and why it is important to detecting your signal. Now, one should refer the paper **Fourier techniques in Xray timing (1988) by M. Van Der Klis**, this is a beautiful paper which one should read if one needs to get a brief understanding of the Fourier techniques involved in obtaining a power spectrum.

Now, the two important parameters are:

1. **Dividing the entire light curves into equal frequency bins (W)**

2. **Dividing the light curve into equal intervals/segments (M)**

Now, a detailed explanation of the aforementioned parameters can be found in the paper by van der klis, however, one thing to note is that these are the two parameters that you would have to change in order to bring out narrow features (NS rotation frequencies, pulsar frequencies e.t.c.) or broad features (QPOs, red noise e.t.c.). Note that changing the newbin interval sizes changes the number of segments that the new powerspectrum plot would have. Changing this parameter would also change the Nyquist frequency (which is half the sampling frequency, which decides the maximum frequency of the powerspectrum) hence this parameter is not changed as much. However, the other parameter, changing the frequency bins is what is preferable if anyone wants to detect any broad or narrow features in the signal.

Coming back to powspec, Now that you have entered a newbin value (or just kept it at default value) it will ask you for the number of newbins per interval, you can go with the default value (by typing **INDEF**) or enter whatever value you see fit.

Once done, the program would ask you for the number of intervals per frame. One is the default value, in any integer is entered above 1, then the software might calculate the average out of the entered frames and then display the averaged results.

Then powspec asks for the frequency re-binning, i.e. the first parameter, W. This, as mentioned above plays an important role in observing any features in the data. Now, at this stage there are three options available to the user, if the user wants a **geometric re-binning** (then enter any value less than -1), from what I have observed, this logarithmically bins your frequency, with a steady increase of the bin size (however, I might be wrong), the second option is to have **no frequency rebinning**, i.e. 0, and the third option is to have a linear rebinning, i.e. constant rebinning i.e. > 1. The user is free to choose whatever rebinning suits the feature they are trying to observe.

Once the above step is done, powspec would ask for the output file name, the plotting device (a list of which could be found in the help command) till now I have used /xw (Xwindows device, helps you view the results immediately and make changes to it in the plot window) however, one is free to use whatever plotting device (/gif, /ps etc.) one sees fit, after the plotting device it would ask if the user wants to plot the results, clicking yes on this would plot the powerspectrum and move you to **PLT>** terminal where you can make changes to it however you see fit.

5.2.4 Background Subtraction from the light curve

Now, the reason why I have put this after powspec is because, as I had mentioned above, powspec is used when one wants to plot a power spectrum out of "any" light curve, be it light curve with or without background. Now, in order to perform background subtractions, heasoft has a tool called the **lcmath**, which you can access using lcmath command.

Upon entering the command, the software would ask for your light curve file. In case of laxpc analysis, we would input the recently created laxpc lightcurve fits file **lxpilevel2.lcurv**.

On doing the above, lcurve would ask for the background fits file. You would then have to enter the name of the background fits file. In case of laxpc it is recommended that you use the shifted background fits light curve you obtain from the backshiftv2 (at the time of writing this report) command. Upon entering the file, it would ask for the output file name.

Upon entering the above it would ask for the scaling factor (which is 1 by default, so better leave it at that for now) for both lc and background.

Then it would ask whether you would like to add the background instead of subtract, select what you would like to do. I think it would be advisable to add the background instead of subtract when you intend to look at the background fluctuations, and other features such as QPOs or red noise. However I myself am doubtful about the same since some sources say that QPOs and red noise are a part of the background, but are also related to the source in a sense, which I fail to understand at this moment (..insert QPO reference here..). Now, coming back to the add or subtract background part, you could subtract the background to obtain a light curve that would give you a power spectrum without the background periodicities. Once done, the software would give you a light curve that is background subtracted.

NOTE: Don't forget to use shifted background.

Since, as mentioned above, one of the main intentions of LAXPC is to detect timing properties of an object, we focused on this up until now. However another important function of LAXPC is to obtain energy spectrum, much like any other PCA available. Given the huge energy sensitivity of LAXPC (however with inferior energy resolution than SXT) it is also useful while plotting energy spectrum above the energy sensitivities of SXT. Now, remember that one of the products of laxpcl1 were two .spec extension files. These are the files you would use to obtain the energy spectrum of the source to be observed. The files I am referring to are:

1. lxp2level2.spec
2. lxp2level2back.spec
3. (The response file you used to obtain the channel numbers for energy filtering).rmf

Note Here, as mentioned in the previous sections, you would have to use the shifted background spectrum file, which would be something like **lxp2level2back_shifted.spec**. Also, the response file mentioned above, which would be needed as an input for xspec is the same response file that you used to obtain the channel to energy relation while performing energy filtration of the particular light curve.

Now, we use **xspec** to obtain the energy spectrum even in this case, with the same methodology as mentioned in case of SXT. However, one difference is that we do not have an auxiliary response file in this case because of obvious physical reasons (LAXPC is a PCA.. unlike SXT which is a CCD sensor).

