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SC20B152
DUAL DEGREE 2020 BATCH

X-Ray Data Analysis Lab Report

The software used in this lab was **Heasoft** which is used for analysis of high energy astrophysical objects. Specifically, we have used xspec over here which dives into the x-ray spectrum analysis of various sources.

The source which we used for our lab is: **MAXI J1820+070**, which is a black hole X-ray binary.

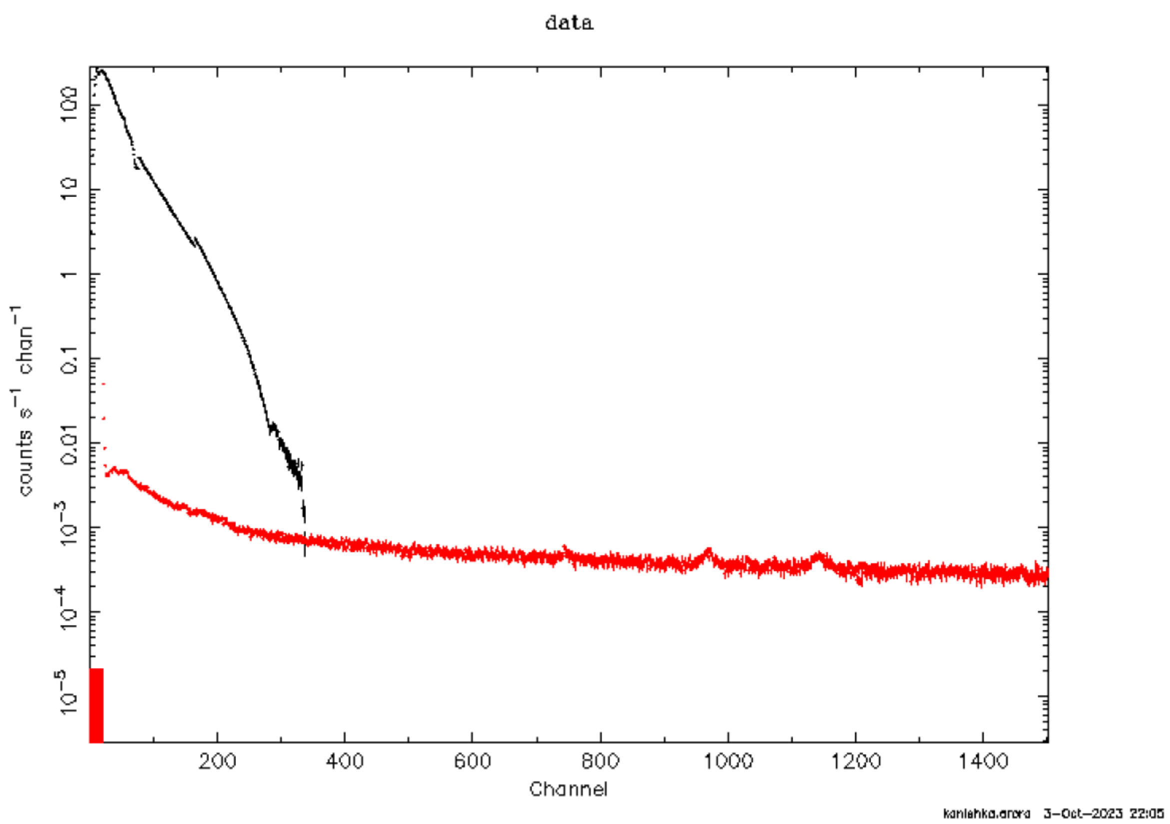
The X-Ray payload onboard the **ISS** (International Space Station) is **NICER** (Neutron Star Interior Composition Explorer Mission) which was launched aboard using the SpaceX Falcon 9 rocket on June 3, 2017.

Task 2:

Plot and save both the source and background spectrum vs channel number in a single plot.

I have loaded the source spectrum and background spectrum on the same plot along with the response files.

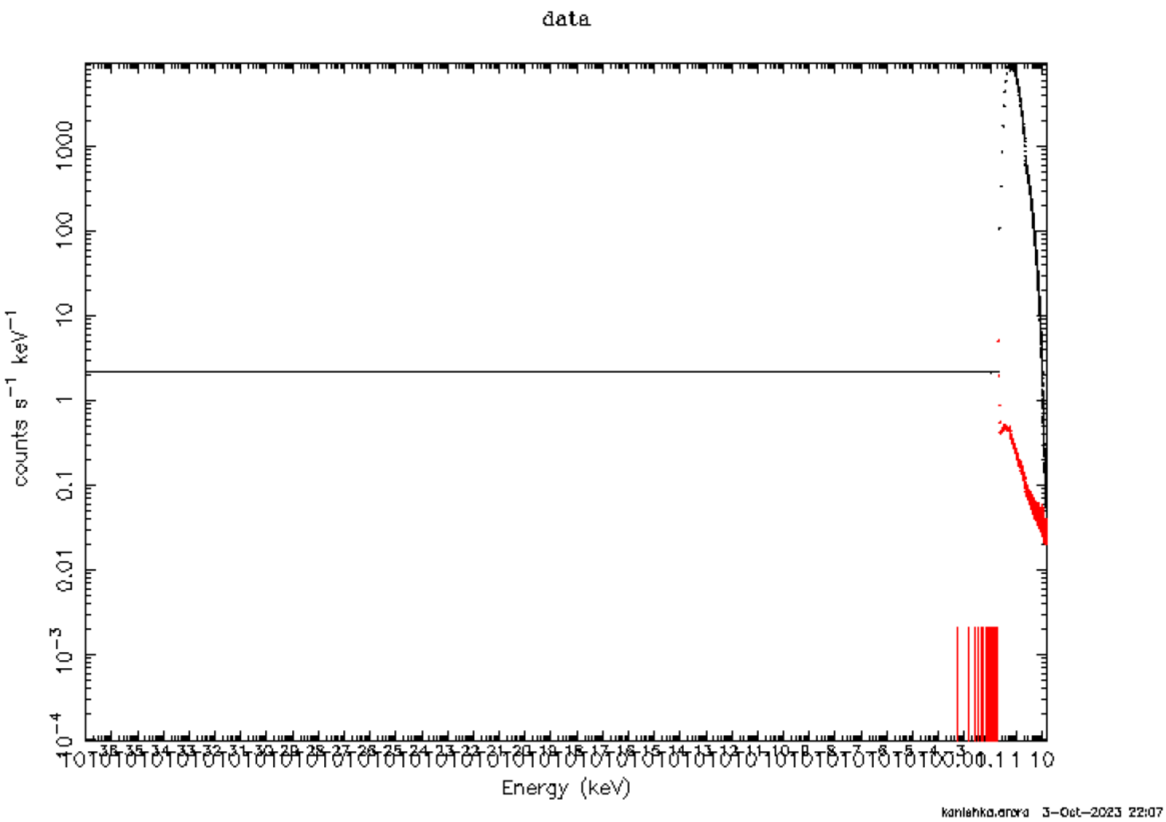
Here is the plot I obtained for number of counts vs channel number.



Task 3:

Plot and save both the source and background spectrum vs energy in a single plot. Justify the energy range which contains good data.

This is the plot that I obtain after I converted channel to energy.
This can be done using the **xspec>setplot energy** command on xspec.



The energy range for which I would choose to obtain good data from the spectrum is **0.1 – 10 keV** and that can be seen if you closely view the plot.
XSPEC12>ignore **-X Y-**

Task 4:

Plot and save both the source and background spectrum vs energy in a single plot up to the acceptable energy range.

As mentioned before the acceptable energy range is **0.1 – 10 keV**.

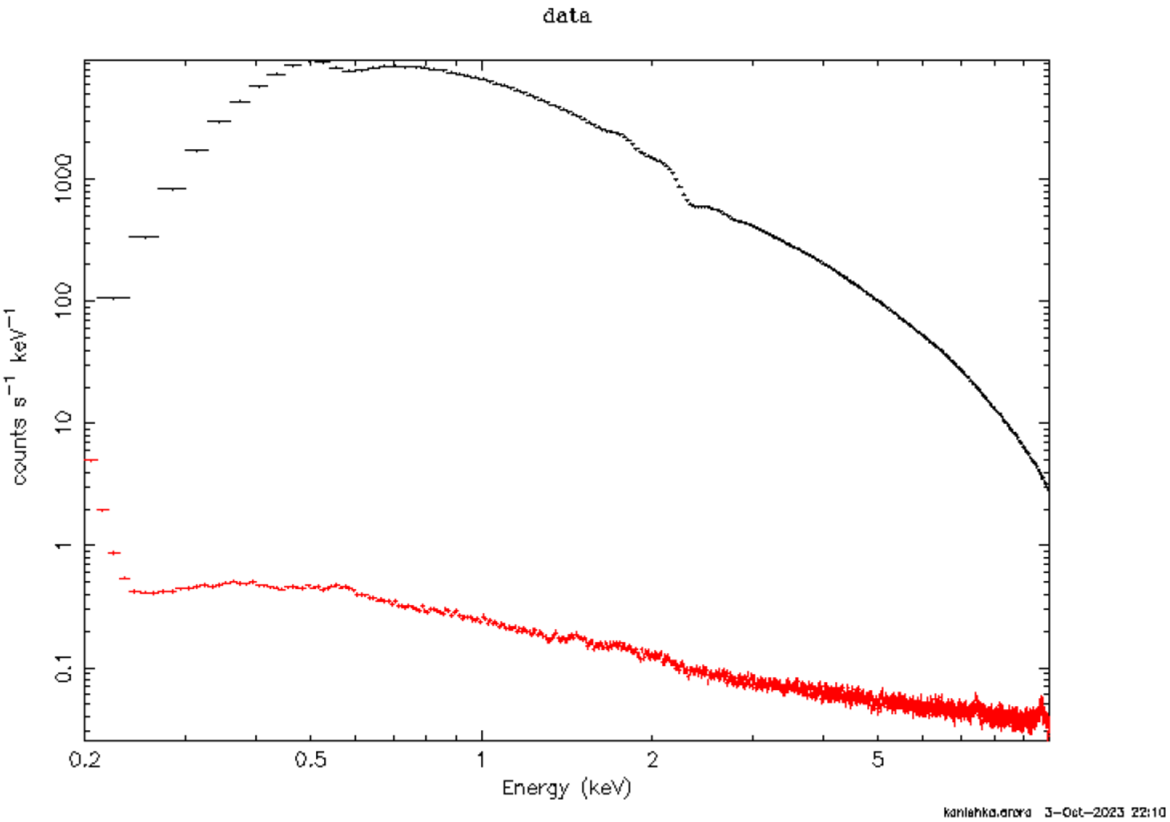
This range can be given as input into xspec using the following command.

