X-Ray Spectroscopy

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Abstract

X-ray spectroscopy involves examining energy spectra from astrophysical sources and attributing various regions of the spectra to different physical processes within the source. In general, this involves creating theoretical models of the physical processes within such sources and the resulting emission. We can then convolve our theoretical spectra with the response function of the X-ray telescope used in order to try to minimise the difference between our modelled and observed spectra. Once such minimisation has been achieved, we have a feasible physical model to understand the source being observed. In this report, we present the method used to find spectral fits for two different sets of energy spectra. Of these, one was an observation of the Crab pulsar with the LAXPC instrument of the satellite AstroSat, and the other is simulated data.

1 Theoretical Background

X-ray astronomy encompasses imaging, spectroscopy, and timing. An X-ray observatory can have any or all of these functions. In general, X-ray observatories are space-based due to the atmospheric absorption of high-energy radiation. The Large Area X-Ray Proportional Counter (LAXPC) aboard the Indian satellite AstroSat is a gas detector used for spectroscopic and timing applications. There are 3 LAXPC units aboard the satellite. A gas detector consists of a chamber filled with gas such that an incident X-ray photon causes a cascade of electrons through the gas which can be detected by electrodes in the chamber. In the case of the LAXPC, there are five detection layers within the gas chamber.

Since these detectors are generally placed in space-based observatories, they are inundated by cosmic rays which are high energy charged particles and can thus initiate the same cascade of electrons as the signal of interest. The photons of interest will always enter the gas from the pointing side of the detector. Thus, in order to discount all detections due to cosmic ray illumination, LAXPC has detectors lined along the other three sides of the gas detector outside the main detection volume. These additional detectors are known as 'veto' detectors. Charged particles that enter the photon detection volume will always escape the gas chamber after exciting the gas. When they leave the volume, they will also be detected by these additional detectors. Now, if we discount

all events which occur simultaneously in the main volume and the veto detectors, we will remove all effects of cosmic rays.

Now, since detection relies on the gas being ionised, we need the gas to be in its 'active' state in order to detect incoming photons. However, after a certain number of incident photons, all the gas in the chamber will be ionised. This will prevent the next detection until the gas returns to its active state. The amount of time taken for the detector to recover from a detection and be ready for the next detection is known as 'dead time'. Corrections for dead time must be applied offline during analysis. The higher the frequency of variation in the observed signal, the larger is the required dead time correction. Since it is often the charged particle incidence rate and not variation in the signal that produces dead time effects, we need to characterise both in order to compute the dead time correction. A *background file* is used to characterise the background over which the signal is recorded.

The voltage recorded by the anode in the detector is stored digitally. This digital value is known as a 'channel number'. The recorded data contains the time, channel number and anode layer ID for each event. This data can also include a rough estimate of the energy corresponding to each channel. All of this data is contained within an *event file*. From the event file, we can make a file which contains count rate and channel number, known as the *pulse height analyser* (.pha) file.

Since each incoming photon creates a cascade of electrons, there is a probabilistic relationship between the energy of the photon and the voltage generated at the detector. For any given detector, we can characterise this probability distribution. This relationship is represented as a matrix and stored in a *response matrix file* (.rmf).

Once we obtain the energy spectrum from the recorded data, we want to characterise the physical processes which can produce the observed spectrum. To do so, we first create a model of the source spectrum and then use the known response of the detector to model our observation. We start with the physical model (intensity vs energy plot) expected from the source, then we convolve it with the response matrix and compute the difference between this convolved spectrum and the observed spectrum. We iteratively modify the parameters of the physical model to minimise the residuals in order to obtain our final best-fitting model. This model is known as the 'folded model'. This procedure is executed on the HEASOFT module XSpec which contains predefined models for various physical processes which can contribute to the energy spectrum of an X-ray source.

XSpec contains two main classes of models, additive and multiplicative, on the basis of how they combine with other models. While XSpec contains a very large range of physical models, we have limited ourselves to a small set of models for the purpose of this report. These models have been described below.

Model	Function
powerlaw	simple photon power law
cutoffpl	powerlaw with exponential decay at cutoff energy
bknpower	two powerlaws with different slopes; change at break energy
bbody	simple blackbody spectrum (single temperature)
diskbb	blackbody spectrum due to accretion disk (temperature gradient)
mekal	brehmsstrahlung and recombination radiation
gaussian	gaussian emission line profile

Table 1: Additive XSpec models used in this report.