Quick fact: Given what I just said above, you can actually get the energy spectrum without using the arf file for SXT, however it is not recommended that you do so.

A sample plot using data for LAXPC2 without back shifted spectrum is as follows:

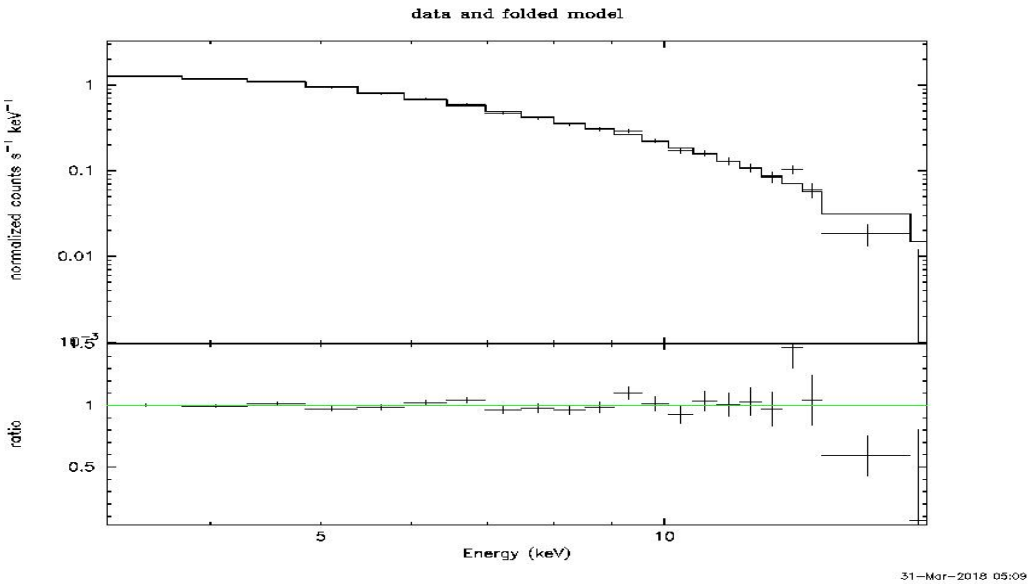


Figure 5.19: LAXPC energy spectrum sample

5.3 Plotting Combined energy spectrum using SXT and LAXPC data

Following the previous sections we know that we use Xspec for both LAXPC and SXT energy spectrum, the only difference being in the models we use for both, which are just slightly different. However, in this section we would look at the combined energy spectrum plot using both LAXPC and SXT data.

Now, when it comes to initializing the data, the response and the background files for both plots (for now it is two, later we can plot multiple spectra within one plot), we use the following line within the xspec terminal.

XSPEC> data 1:1 (low energy spectrum 1) 2:2 (high energy spectrum 1)

We need to keep in mind that we enter the location of the FITS files if the directory we are working on does not hold the input files. Once done we enter:

XSPEC> back (back for low energy spectrum 1) (back for high energy spectrum 1)
XSPEC> resp (resp for low energy spectrum 1) (resp for high energy spectrum 1)

Note: Maintain the order as in the data file sequence.

XSPEC> setplot energy
XSPEC> ig 1: **-(low energy limit) (high energy limit)-**
XSPEC> ig 2: **-(low energy limit) (high energy limit)-**

Apart from this, the rest is the same with the models, xsect, abund, systematics, e.t.c. However, one thing to note would be the models, since there are two spectra being used here, xspec would prompt for two different parameters for both the models. Also, another thing to note while inputting the models is that, because the instruments are different, when we want to plot the energy spectrum, because of their different responses, we would have different normalizations, this would give different results than what one could expect. Hence to mediate for this, we use a constant which we multiply with all the data points to mediate for the difference in response of the two devices. Now, xspec does the calculation on it's own and based on the best fit parameters selects the constant and plots the corrected spectrum. This is relevant mostly in case of high energy xrays. Now, in order to perform the corrections, we just enter the model as follows:

model constant*tbabs (bbody + powerlaw)

And when it prompts for the first model, we just enter **1 0** to freeze the constant for lower energy to 1, and skip the rest. So, essentially, what we end up having is one of the constants is frozen to 1 and the software calculates the offset (constant) in the second data set's case based on the best fit parameters and spews out the result.

Note Even when you wish to enter the gain fit command, you need to keep in mind that you would have to enter gainfit for both spectrum as follows:

gain fit 1 for the first data set
gain fit 2 for the second data set
... so on and so forth

The rest is the same as that mentioned for SXT, i.e. freezing the slope as 1 and calculating the best fit offset value. The following is a good example of a combined light curve which gives a good estimate of the energy spectrum of the object within 0.4 KeV to 20 KeV. Now one of the reasons why this is important is that it allows the object to be seen through several instruments and helps compare them all in one plot.