XSPEC12>ignore **-X Y-**
(Where X and Y are integers with decimal points included)

Hence in this case we write,

XSPEC12>ignore **-0.1 10.0-**

This the plot that I obtained in the end. We can see that it is much better looking than the previous one.



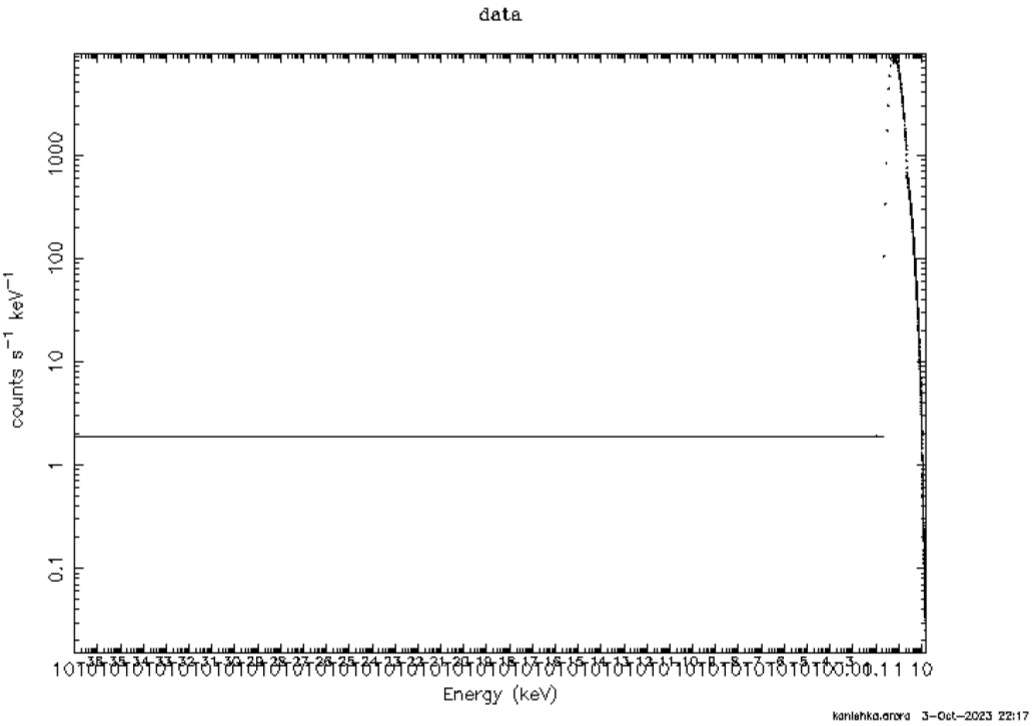
Plot and save the background subtracted source spectrum vs Energy (keV).

<u>Task 5</u>:

Plot and save the background subtracted source spectrum vs Energy (keV).

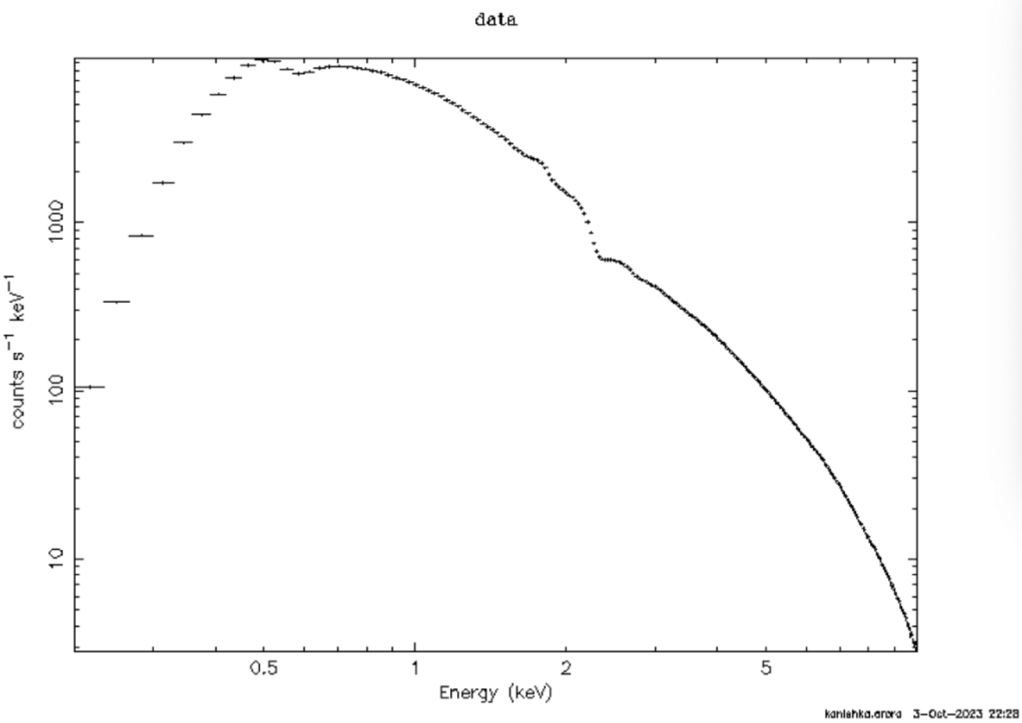
In this case we have to load the background file into xspec. This can be done in the following way.

XSPEC12>back nibackgen3C50_bkg.pi
(*using a sample file name here***)**



This is the plot that we get after loading the background file. As we can see we need to ignore some portion of the spectrum like we did in Task – 4.

Upon doing that we get the following. As we can see it is much better looking than the previous plot.



This can be achieved through the following command(as mentioned before)

XSPEC12>ignore **-0.1 10.0-**

Understanding the data: Model fitting

This is the most interesting feature and probably the most useful as well. This the part where we will try to model the spectrum we obtained from the source using various models stored in xspec by default.

We have many types of models such as **tbabs**, **diskbb**, **gauss**, **powerlaw**, zxipcf etc each having its own use.

One can even obtain information on a specific model in xspec. You simply have to type the command.

XSPEC12>help model *model name*
XSPEC12> help model tbabs (check details of absorption model)
XSPEC12> help model diskbb (check details of multicolour black-body model)
XSPEC12> help model powerlaw (check details of powerlaw model)

To apply a certain model to a spectrum one can simply type the command.

XSPEC12>model powerlaw

After this it will ask you a bunch of values which you have to input. These are nothing but parameters of the model. Every model has a certain number of parameters and the number of parameters depend on the type of model.

```
XSPEC12>model powerlaw

Input parameter value, delta, min, bot, top, and max values for ...
             1       0.01(      0.01)        -3         -2          9         10
1:powerlaw:PhoIndex>
             1       0.01(      0.01)         0          0      1e+20      1e+24
2:powerlaw:norm>
```

By pressing enter key on your keyboard the parameter will take its default value.

Then what will appear is a table which shows all the parameter values which we have given(in this case the default value). This I show the table should look like in your terminal window.

```
========================================================================
Model powerlaw<1> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   powerlaw   PhoIndex            1.00000      +/-  0.0
   2    1   powerlaw   norm                1.00000      +/-  0.0
________________________________________________________________________

Fit statistic  : Chi-Squared                260733.7     using 243 bins.

Test statistic : Chi-Squared                260733.7     using 243 bins.
 Null hypothesis probability of 0.0e+00 with 241 degrees of freedom
 Current data and model not fit yet.
```

Over here the degree of freedom is **241**.

The reduced chi-squared value is 1072.978

More the chi squared value is close to 1, the better the fit you obtain. This is obviously along with the fact that the parameter values that you get at the end of the fit are reasonable. The fitting has to be done in an optimised way such that there is a good balance between the parameter values and the reduced chi squared value.

We can also see that it says "**Current data and model not fit yet**"

This is where we use the fit command.

XSPEC12>>fit

Xspec will take this command and begin the fitting process. Since over here we have only one model in use, it will take little time. But in case of more number of models, fitting can be tedious.