Model	Function
phabs	photoelectric absorption
gabs	gaussian absorption line

Table 2: Multiplicative XSpec models used in this report.

2 Data and Software Used

The first set of data used for this analysis was obtained using the Large Area X-ray Proportional Counter (LAXPC) instrument aboard the Indian satellite AstroSat. The data include an observation of the Crab pulsar obtained in 2016. The pulse height analyser, background, and response files were provided to us. The spectral data is contained within the file *spectrum_grp10_10.pha*, while the background and response files are *backlxp10.pha, lx10cshp13v1.0.rmf*, respectively.

The second set of data used here contains simulated observations modelling an unknown set of physical processes. The simulated data used here was *Spectrum 4* data. Once again, the pulse height analyser, background, and response files were provided to us. The spectral data is contained within the file *lx10_spec4_grp_10.pha*, while the background and response files are *lx10bkg.pha, lx10cshp13v1.0.rmf*, respectively.

Spectral model fitting for both sets of data was performed using the HEASOFT package XSpec. Specifically, the models listed in Tables 1, 2 were used to find the best fit to the provided spectra.

3 Analysis

We launch heasoft using the command `heainit` and then launch xspec using the command `xspec`. We can open a plotting window with the command `cpd /xw`.

3.1 Crab Pulsar Spectrum

We can load the data to be used with the command `data spectrum_grp10_10.pha`. This should then print out details about the loaded data file including the filenames for the background and rmf files to be used. In case these need to be edited, this can be done with the commands `background file_name.pha` and `response file_name.rmf`.

Now, we can plot the data using `plot data`, or plot it on a log scale using `plot ldata`. This shows us a plot of counts against channel number as shown in Figure (1) below.

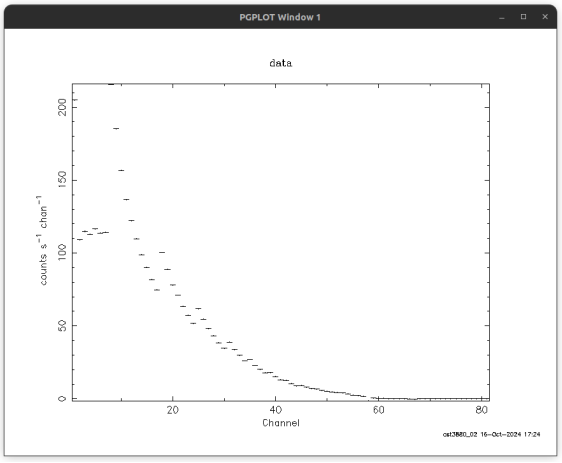

Figure 1: Linear plot of channel number against counts s^{-1} $chan^{-1}$.

To obtain a plot of energies, we can use the command `setplot energy`. We can now obtain an energy plot using the same plotting commands.

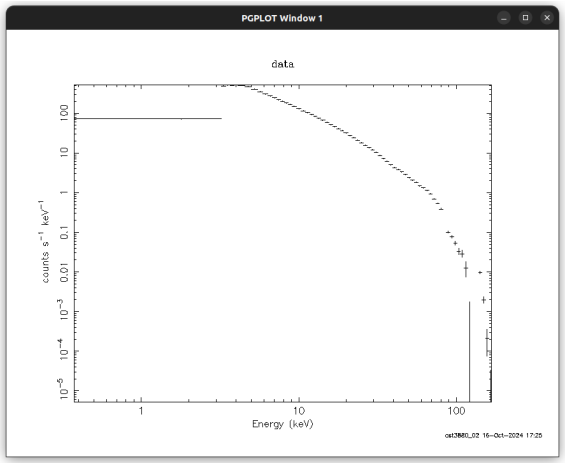

Figure 2: Energy spectrum plotted on a log scale.

LAXPC best records data in the middle energy bands. We can thus ignore the data in the initial and final bins by running the command `ignore **-5.0, 70.0-**`, which ignores counts for energies below 5 keV and above 70 keV.

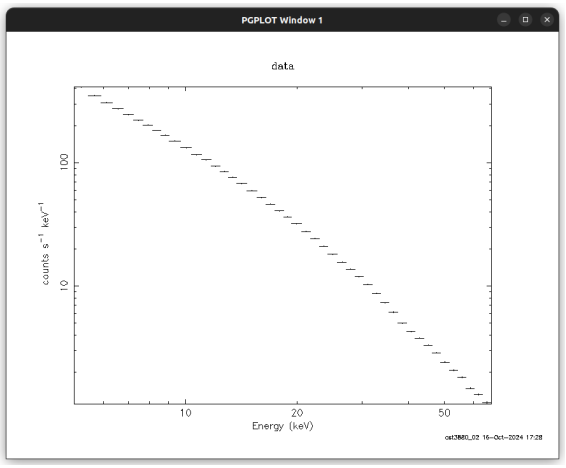

Figure 3: Energy spectrum plotted on a log scale with the very low and high energy bins ignored.