Now as I had mentioned earlier, it is not mandatory that this should contain just two plots, it can contain more than two plots, and each can overlap one another. The black spots data points are the SXT data set, and the red data points are the LAXPC PCA 2 data points. One can also add LAXPC 1 and SXT FW mode data points as well, however, I do not yet have the FW mode data for this source. A combined energy spectrum for LAXPC1 (green), LAXPC2 (red) and SXT (black) is as follows:

Another minor detail to note would be that time bin chosen for the data is of no concern in this case since the time element is lost when one tries to plot the energy spectrum of the data.

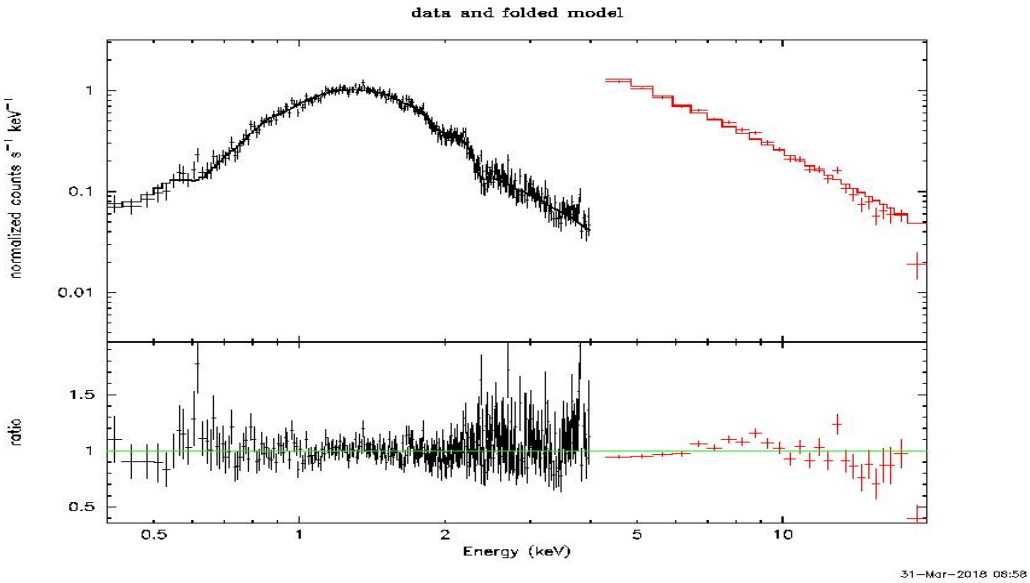


Figure 5.20: LAXPC2 + SXT combined energy spectrum

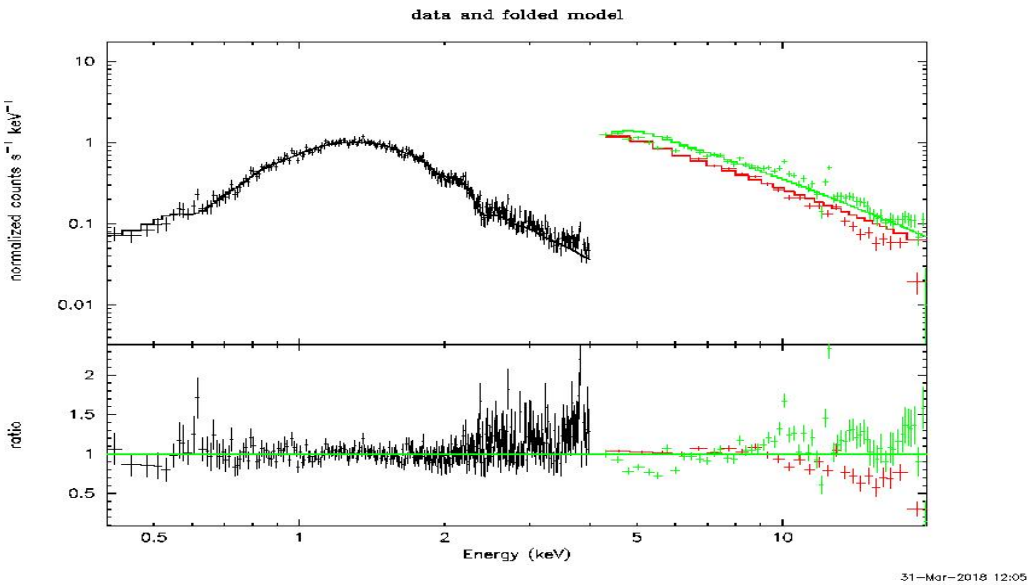


Figure 5.21: LAXPC2 + LAXPC1 + SXT combined Spectrum

5.4 RXTE Data Analysis

Now, assuming that one has access to the data from HEASARC. Upon downloading the data it would be sorted as per the proposal numbers numbers. These files have **PXXXXX** format, where P stands for proposal followed by the five digit proposal number, these stay the same throughout the mission. Upon entering the file one would find multiple files, they are of the following format:

NNNNN-TT-VV-SSX

Where:

1. **NNNNN** is the five digit proposal number, identical to the parent directory.
2. **TT** is the two digit target number. In case of one target the target number may be zero.
3. **VV** is the two digit viewing number which tracks the number of scheduled looks at the target, in particular the viewing number corresponds to:
   (a) different (requested) observations of the same target,
   (b) different instrument configurations during the same pointing.
4. **SS** is the two digit sequence number used for identifying different pointings that make up the same viewing:
   (a) for different scans, for scan mapping of extended sources,
   (b) if it is decided that for operational reasons, to split the viewing into more than one chunk, or,
   (c) if it was split "by accident", by a TOO (Target Of Opportunity), for instance.
5. **X**, the 15^{th}character, when present, indicates
   (a) **A** a slew before observation
   (b) **Z** a slew after observation
   (c) **S** scan observation
   (d) **R** Raster grid observation
   (e) **G,C,D** ObsIDs that may contain the data gaps
   (f) **0-9** segments of a long observation (i.e. > 8 hours)
   (g) **b-r** reserved for real time configuration changes

   When not present, it indicates a regular pointed observation of <8 hours, or the last segment of a long observation.

Note: The above and what is followed can be found at [16]. It is highly recommended that one refer that link if need be.

Now, once in, each of these subdirectories contain a set of 15 sub-directories, each containing data files derived from a single spacecraft subsystem. They are as follows:

1. **ace** : Attitude Control Electronics and star trackers.
2. **acs** : Attitude Control System.
3. **cal** : References to files in the Calibration Database*.
4. **clock** : Time delta correction data from Mission Operations Center*.
5. **eds** : Experiment Data System housekeeping.
6. **fds** : Flight Data System.
7. **gsace** : Gimbals and Solar Array Control Electronics.
8. **hexte** : HEXTE science and housekeeping data (Important).
9. **ifog** : Interferometric Fiber Optics Gyroscope.

10. **ipsdu** : Instrument Power Switching and Distribution Unit.
11. **orbit** : Orbit ephemeris from the Flight Dynamics Facility*.
12. **pca** : PCA science and housekeeping data (Important).
13. **pse** : Power System Electronics.
14. **spsdu** : Spacecraft Power Switching and Distribution Unit
15. **stdprod** : Standard Products - cleaned light curves, spectra etc (Important).

*****If the top level Cal, Clock, and OrbitEphem directories exist, then these subsystems simply contain links to those files. The links exist so you can find the appropriate files using the index files via XDF. If those directories do not exist, then the files themselves should reside in each subsytem, so there may be many duplicate files in different ObsIds.

Note: ASM is not included.

Now, within the above subsystems, each one of them are a set of several distinct sources of telemetry. These telemetry sources are known as **Applications** and are designated by **AppIds**. In all there are 255 AppIds, and the telemetry packets they produce end up in corresponding RXTE data files after conversion to FITS on the ground. For now, let us focus on the AppIds of PCA and HEXTE since those would be the ones we would be working on.

PCA AppIds:

1. **55 EA1**
2. **59 EA2**
3. **63 EA3**
4. **70 EA5 Standard 1** (Binned Mode)
5. **74 EA6 Standard 2** (Binned Mode)
6. **79 EA7**
7. **90 PCU0 Hk**
8. **91 PCU1 Hk**
9. **92 PCU2 Hk**
10. **93 PCU3 Hk**
11. **94 PCU4 Hk**

HEXTE AppIds:

1. **80 Cluster 0 Science data**
2. **81 Cluster 0 Burst data**
3. **82 Cluster 0 Archive data**
4. **83 Cluster 0 16-s Hk**
5. **84 Cluster 0 Calibration spectrum**
6. **85 Cluster 1 Calibration spectrum**
7. **86 Cluster 1 Science data**
8. **87 Cluster 1 Burst data**
9. **88 Cluster 1 Archive data**

10. **89 Cluster 1 16-s Hk**
11. **251 Cluster 0 64-s Hk**
12. **252 Cluster 1 64-s Hk**
13. **253 Cluster 0 128-s Hk**
14. **254 Cluster 1 128-s Hk**

Note that the above can be found in [16] and it is recommended that if there arises a need for other AppIds then one would do good to refer the webpage.

Now, the contents of the telemetry packets from the three scientific subsystems, ASM, PCA and HEXTE can be arranged in different ways to maximize the science return in the available telemetry budget. This amounts to choosing an observing mode and setting the adjustable parameters which define the mode. The combination of mode and mode parameters is known as the **configuration**. This is important since data from the same AppId and configuration have a truly homogeneous format and can be reduced together in the same way.

RXTE has several possible configurations however along with the flexibility to add new ones, however, the data that we get from the Internet download will only have those configurations chosen for that particular observation.

The RXTE data files -FITS data tables to be exact- follow these design principles:

1. **Homogeneous contents:** The contents of an individual data file come from the same application.
2. **Time Span:** A new data file is started when:
   (a) a new observation begins,
   (b) the configuration changes, or
   (c) the application is rebooted (**Note:** Event Analyzers are rebooted once per orbit)
3. **Rows:** One row per packet or logical group of packets in time order.
4. **Columns:** Data from different data sources will be separated into different columns, some of which may contain arrays rather than single values.