This is what we obtain after the fit command.

```
========================================================================
Model powerlaw<1> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   powerlaw   PhoIndex            0.940994     +/-  1.11803E-03
   2    1   powerlaw   norm                0.782070     +/-  1.55533E-03
________________________________________________________________________


Fit statistic  : Chi-Squared                232689.0     using 243 bins.

Test statistic : Chi-Squared                232689.0     using 243 bins.
 Null hypothesis probability of 0.0e+00 with 241 degrees of freedom
```

Over here the degree of freedom is **241**

The chi-squared value is **965.51**

<u>Task 7</u>:

What is chi-squared value? Calculate the degrees of freedom (DOF). Note the Reduced chi-squared value. Are you Happy with the fitting?

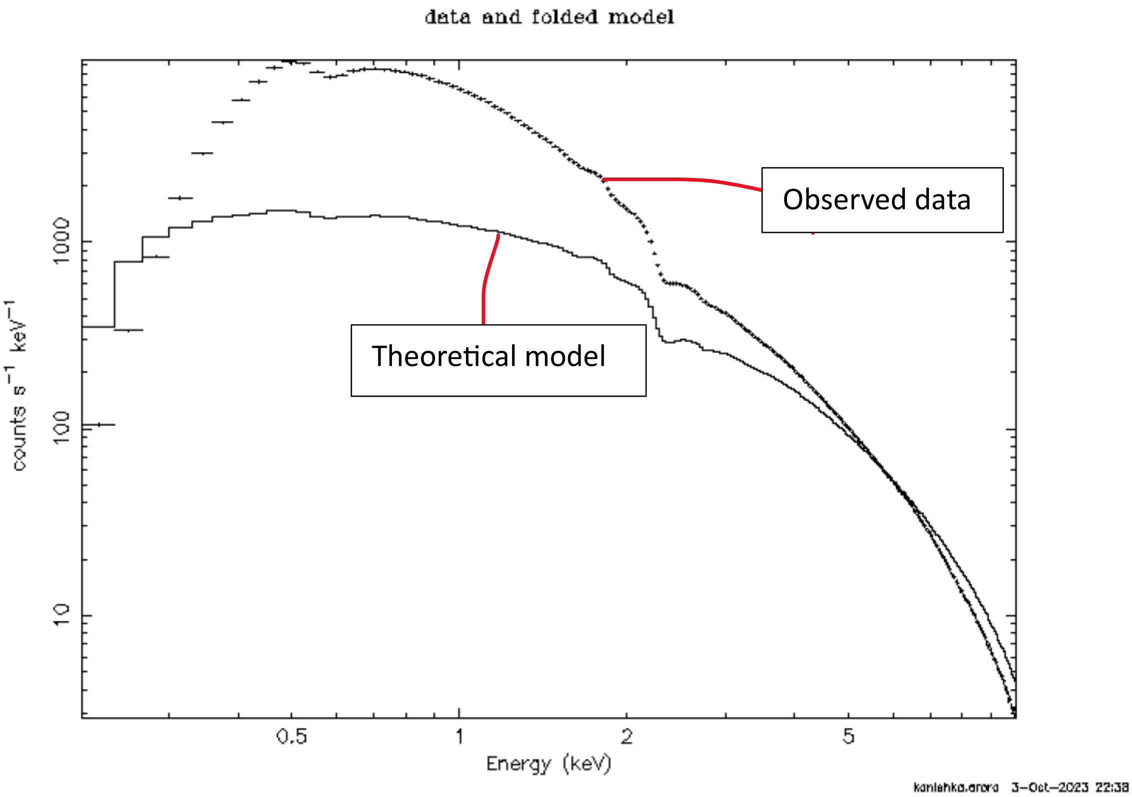
Chi-squared value is a statistical measure used to evaluate the goodness of fit between a theoretical a theoretical mode and the observed data.

The number of degrees of freedom is **241**

The reduced chi squared value is **965.51**

No I am not happy with the fit because the chi squared value is much larger than 1. For a good fit, the value should be as close to 1 as possible.

This is the plot that we obtained in the end. We can clearly see that the model and the observed data are nor matching.



Task 8:

Try with other models "tbabs*powerlaw", "tbabs*diskbb", "tbabs*(diskbb+powerlaw)" and note the chi-squared value, DOF and reduced chi-squared value in each case.

1. Tbabs*powerlaw:

   Again we assume default values for input.

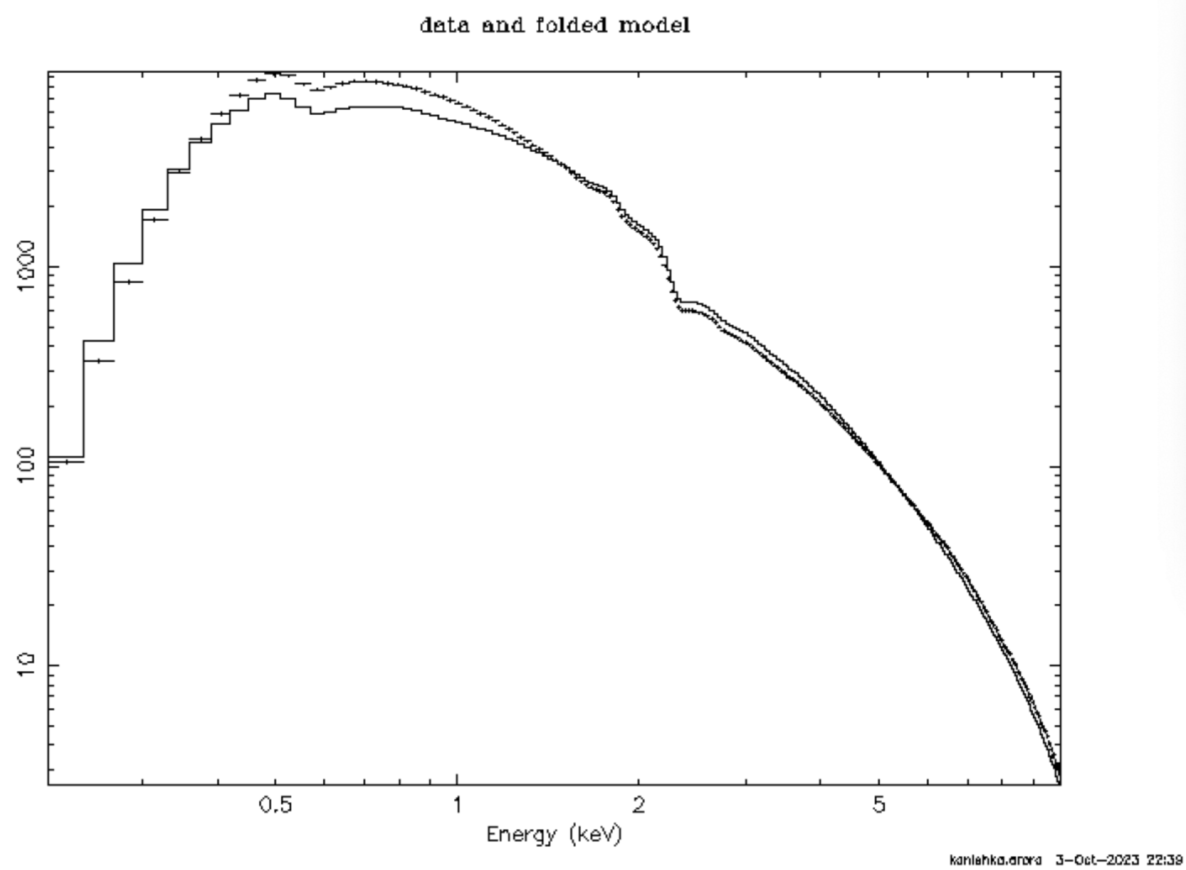
```
XSPEC12>model tbabs*powerlaw

Input parameter value, delta, min, bot, top, and max values for ...
             1      0.001(      0.01)         0          0     100000      1e+06
1:TBabs:nH>
             1       0.01(      0.01)        -3         -2          9         10
2:powerlaw:PhoIndex>
             1       0.01(      0.01)         0          0      1e+20      1e+24
3:powerlaw:norm>

========================================================================
Model TBabs<1>*powerlaw<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    1.00000      +/-  0.0
   2    2   powerlaw   PhoIndex            1.00000      +/-  0.0
   3    2   powerlaw   norm                1.00000      +/-  0.0
________________________________________________________________________
```

After the running the fit command we get the following.

```
========================================================================
Model TBabs<1>*powerlaw<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.102376     +/-  3.25954E-04
   2    2   powerlaw   PhoIndex            1.93626      +/-  1.81397E-03
   3    2   powerlaw   norm                4.38594      +/-  1.13535E-02
________________________________________________________________________


Fit statistic  : Chi-Squared                11898.72     using 243 bins.

Test statistic : Chi-Squared                11898.72     using 243 bins.
 Null hypothesis probability of 0.00e+00 with 240 degrees of freedom
```

The reduced chi-squared value in this case is **49.575**

This is the plot that we obtain.



We can observe that the it is a better fit than in the previous task.