Now, in order to find the physical model which best describes this spectrum, we can use the `model` and `fit` tasks. There are many possible models to be used while performing a spectral fit with xspec, and we can create different combinations of these models to find the best description of the data.

We know that this spectrum describes the Crab pulsar, and thus is not thermal radiation. Since we want to describe non-thermal radiation, a power-law spectrum is a good initial guess. In this case, such a spectrum can describe synchrotraon radiation. We can begin by trying to fit a powerlaw spectrum by running the command `model powerlaw` after which xspec prompts us to define estimates for the model parameters. In this case, the model parameters are *PhoIndex* and *norm* for which we pick estimates 2.0, 9.0, respectively. Now, we can run the `fit` command to find the best-fitting values of these parameters for our data. Xspec computes the spectrum expected from a source given the model we have just defined, and then tries to minimise the difference between the model and observed spectra by adjusting the model parameters. This allows it to define the best fitting parameters.

We use the command `fit 100` to run 100 iterations of model fitting. Xspec gives us a chi-squared value for each fit- for a good fit, we expect that this value is roughly equal to the number of spectral bins used for fitting. We can use this value to estimate the goodness of the fit. To plot the observed data, folded model, and the fitting residuals together, we run `plot ldata delchi`. Here, the 'folded model' is the theoretical model convolved with the response of the detector to show the observations that we would expect for the chosen model.

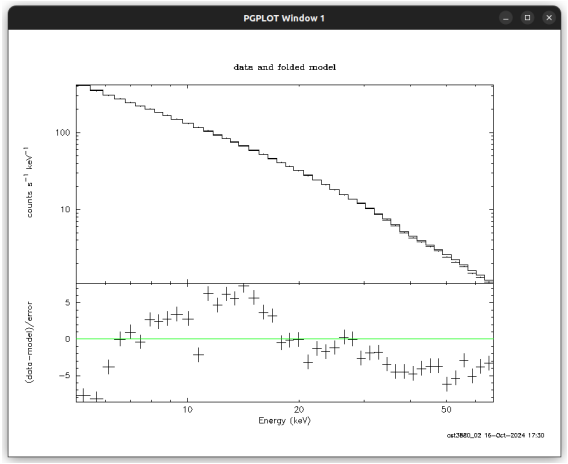

Figure 4: The observed and model energy spectrum along with the residuals for the fit.

The chi-squared value for this fit was ~ 705 using 45 bins. Evidently, the power law model alone does not describe the provided data very well. In order get a more faithful description of the observed data, we need to introduce other models into our fit.

A strong candidate for the other model to use is *phabs*. This model describes the deviations that can occur in a power spectrum due to the medium through which the signal travels to us. The intervening ISM can lead to some absorption and thus can modify the observed spectrum. This is modelled by phabs which takes in two parameters- N_H which is the column density of the Hydrogen in the intervening ISM.

We try fitting with the phabs and powerlaw models combined. We retain the same initial guesses for power law parameters as before (PhoIndex 2.0, norm 9.0), and use nH 3.0 for phabs. The folded model thus obtained has been shown in the fig-

ure below. The chi-squared value for this fit was ~ 275 using 45 bins.

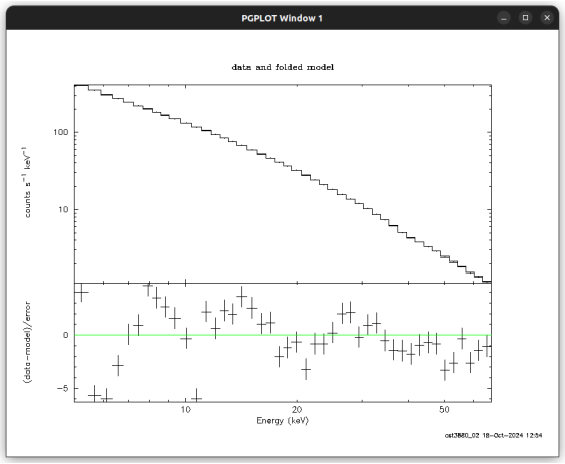

Figure 5: The observed and model (phabs*powerlaw) energy spectrum along with the residuals for the fit.