For each ObsID, the stdprod directory should contain an XTE filter file, named **FP_xxxxxxx-yyyyyyy.xfl** (where xxxxxxx and yyyyyyy are start and stop time in hexadecimal mission elapsed seconds). The filter file incorporates much of the housekeeping data from other subsystems and is intended for creating GTI based on those data. Checking, and remaking if necessary, this file is one of the first steps to data analysis. Make sure it includes everything needed (by plotting the columns ELV, OFFSET, PCUn_ON, BKGD_THETA, BKGD_PHI, NUM_PCU_ON, TIME_SINCE_SAA, and ELECTRONn at minimum).

Now, to start the data analysis, we need to find the files needed to do so, we do this using a tool available with the heasoft package called XDF (XTE data finder) which is a GUI based tool to make browsing the hierarchical directory structure much easier. It's end-product is a list of filenames corresponding to the data you want to analyze, as chosen by the target name, the time of observation, the instrument and configuration.

To start XDF, one would first have to initialize heasoft, and then type '**xdf**' in the system prompt. After this, the following steps are to be followed, as per the requirement (*Change this as required*):

1. Set the path to the directory containing the FMI (FITS Master Index) file - This is usually the directory with the aforementioned file name syntax, i.e. **NNNNN-TT-VV-SSX**. The significance of that file name is given above. Copy and paste the file's location on the **Path:** section, and press **Make ObsList**.
2. This fills the **Observations** box with one-line summaries of the **ObsIds** in the top level directory. For each ObsId, the directory name, target name, and time range are listed. At this point you can choose a particular target or time range, though for most GOs this option is not needed.
3. You select **ObsIds** themselves by clicking on them with the mouse or by pushing the **All/None** button.

4. The next step would be to select the **subsystems**, from the subsystems box by clicking on the names of the ones you are interested in.
5. Now, to see the **AppIds/Configurations** of the chosen subsystem, click on the **Make AppIdConfigList** button and you would see that the AppIds/Configurations section shows only those AppIds that are relevant to the subsystem you selected. You need to select the subsystems needed from this window.
6. (*Solve the core dump problem and then add the steps here*)

The above can work for both binned (eg. standard-2 data) and event mode data.

Chapter 6

Background Physics

Now that we have discussed the data processing techniques, let us first brush up on a few important concepts regarding the background physics one might need in order to understand the data received, and make sense of the numbers.

6.1 Stars and their life cycles

The story of a remnant body starts from the death of a star. This is when the nuclear fusion in the core of the star is not able to balance the immense gravitational attraction of the mass that makes it up. Hence it collapses under its own weight, much like an implosion. Let us discuss these things one step at a time.

6.1.1 What happens to the stellar core on collapse

Let us try and understand this step by step.

A star forms when there is enough gas, cold enough (10 to 20 K) to condense to such an extent that, after a certain period of darkness caused due to their temperature and low optical depth for visible light (however we do see emissions in the IR spectrum e.g. Bernard 68 since the optical depth is wavelength dependent) and their density, and a tinge of push from any strong enough neighboring event (could be anything from supernovae explosion to fluctuations i.e. Jean's instability in the massive gas cloud etc. or, the galactic density wave interacting with a cloud), could trigger further collapse, but not nuclear burning, in this stage the star is a proto star, i.e. a dense gas cloud that is well on its way to become a star, but doesn't have nuclear fusion happening at its core. However, as more matter is pulled in and the core keeps getting hotter and hotter, eventually triggering nuclear fusion at its core. Hence, at this stage the star enters the main sequence.

Now, depending on how much mass the proto star had when it was forming, it steps into the main sequence stage at different times (the less massive star enters the main sequence later than the high mass star since the "big one" starts burning hydrogen earlier attributed to the higher density at it's core), depending on several conditions such as the mass of the collapsing gas cloud, e.t.c. This also decides where in the main sequence the star will end up when it enters, the massive ones ending up at the upper end and the less massive ones in the lower end of the HR diagram. Note that in order for the hydrogen burning to start, the molecules would have to cross the coulomb potential barrier. However, given the temperatures at the stellar cores which are of the order of $\approx 10^8$ K, we could rarely expect that to happen, however, the only other mechanism that could cause fusion at such energies would be Quantum Tunneling (George Gamow, 1928). Upon doing some Q value calculations, we can see that the maximum energy release is by hydrogen burning and it decreases all the way to iron, after which it goes to negative (i.e. in order to fuse nuclei heavier than Iron one would have a net loss in energy, in other words, one would lose energy implying no outward force to maintain a spherical shape).