2. <u>Tbabs*diskbb</u>:
   Again we assume default values for input.

```
XSPEC12>model tbabs*diskbb

Input parameter value, delta, min, bot, top, and max values for ...
              1      0.001(      0.01)         0          0     100000      1e+06
1:TBabs:nH>
              1       0.01(      0.01)         0          0       1000       1000
2:diskbb:Tin>
              1       0.01(      0.01)         0          0      1e+20      1e+24
3:diskbb:norm>

========================================================================
Model TBabs<1>*diskbb<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    1.00000      +/-  0.0
   2    2   diskbb     Tin        keV      1.00000      +/-  0.0
   3    2   diskbb     norm                1.00000      +/-  0.0
________________________________________________________________________


Fit statistic  : Chi-Squared                938760.1     using 243 bins.

Test statistic : Chi-Squared                938760.1     using 243 bins.
 Null hypothesis probability of 0.0e+00 with 240 degrees of freedom
```

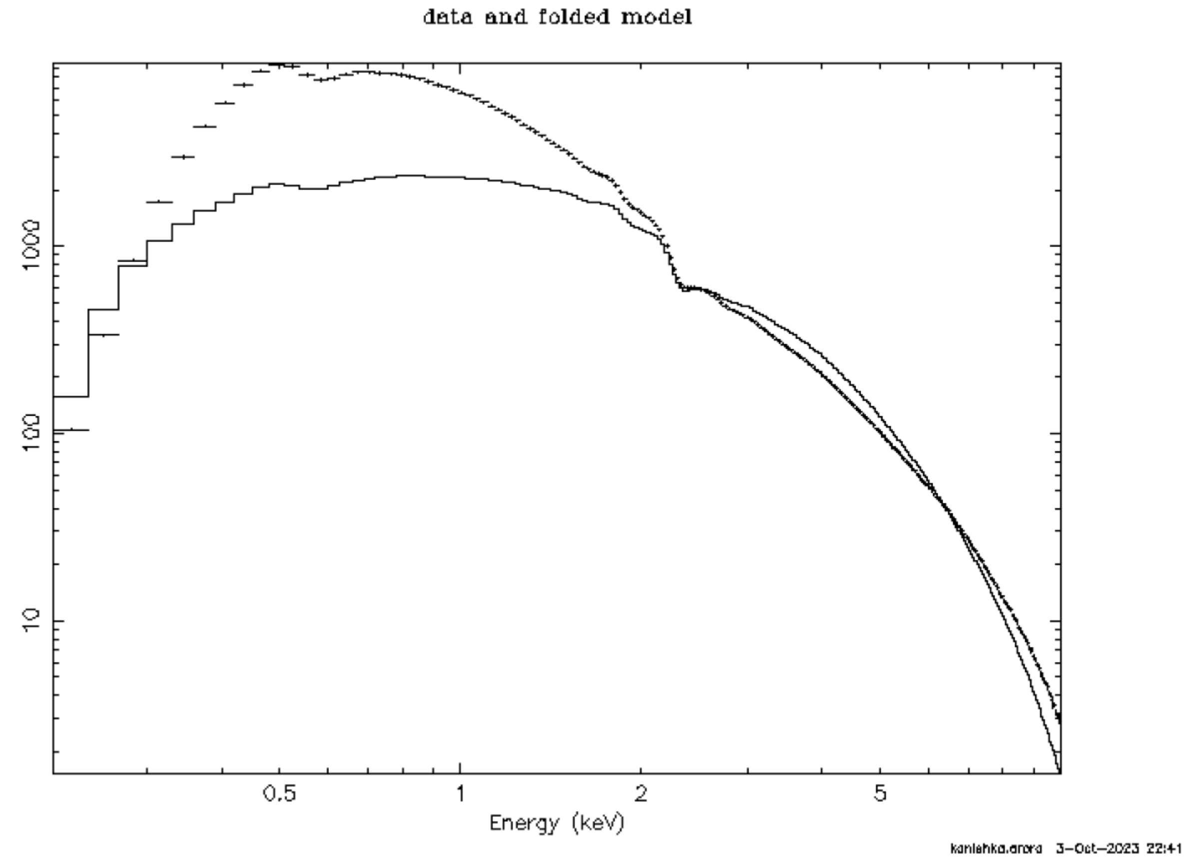
After the fitting process we obtain the following parameter values.

```
========================================================================
Model TBabs<1>*diskbb<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    2.41090E-02  +/-  1.89605E-04
   2    2   diskbb     Tin        keV      2.09655      +/-  3.41693E-03
   3    2   diskbb     norm                44.0112      +/-  0.283703
________________________________________________________________________


Fit statistic  : Chi-Squared                107005.7     using 243 bins.

Test statistic : Chi-Squared                107005.7     using 243 bins.
```

The reduced chi-squared value that we get is **445.85**

This is not a good fit as the chi-squared value is much larger than 1.

Below is the following plot that we obtain.



3. **<u>Tbabs*(diskbb + powerlaw)</u>:**

Again over here we take default values.

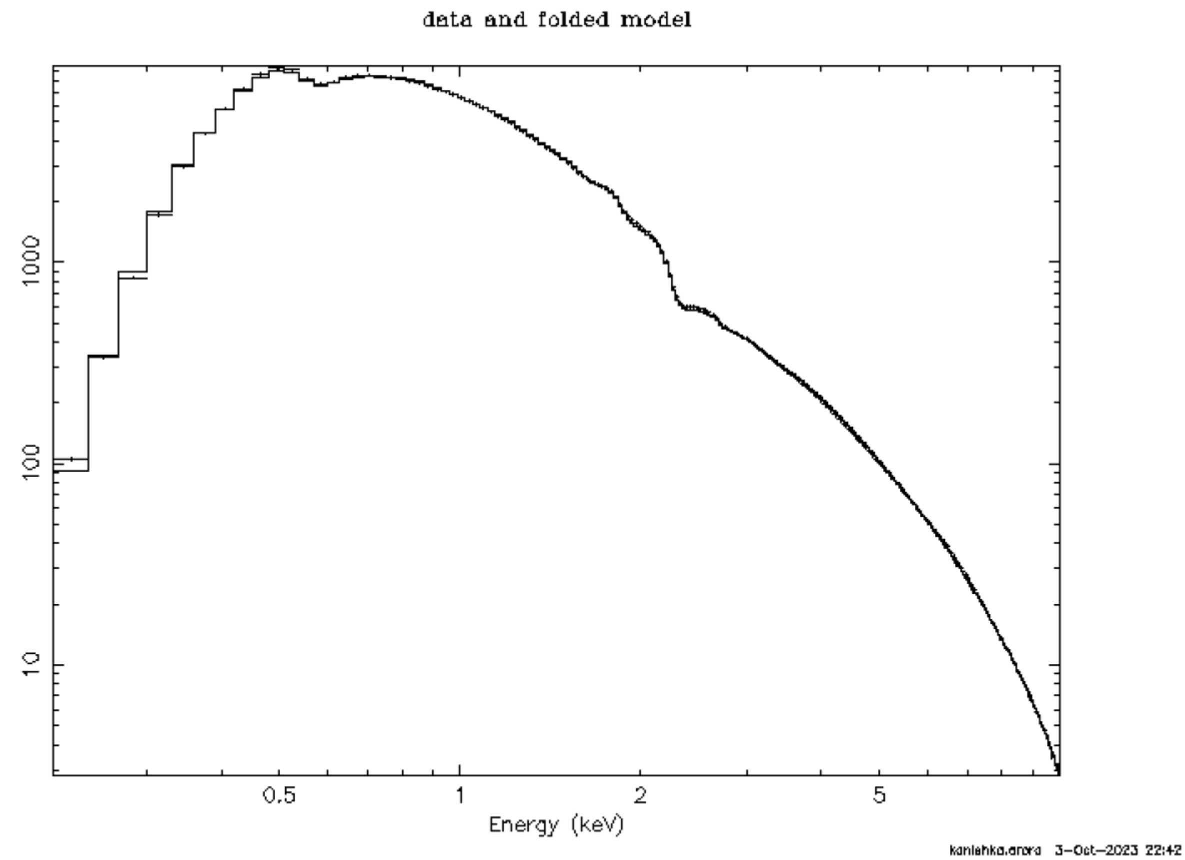
```
========================================================================
Model TBabs<1>(diskbb<2> + powerlaw<3>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    1.00000      +/-  0.0
   2    2   diskbb     Tin        keV      1.00000      +/-  0.0
   3    2   diskbb     norm                1.00000      +/-  0.0
   4    3   powerlaw   PhoIndex            1.00000      +/-  0.0
   5    3   powerlaw   norm                1.00000      +/-  0.0
________________________________________________________________________

Fit statistic  : Chi-Squared                303958.0     using 243 bins.

Test statistic : Chi-Squared                303958.0     using 243 bins.
 Null hypothesis probability of 0.0e+00 with 238 degrees of freedom
 Current data and model not fit yet.
```

After the fitting process we obtain.

```
========================================================================
Model TBabs<1>(diskbb<2> + powerlaw<3>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.114202     +/-  5.75564E-04
   2    2   diskbb     Tin        keV      0.265542     +/-  1.76682E-03
   3    2   diskbb     norm                1.00115E+05  +/-  3329.72
   4    3   powerlaw   PhoIndex            1.71378      +/-  3.33704E-03
   5    3   powerlaw   norm                3.05086      +/-  1.70897E-02
________________________________________________________________________

Fit statistic  : Chi-Squared                  582.14     using 243 bins.

Test statistic : Chi-Squared                  582.14     using 243 bins.
 Null hypothesis probability of 7.85e-31 with 238 degrees of freedom
```

Over here the reduced chi-squared value is **2.45**

This is a very good value as it is the closest to 1 compared to the previous 2.