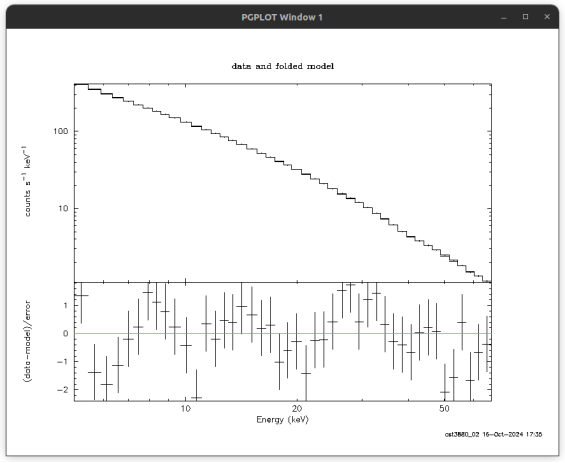

Figure 6: The observed and final model (phabs*powerlaw with systematic=0.007) energy spectrum along with the residuals for the fit.

While the folded model looks like it describes the observation well, we still have a very high chi-squared value. This is likely due to systematic errors in the observation (such as errors in the response matrix or background files). We can correct for these using the parameter `systematic` on XSpec. Through trial and error, we find that a systematic error value of 0.007 describes the observations well. Upon using this (run `systematic 0.007`), we find a chi-squared value of 43.91 using 45 bins. This fit has been shown in Figure 6. This is a good value, and indicates that we have found a good fit. The converged values for the final parameters along with the fit statistics have been shown in Figure 7 below, and reported in full in Section 4. The use of the systematic error parameter has been discussed in Section 5.

```
========================================================================
Model phabs<1>*powerlaw<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   phabs      nH         10^22    3.24096      +/-  0.314306
   2    2   powerlaw   PhoIndex            2.13403      +/-  4.49057E-03
   3    2   powerlaw   norm                9.22457      +/-  0.136510
------------------------------------------------------------------------

Fit statistic  : Chi-Squared                   43.91     using 45 bins.

Test statistic : Chi-Squared                   43.91     using 45 bins.
```

Figure 7: The converged parameter values and fit statistics given by XSpec for the final fit.

3.2 Simulated Energy Spectrum

The simulated spectrum used here was **spectrum 4**. Fitting involves the very same steps as with the case above. The spectrum provided to us has been plotted below.

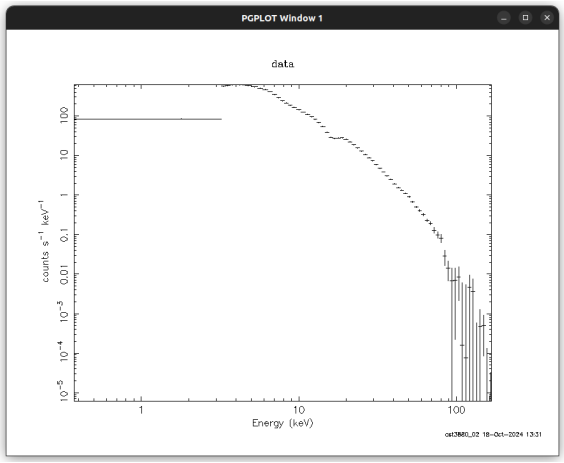

Figure 8: The provided energy spectrum plotted on a log scale.

Upon trying a power-law model (with initial guess parameters PhoIndex 2.0, norm 5.0), we find that it describes the model well upto ~ 12 keV point beyond which it decays faster than the power law.

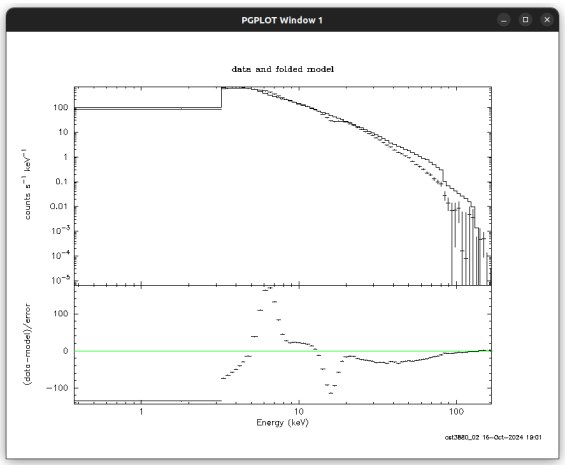

Figure 9: The observed and model (powerlaw) energy spectrum along with the residuals for the fit.