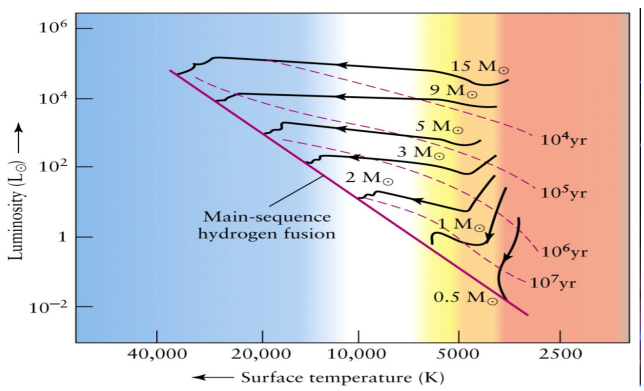


Figure 6.1: Star's transition from proto to Main sequence (Hayashi and Henney track)

Since the the amount of light fuel is limited within the star, (H and He are the "light" fuel, and in astronomy terms, anything heavier is termed as a metal, so oxygen is a metal, and the abundance of such elements would increase the star's "metallicity"), the product that forms when a star dies varies with what was the last thing that was burnt in it's core, which essentially dictates the consecutive outer shell composition of the star, which in turn decides the energies radiated when collapse occurs, which then would decide the luminosity of the (super/hyper) nova and would also decide what the core would end up as. Now, given the nuclear reaction chains, when hydrogen burns in it's core the star remains in the main sequence, however, the amount of hydrogen fuel in it's core is limited and hence once it runs out, the star starts to burn heavier elements, the next element being helium. Once it starts burning helium at its core, the region around the core (spherical shells called cells) gets hot enough to burn hydrogen, and hence the core now ends up burning helium and the first shell around the core starts burning hydrogen. This is when the star grows in size since now both hydrogen and helium burning increases the radiative pressure and hence causing the star to bloat. A better illustration would be to look at Figure 6.2. Now, one more thing to note is that the diagram shows an ideal case, in reality, because of the inhomogeneities in the star, one shell of the star may burn different elements at one time depending on several factors. All the while the star burns different fuel, it grows and shrinks in size and goes back and forth form the main sequence towards the top right side of the HR diagram (the red giant phase). This is where most of the variable stars are located at (however, this uis a debatable concept and is up for discussion). However, once the star starts to form iron in it's core, that is when stuff starts going out of hand (or limb of the star), since we loose energy while fusing iron, the star would no longer be able to push the shells and maintain it's shape, and hence, the star's core would contract (the star doesn't contract as a whole, it's just the core that does), once the core collapses, the amount of photons released causes photo-disintegration of most of the iron present in the core releasing a lot of energy (of the order of $\approx 10^8$ to 10^9 K).

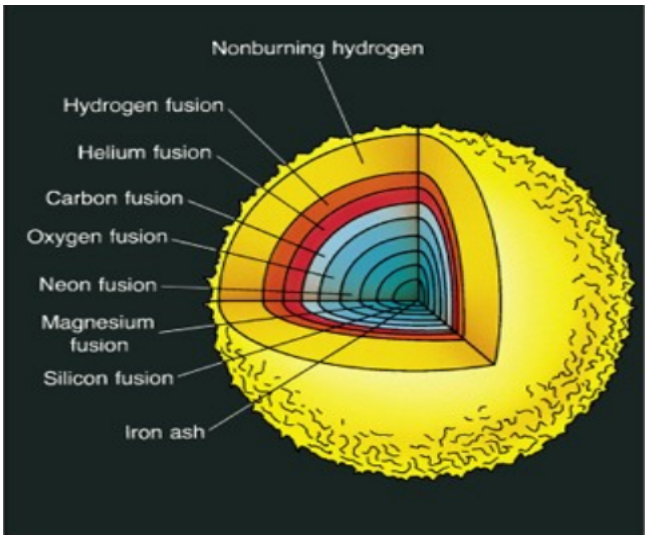


Figure 6.2: Shell structure of high mass stars

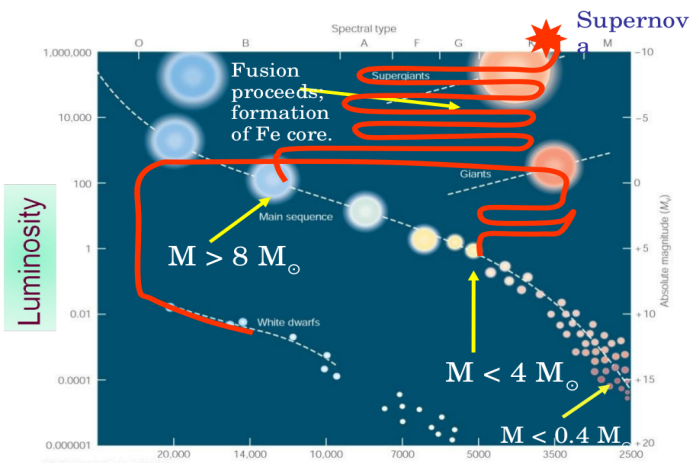


Figure 6.3: Story of evolution of the stars (*instert diagram ref here*)

The pressure during these times is so high that the electron degeneracy pressure can't stop it (if it is enough to halt the collapse, the remaining core forms a dwarf star), nor can the atomic structure can stop it, at this stage the electrons and protons are crushed together to produce neutrons, with a heck load of gamma radiation and neutrinos. This is when the in-falling lighter material gets ejected out (as a rebound to the in-falling heavier element that crashes into the core). This, added to the huge amounts of photons that are released during the photo-dissociation of elements in the core, causes the outer shells of the super giant to expand exponentially. This expansion causes the optical depth of the material to decrease letting the huge quantities of photons, that would otherwise be scattered and absorbed by the inner layers of the star, to be sent out into space, leading to huge flux of photons radiated at all directions. This would explain the huge EM flux radiated from the core during this process, leading to supernovae being few of the brightest events to occur in a galaxy (or maybe even the universe). This is the time when most of the heavy elements (heavier than iron and a few that are lighter) form in the universe and are scattered throughout the galaxy.