<u>More rigorous fitting</u>:

Now we will move ahead with a little bit more complicated model.
We will use tbabs*(diskbb + gauss + powerlaw)
This is done for getting an even better fit.
We will again take default values.

```
XSPEC12>model tbabs*(diskbb+gauss+powerlaw)

Input parameter value, delta, min, bot, top, and max values for ...
              1      0.001(      0.01)          0          0     100000      1e+06
1:TBabs:nH>
              1       0.01(      0.01)          0          0       1000       1000
2:diskbb:Tin>
              1       0.01(      0.01)          0          0      1e+20      1e+24
3:diskbb:norm>
            6.5       0.05(     0.065)          0          0      1e+06      1e+06
4:gaussian:LineE>
            0.1       0.05(     0.001)          0          0         10         20
5:gaussian:Sigma>
              1       0.01(      0.01)          0          0      1e+20      1e+24
6:gaussian:norm>
              1       0.01(      0.01)         -3         -2          9         10
7:powerlaw:PhoIndex>
              1       0.01(      0.01)          0          0      1e+20      1e+24
8:powerlaw:norm>
```

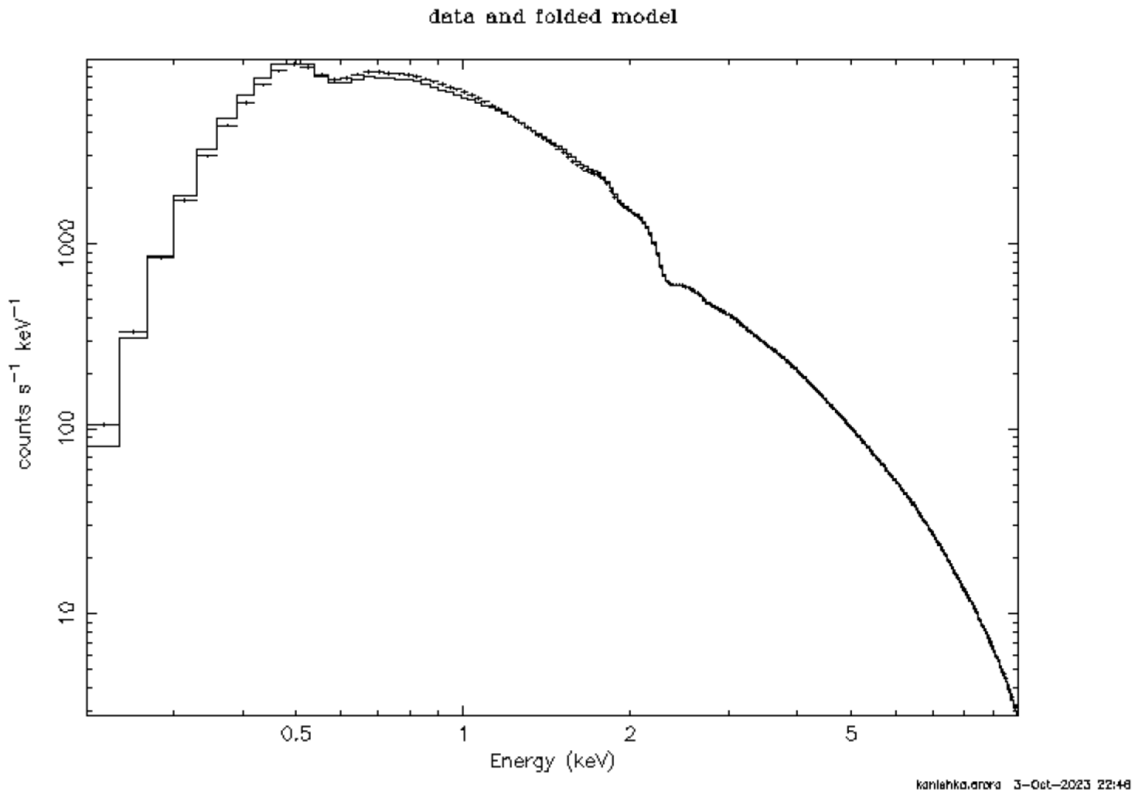
```
========================================================================
Model TBabs<1>(diskbb<2> + gaussian<3> + powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    1.00000      +/-  0.0
   2    2   diskbb     Tin        keV      1.00000      +/-  0.0
   3    2   diskbb     norm                1.00000      +/-  0.0
   4    3   gaussian   LineE      keV      6.50000      +/-  0.0
   5    3   gaussian   Sigma      keV      0.100000     +/-  0.0
   6    3   gaussian   norm                1.00000      +/-  0.0
   7    4   powerlaw   PhoIndex            1.00000      +/-  0.0
   8    4   powerlaw   norm                1.00000      +/-  0.0
________________________________________________________________________


Fit statistic  : Chi-Squared              1.127551e+07     using 243 bins.

Test statistic : Chi-Squared              1.127551e+07     using 243 bins.
 Null hypothesis probability of 0.000000e+00 with 235 degrees of freedom
 Current data and model not fit yet.
```

The picture will give you a better view.
Now we used the fit command.

These are the parameter values we obtain after a while.

```
========================================================================
Model TBabs<1>(diskbb<2> + gaussian<3> + powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.149184     +/-  1.27847E-03
   2    2   diskbb     Tin        keV      13.1655      +/-  68.9608
   3    2   diskbb     norm                1.04892E-02  +/-  0.191515
   4    3   gaussian   LineE      keV      2.50855E-03  +/-  8.54099
   5    3   gaussian   Sigma      keV      6.26904      +/-  4.79615
   6    3   gaussian   norm                1.70636      +/-  4.05128
   7    4   powerlaw   PhoIndex            2.54340      +/-  3.70219E-02
   8    4   powerlaw   norm                5.61417      +/-  0.133955
________________________________________________________________________

   Using energies from responses.

Fit statistic  : Chi-Squared                  991.37     using 243 bins.

Test statistic : Chi-Squared                  991.37     using 243 bins.
 Null hypothesis probability of 1.86e-93 with 235 degrees of freedom
```

Below is the plot that we obtain for this fit.



The chi-squared value over here is **4.22**

In xspec between the fitting procedure, if one wants to change the value of the parameter, the **newpar** command can be used. It has the following syntax.

XSPEC12> newpar 1 *newvalue* -1

That value will then be frozen and will not change as the fitting happens.

Similarly if one wishes to undo the freeze command, the **thaw** command can be used.

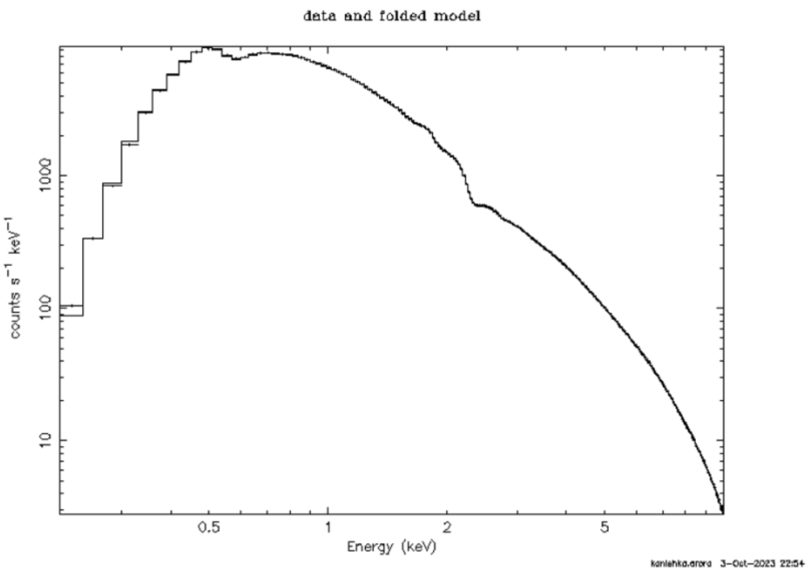
XSPEC12> thaw 1

In the end the best fit that I have obtained is the following

```
========================================================================
Model TBabs<1>(diskbb<2> + gaussian<3> + powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   TBabs      nH         10^22    0.122612     +/-  1.07554E-03
   2    2   diskbb     Tin        keV      0.241155     +/-  2.70330E-03
   3    2   diskbb     norm                1.23892E+05  +/-  5947.06
   4    3   gaussian   LineE      keV      6.75368      +/-  0.235060
   5    3   gaussian   Sigma      keV      2.73146      +/-  0.305661
   6    3   gaussian   norm                0.137018     +/-  3.37271E-02
   7    4   powerlaw   PhoIndex            1.91022      +/-  2.61722E-02
   8    4   powerlaw   norm                3.75345      +/-  7.94696E-02
________________________________________________________________________


Fit statistic  : Chi-Squared                   283.22     using 243 bins.

Test statistic : Chi-Squared                   283.22     using 243 bins.
 Null hypothesis probability of 1.71e-02 with 235 degrees of freedom
```

This is a very good ratio that we have obtained. The best till now in fact.
The chi-squared ratio over here is **1.165**

Below is the plot for the above fit.