The trial power law fit has a chi-squared value of $\sim 1.8 \times 10^5$ for 81 bins. Clearly, this is not the correct model to describe this system. Given that this data seems to have power law behaviour initially and then fast decay, we next try modelling it with a cutoff powerlaw. We use the command `model cutoffpl`, and enter parameters as PhoIndex=2.0, HighECut=12.0, norm=5.0.

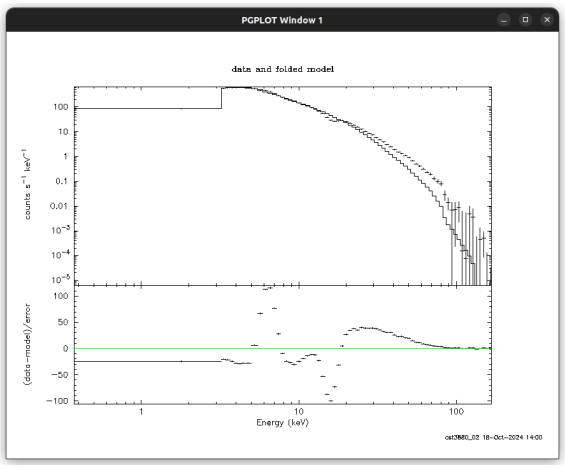

Figure 10: The observed and model (cutoffpl) energy spectrum along with the residuals for the fit.

The chi-squared value is now found to be $\sim 9.3 \times 10^4$. From the shape of the resiudals, it looks as if a Gaussian emission line (around 8 keV) and Gaussian absorption (around 12 keV) is needed to improve the fit. This can be achieved by the XSpec models *gaussian, gabs*, respectively. We can run `model gabs*(cutoffpl+gaussian)` retaining the previous parameters (cutoffpl: PhoIndex=2.0, HighECut=12.0, norm=5.0), and using gaussian: LineE=8.0, Sigma=1.0, norm=5.0; gabs: LineE=12.0, Sigma=1.0, Strength=3.0. This fit has been shown in Figure 11.

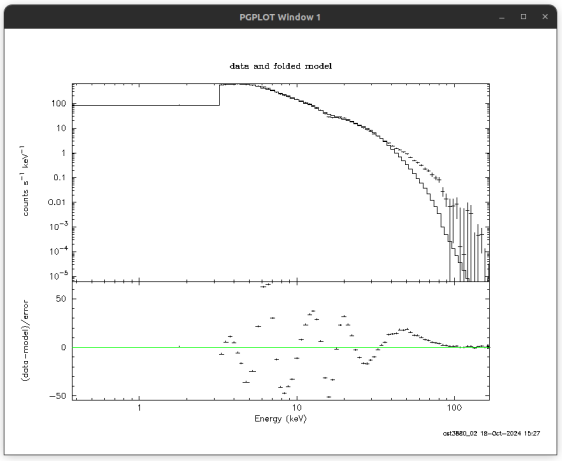

Figure 11: The observed and model [gabs*(cutoffpl+gaussian)] energy spectrum along with the residuals for the fit.

We find that the chi-squared value for this fit is $\sim 33,000$ with 81 bins. Now, the higher energy part of the folded spectrum appears to be decaying too quickly. We need some overall increase to slow the fall. Through trial and error, we find that this is well described by adding the *diskbb* model with initial guess parameters Tin=10.0, norm=1.0. Iterating to find the best fit, we get a chi-squared value of 78.48 using 81 bins (fit shown in Figure 12). This appears to be a good fit, and the values presented in Figure 13 are taken to be our final model for this spectrum. These have been reported in full in Section 4.