Out of this craziness, there are several things that are born, i.e. there are several different phases of the core that is left behind. All these depend primarily on the mass of the star's core during the collapse. The fate that we are interested in is the remnant left behind after the core shrinks (because no fusion = no outward force = gravity rulez!! = shrinks the core), and not just any remnant, but a neutron star. Now, these cores, are primarily made up of neutrons, (*mention NS formation ref.*), however, the outer layers could be made up of iron left over from the core of the star. Because of this core collapse, and because the the star being an isolated body needs to conserve angular momentum, the remnant core spins up to conserve AM(*NS star spin reference enter here*). Now, one thing to note would be that neutron stars are not entirely made up of neutrons, and because of the end stages of the stellar core ending in iron, the neutron star has a thin crust of iron, this and a few other charged particles could be the reason for the magnetic field of the neutron star (*NS B field reference here*).

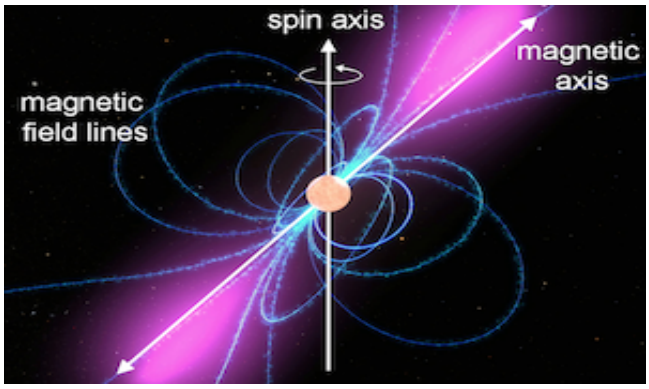


Figure 6.4: Neutron Star diagram (ref. Hayashi-Henny Track)

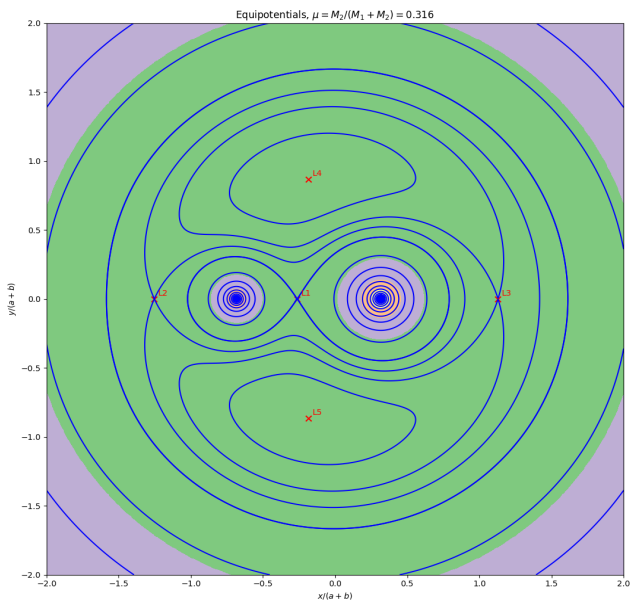


Figure 6.5: Equi-potential surfaces with $\mu = 0.316$

Now when the matter falls into the star, i.e. if there is any star nearby that has a size larger than it's Roche limit, (ref. two body interaction figure 6.5) the extra mass (outside the lobe) spirals into the neutron star. Now, while on it's way towards the star, due to the extreme conditions (velocities, friction, etc.) while the matter falls into the neutron star, it leads to the ionization and hence emission of radiation from the neutron star and the inner regions of the accretion disk, (*Insert accretion disk reference and optical depth reference*), some of this matter that makes it to the surface leads to impart some of it's momentum to the NS causing it to spin up. There are many other things such as nuclear fusion e.t.c. that happen at the surface leading to high energy emissions such as x and gamma rays (*insert NS reference here*), and some of the charged matter that gets influenced by the magnetic fields of the star gets funneled out of the star (in the process, carrying some of the star's angular momentum away *insert NS slowing ref. here*). This funneled matter is what is detected by the radio telescopes and X ray telescopes as pulses (*insert Pulsar astronomy book ref here*), much like a light house.

These are just some of the activities that go on within the neutron star, and the best thing is, there are several activities that I do not yet know about, hence in this project we tried to look at the photon flux and their energies to try and piece together some of the properties of the Neutron star binary.