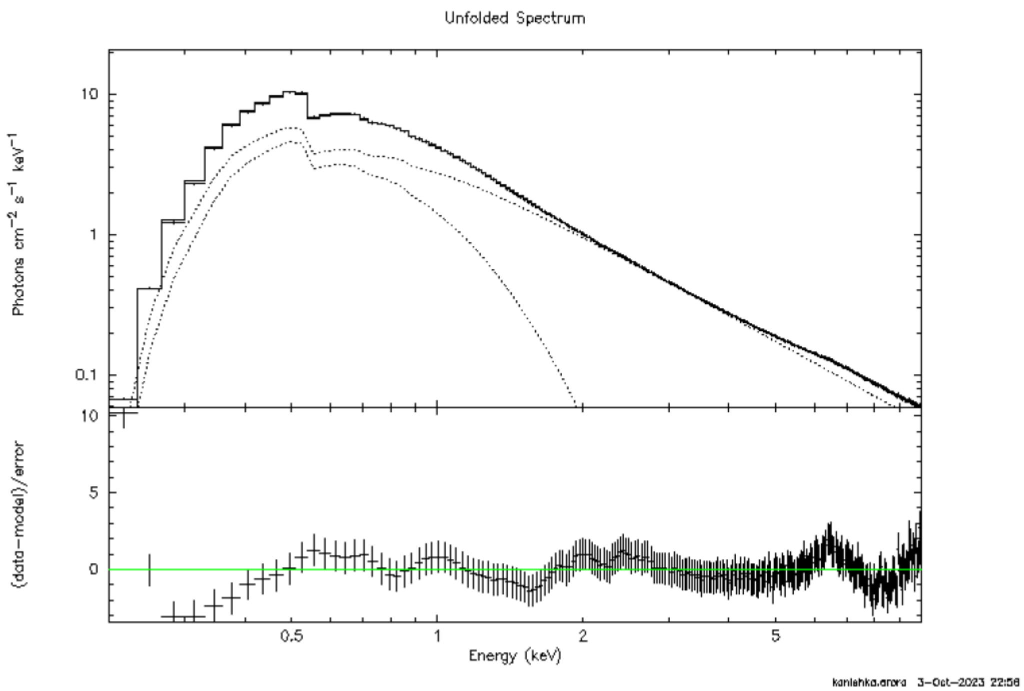
We can see that the our model(which is a combination of further models) is fitting quite well with the observed spectral data.

<u>Task 9</u>:

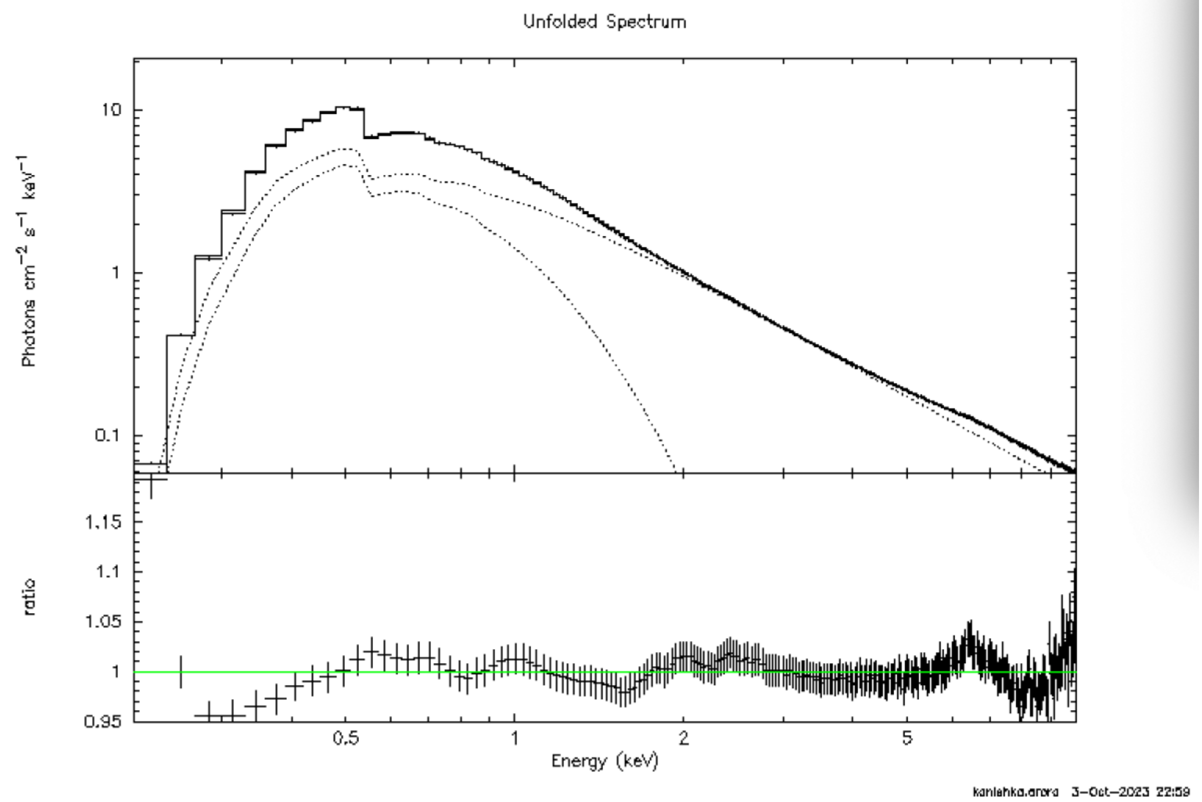
Save the unfolded data-model and ratio in a figure.

I will now show the plots for the unfolded data-model and unfolded ratio.

1. <u>Unfolded data-model:</u>



2. <u>Unfolded ratio:</u>



<u>Task 11:</u>

Make a table of all model parameters with errors for the best fit model and flux values in (0.8-10) keV

To calculate the error for each parameter, we have to use the **error** command available in xspec.

Suppose I want to calculate the error for parameter 1. I will type the following in xspec.

XSPEC12>error 1

(This will calculate the error in 1 sigma confidence interval i.e. with a 68%confidence interval centred around the mean)
The below image will give you a better picture.

```
XSPEC12>error 1 2 3 4 5 6 7 8
 Parameter   Confidence Range (2.706)
     1      0.120984      0.124203     (-0.00157971,0.00163862)
     2      0.236818      0.245592     (-0.00438752,0.00438676)
Number of trials exceeded: continue fitting?
     3        114621        134165     (-9399.09,10145.4)
     4       6.42605        7.0119     (-0.344664,0.241186)
     5       2.35982       3.14003     (-0.350675,0.429538)
     6     0.0989637      0.185899     (-0.0357559,0.0511793)
     7       1.87649        1.9444     (-0.0320777,0.0358279)
     8       3.64302       3.85946     (-0.105978,0.110464)
```

Putting these values in a table we get,

Parameter No.	Parameter type	Parameter Value	Min Value	Max Value	Range
1	nH (Tbabs)	0.122571	0.120984	0.124203	(-0.00157971,0.00163862)
2	Tin (diskbb)	0.241191	0.236818	0.245592	(-0.00438752,0.00438676)
3	Norm(diskbb)	1.24027E+05	114621	134165	(-9399.09,10145.4)
4	LineE(gaussian)	6.76943	6.42605	7.0119	(-0.344664,0.241186)
5	Sigma(gaussian)	2.71235	2.35982	3.14003	(-0.350675,0.429538)
6	Norm(gaussian)	0.134943	0.0989637	0.185899	(-0.0357559,0.0511793)
7	PhoIndex(powerlaw)	1.90876	1.87649	1.9444	(-0.0320777,0.0358279)
8	Norm(powerlaw)	3.74957	3.64302	3.85946	(-0.105978,0.110464)

Next we want to calculate the flux of electrons in a given energy range.
This can be done by the following command.

XSPEC12>flux 0.8 1.0

This will give the energy range between 0.8keV and 1.0keV
The below table will give you some more insight.