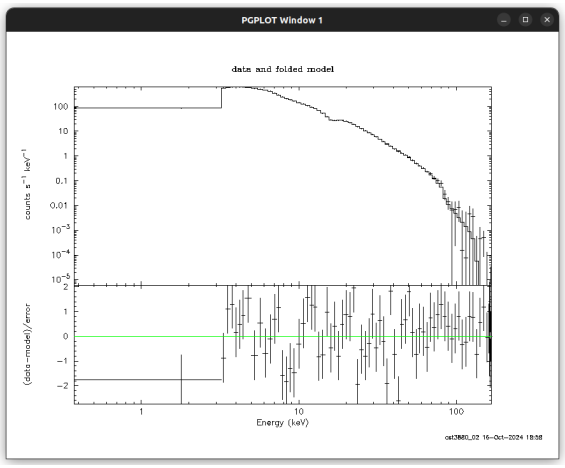

Figure 12: The observed and final folded model [gabs*(cutoffpl+gaussian+diskbb)] energy spectrum along with the residuals for the fit.

```
========================================================================
Model gabs<1>(cutoffpl<2> + gaussian<3> + diskbb<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   gabs       LineE      keV      16.0094      +/-  1.19090E-02
   2    1   gabs       Sigma      keV      0.977217     +/-  1.75756E-02
   3    1   gabs       Strength              1.96347     +/-  1.77227E-02
   4    2   cutoffpl   PhoIndex              1.83984     +/-  1.58903E-02
   5    2   cutoffpl   HighECut   keV      13.6534      +/-  0.848493
   6    2   cutoffpl   norm                  8.81197     +/-  7.07338E-02
   7    3   gaussian   LineE      keV      6.38319      +/-  4.72787E-03
   8    3   gaussian   Sigma      keV      0.506064     +/-  8.82856E-03
   9    3   gaussian   norm                  9.99236E-02 +/-  1.06295E-03
  10    4   diskbb     Tin        keV      12.5691      +/-  0.339850
  11    4   diskbb     norm                  1.22217E-02 +/-  2.30487E-03
------------------------------------------------------------------------

Fit statistic  : Chi-Squared                78.48     using 81 bins.
```

Figure 13: The converged parameter values and fit statistics given by XSpec for the final fit.

4 Results

We found that the Crab pular spectrum provided was best described by a combination of a powerlaw spectrum and photoelectric absorption. We also found that the simulated spectrum 'spectrum 4' provided was best described by a combination of a cutoff powerlaw spectrum, gaussian absorption, gaussian emission line, and disk blackbody emission. The best fit parameters have been summarized in Tables 3,4 below.

Model	Parameter	Value	Error	Unit
phabs	nH	3.20496	0.314306	10^{22}
powerlaw	PhoIndex	2.13403	4.49057×10^{-3}	
powerlaw	norm	9.22457	0.136510	

Table 3: Final parameters for the best fitting model (phabs*powerlaw) describing the energy spectrum of the Crab pulsar.

Model	Parameter	Value	Error	Unit
gabs	LineE	16.0094	1.1909×10^{-2}	keV
gabs	Sigma	0.977217	1.75756×10^{-2}	keV
gabs	Strength	1.96347	1.77227×10^{-2}	keV
cutoffpl	PhoIndex	1.83984	1.58903×10^{-2}	
cutoffpl	HighECut	13.6534	0.848493	keV
cutoffpl	norm	8.81197	7.07338×10^{-2}	
gaussian	LineE	6.38319	4.72787×10^{-3}	keV
gaussian	Sigma	0.506064	8.82856×10^{-3}	keV
gaussian	norm	9.99236×10^{-2}	1.06295×10^{-3}	
diskbb	Tin	12.5691	0.339850	keV
diskbb	norm	1.22217×10^{-2}	2.30487×10^{-3}	

Table 4: Final parameters for the best fitting model gabs*(cutoffpl+gaussian+diskbb) describing the energy spectrum of the Crab pulsar.

5 Discussion

In fitting the spectrum of the Crab pulsar, we made use of a systematic error of 0.007. In general, we need to exhibit some care about modifying such parameters. It is often possible to fit any model by drastically changing such parameters. Ideally, we should only use systematic noise where required by an observatory and only use values provided by them, or otherwise obtained through estimates of the true instrumental errors. Here, we have simply used trial and error to find a value of systematic error which leads to a good fit for our preferred physical model. This is because we know *a priori* the nature of the source (Crab pulsar) and thus know that its spectrum should be well described by a powerlaw as well as photoelectric absorption (phabs*powerlaw on XSpec). Hence, when we found a large value of chi-squared for this model, we could conclude that the disagreement between the observation and the folded model must be due to instrumental errors. The model that was found to best describe our simulated model was a combination of cutoff power law, disk blackbody, gaussian emission and gaussian absorption. A cutoff powerlaw describes a system with optically thin comptonization, while disk blackbody describes blackbody emission due to am accretion disk which has a temperature gradient (colder at the edges, and hotter near the center). Thus, the simulated spectrum describes a system with an accretion disk and an optically thin comptonizing medium.

6 References

1. XSpec User Manual version 12.8.1 by Arnaud, Dorman, Gordon. NASA HEASARC, 2013.