6.1.2 Neutron star binaries

As mentioned in the above section, we would be studying neutron star binaries. Now it is a well known fact given the abundance of stars in the galaxy, and their formation patterns, most of the stellar systems are either binaries or have more than two stars orbiting each other. Our sun being the oddity.

Now, a neutron star binary is a system where one or more members of the system is a neutron star. These could be any number of combinations, and each of those combinations having their own formation history. Hence it would be good for now if we keep that subject aside just to keep this report short.

However, coming back to the neutron star binaries, and the system of my work, Ultra Compact X-ray Binaries (UCXB). Now, from the huge number of neutron star binaries, there are some systems where the companion star is a star with mass <1 $M_\odot$, i.e. 1 solar mass ($M_\odot$). These systems could have anywhere from white dwarfs and sun like stars as companions. These kind of systems are called Low Mass Xray Binaries. X-ray since when they funnel matter into them they emit mostly in X-rays, which as mentioned above could come from neutron star surface or the inner regions of the accretion disk. Now, one might rightly argue that one can have a similar system with a black hole instead of a neutron star. However such a system would have a vastly different X-ray signature from, say the neutron star, and hence would need a separate discussion on their own, and since the object that we are concerned with in this report is a neutron star system, we would leave out the black hole alternatives to LMXBs and UCXBs.

Now, coming back to the topic. we now know/have a brief idea about what a LMXB system is. Now, as mentioned earlier, these kinds of objects are further divided into different categories, out of those an UCXB is a system where the orbital period of the companion is so less that it completes one orbit around the neutron star in less than an hour. These kind of orbits are such that the companion star, in order to maintain the laws of relativity, would have to be extremely close to the neutron star, and hence, in most cases, the star would have matter outside it's Roche limit, and hence we would definitely see some kind of high energy emission, based again on the system.

6.2 1A 1246-588

6.2.1 What we know

As mentioned above, 1A 1246-588 falls under the UCXB category. Now, one might ask how. Now because of the Roche lobe overflow, the mass of the companion star is low, and hence the companion star is faint in optical, however, because this matter is funneled into the neutron star, these systems glow very brightly in X rays, which is correlated to the size of Roche lobe (since the X ray flux would be a function of how much matter is falling into the NS, and hence would be related to the mass of the companion star and it's luminosity, and to a certain degree its composition). Hence by observing the structure of the spectrum and the x ray timing analysis of the source and the color color diagram (CD), one can see that it (1A 1246 588) is a LMXB. (I haven't mentioned the proof since that would make the report even longer that it already is.)

Now, there are two kinds of Neutron Star LMXB sources, i.e. the Z and the Atoll sources (Hasinger & van der Klis 1989). These sources have a characteristic color diagram (CD) and hence by comparing the hard (high energy > 10 keV) and the soft (low energy < 10 keV) luminosities one can classify between them. Now, using the color color diagram, it was observed that 1A 1246-588 falls under the atoll sources (supported by the narrative of atoll sources that they have low luminosity) (*find the ref*)

Now, apart from the fact that it is a candidate UCXB, we also know that this is one of the faintest UCXBs, with an absolute magnitude of M_V=3.4 – 4.0 (Jonker et.al. 2006), i.e. absolute magnitude of the optical counterpart of 1A 1246-588. This also suggests (van Paradijs & McClintock 1994) that these systems are UCXBs, since here the faintness of the counterpart is due to the re-procession of the X-rays in a physically small accretion disk.

This preposition is further supported by the fact that optical spectroscopic data does not show features from hydrogen (Zand et al. 2008) which is in support of the UCXB proposition (by Bassa et al. 2006). The same paper (Zand et al. 2008) also notes that since there are no persistent dips (eclipses) in the X-ray flux implying that the inclination angle is at most 70° (Horne 1985). The correlation factor which is used to derive the accretion flux (as mentioned, periodic dips in the X ray luminosity due to eclipsing caused by the companion star), from the observed flux, is at most 3 (=1/cos70^o). Combining both uncertainties, the ratio between the persistent flux and the Eddington limit is accurate to within a factor of 4. This being a constraint measurement since it is significantly below the 2% mark, a regime in which a source is said to be UCXB. This further confirms that 1A 1246-588 is an UCXB (t'Zant et al. 2007).

This is qualitatively explained by the smaller accretion disks in UCXB needing a smaller irradiation flux to remain in a hot high viscosity state, that sustains accretion into compact object (van Paradijs 1996). For a much more detailed reference, refer the paper by 't Zand et al. 2008.

Now, we also know that this object has a Kilohertz QPO at 1258 KhZ, with a single trial significance of more than 7 σ(Jonker et al. 2007) in the soft high flux state. However this was not observed in our data, more to that later. The same paper also confirmed, using spectral properties that the object is an atoll source. This paper also reports the mass limits of the neutron star is at $M_{NS} < 1.75 M_{sol}$ and R < 15.5 kilometers. The same paper also reported that during the low-flux stage, it's spectrum resembles that of the crab.

These along with several other points were to be, first, verified and then built upon.

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