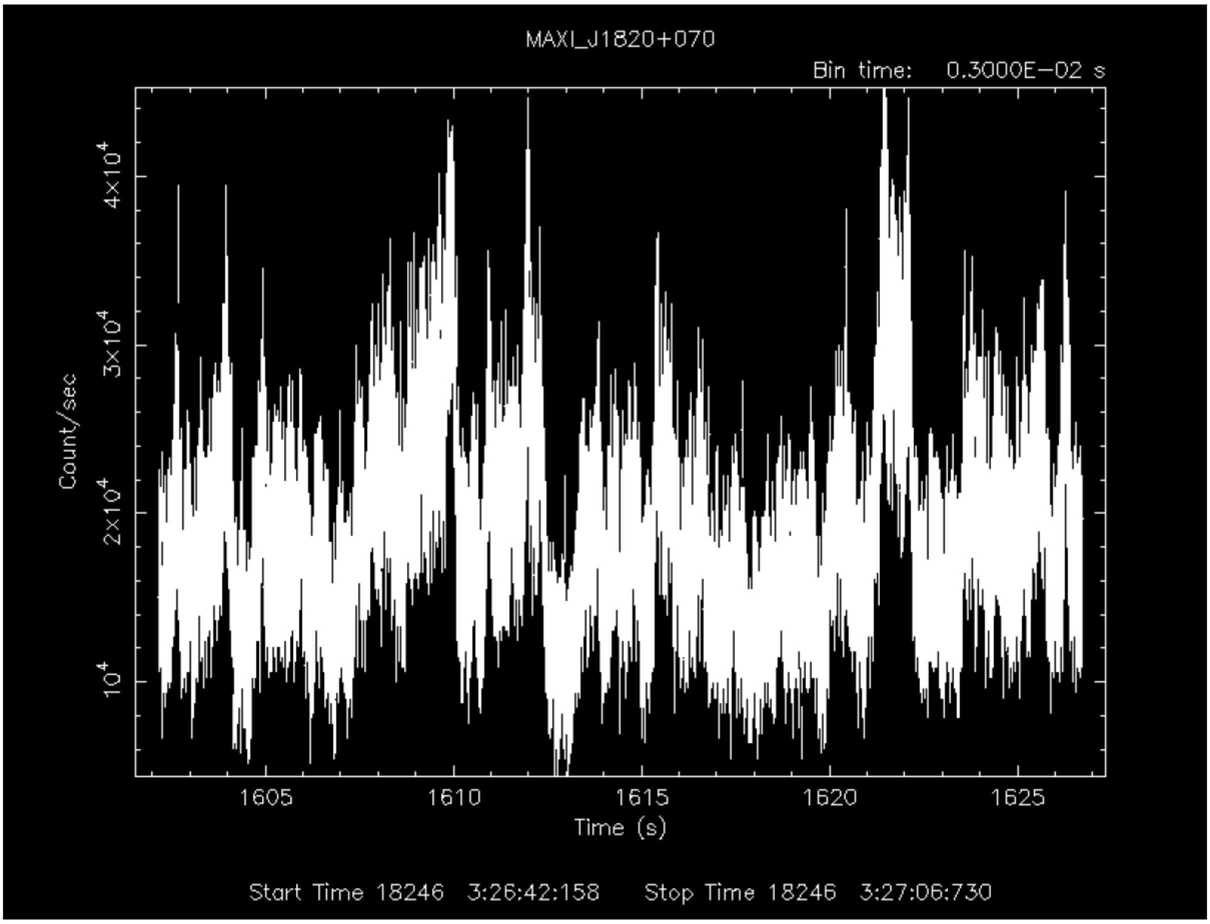
Serial No.	Range	Flux(photons)	Flux(ergs/cm^2/s)
1	0.8 – 1.0	0.99574	1.821e-08
2	1.0 – 1.2	0.70717	1.2399e-09
3	1.2 – 1.4	0.50451	1.0463e-09
4	1.4 – 1.6	0.36929	8.8468e-10
5	1.6 – 1.8	0.28192	7.66e-10
6	1.8 – 2.0	0.22229	6.7536e-10
7	2.0 – 2.2	0.18135	6.0927e-10
8	2.2 – 2.4	0.15179	5.5867e-10
9	2.4 – 2.6	0.12933	5.1749e-10
10	2.6 – 2.8	0.11191	4.8371e-10
11	2.8 – 3.0	0.09809	4.5543e-10
12	3.0 – 3.5	0.20014	1.0385e-09
13	3.5 – 4.0	0.15479	9.2759e-10
14	4.0 – 4.5	0.12436	8.451e-10
15	4.5 – 5.0	0.103	7.8266e-10
16	5.0 – 5.5	0.087421	7.3445e-10
17	6.0 – 6.5	0.066383	6.6419e-10
18	6.5 – 7.0	0.058838	6.3586e-10
18	7.0 – 7.5	0.052385	6.081e-10
19	7.5 – 8.0	0.046814	5.8094e-10
20	8.0 – 8.5	0.041863	5.5304e-10
21	8.5 – 9.0	0.037388	5.2386e-10
22	9.0 – 9.5	0.033332	4.9374e-10
23	9.5 – 10.0	0.029673	4.6331e-10

The total flux between 0.8 – 10.0 keV is **4.8655** photons.

Task 12:

plot (using line) and save the source light curve.

I have taken the bin time as 0.003 seconds and have saved the plot.



Task 13:

What is the maximum, minimum and average counts rate in the original source light curve?

Maximum counts rate = 44330 counts / sec

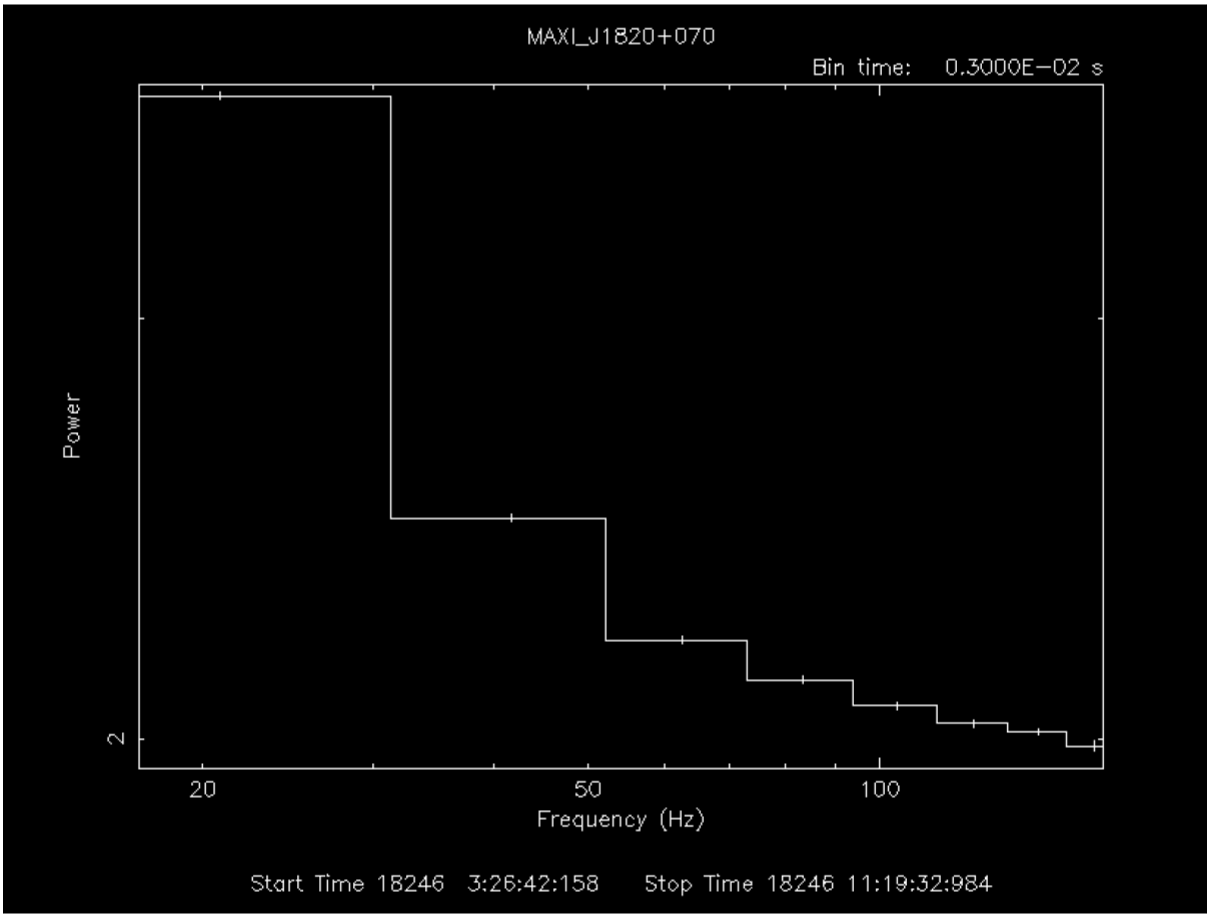
Minimum counts rate = 5333 counts / sec

Average counts rate. =18620 counts / sec

Task 14:

Plot the PDS of the entire light curve. Is the power distribution uniform? If not why? What is the minimum bin time possible for the given data set?

This is the curve that I obtain. It is plotted on a logarithm scale.



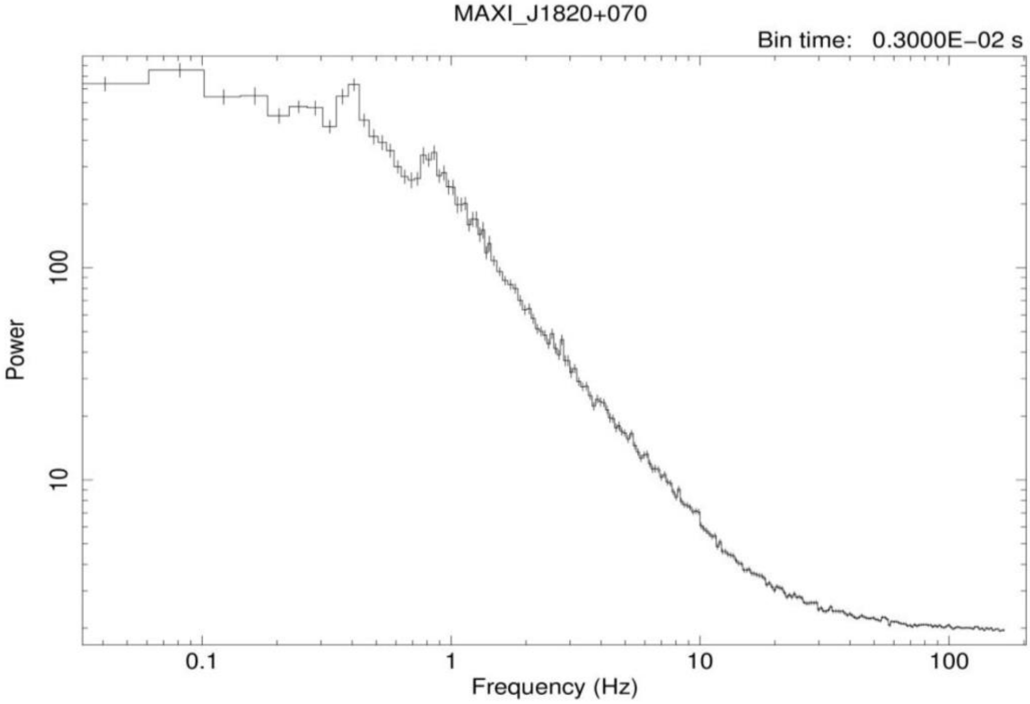
The distribution is not uniform due to the following reasons-

1. Periodic characteristics of Source.
2. Noise in the form of white noise and red noise.

Task 15:

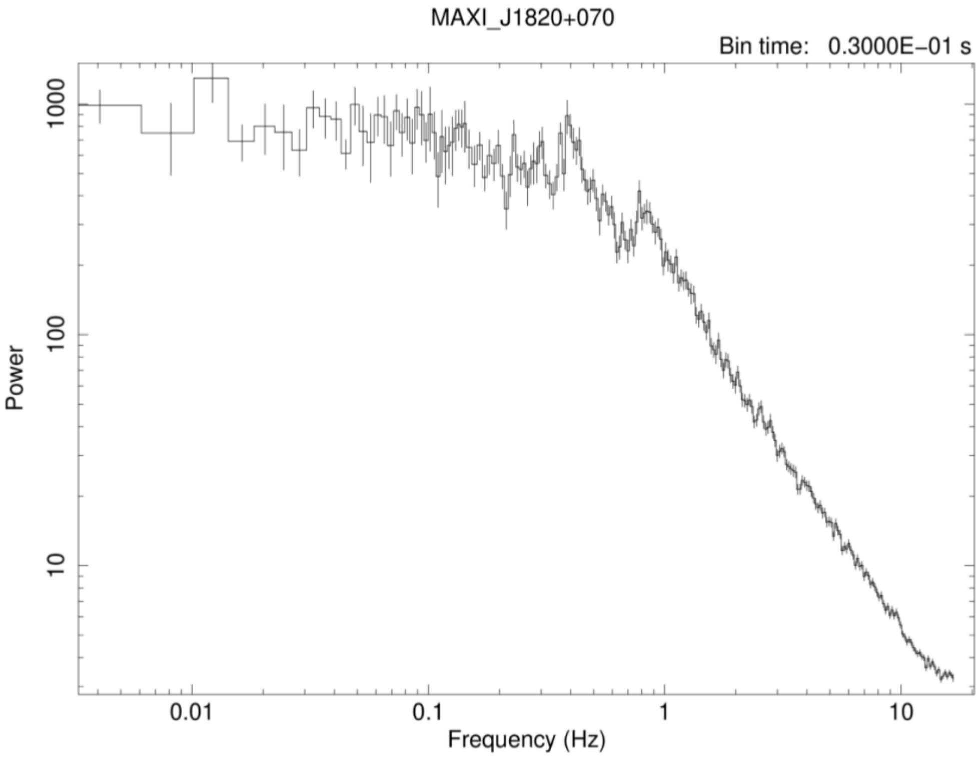
Use two different rebin time (a) minimum bin time and (b) ten times the minimum bin time and redo the PDS. Save the result. Justify the differences in results in (a) and (b). Why do the minimum and maximum frequency in the PDS (a, b) different?

Image: (a) For newbin time= 0.003 s



Start Time 18246 3:26:42:158 Stop Time 18246 11:19:25:297

Image: (b) For newbin time= 0.03 s



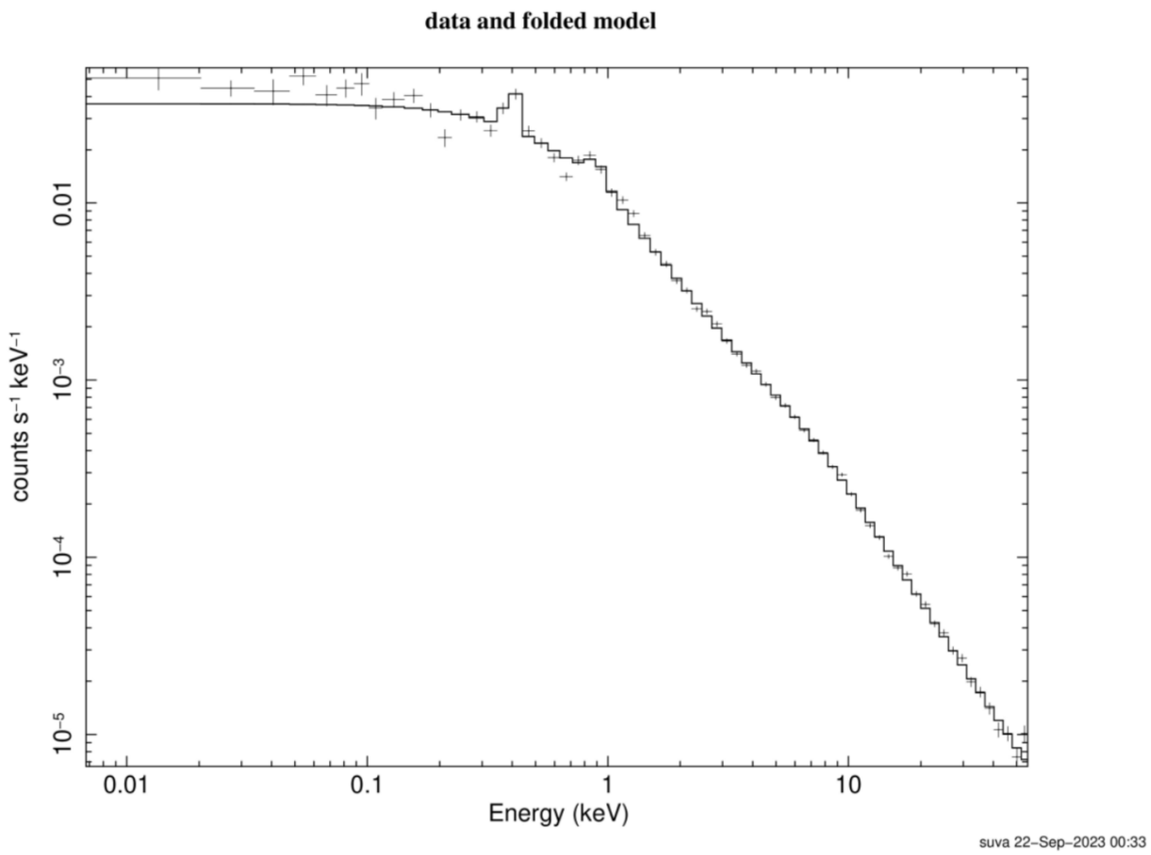
The differences in results between scenarios (a) and (b) happen because of the choice of how we group our data, known as the "newbin time." This grouping affects how well we can see different frequencies in our data.

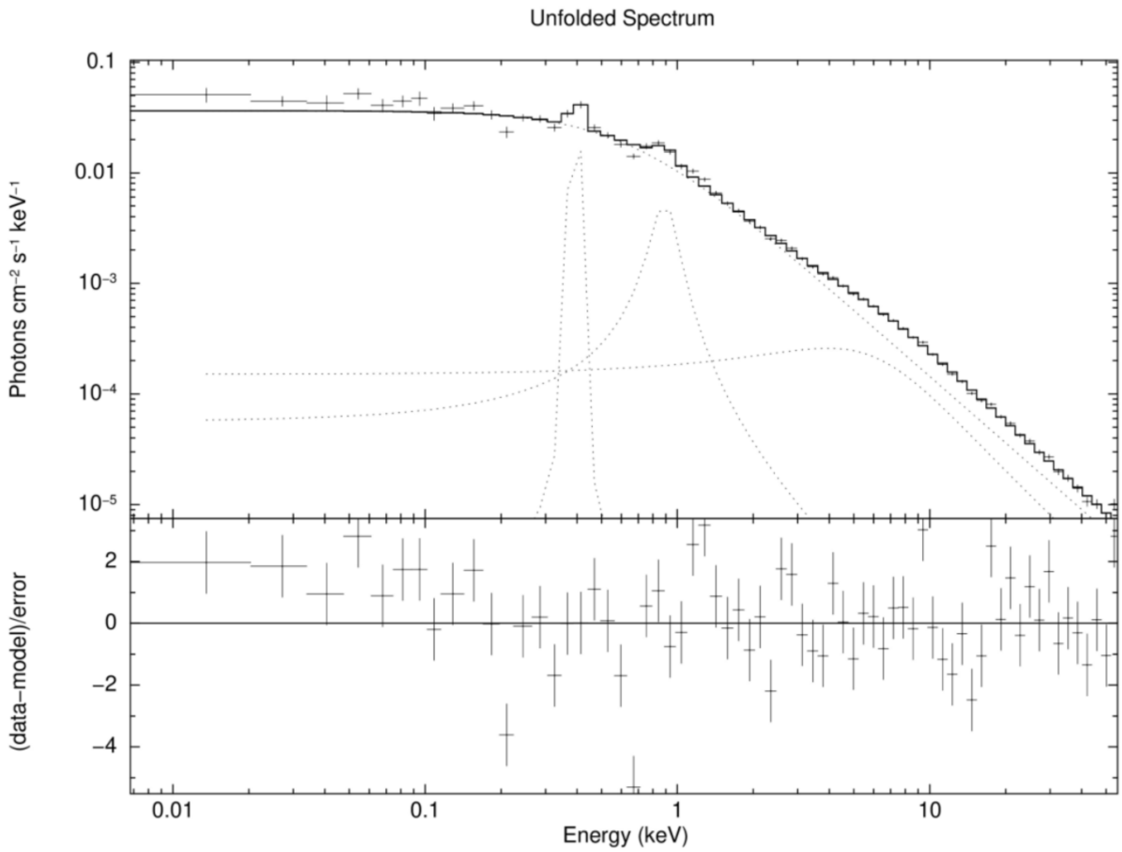
In scenario (a), where we use a very short newbin time of 0.003 seconds, the lines we see are not very clear, and we can observe a wide range of frequencies from about 0.08 to 110 Hz. This is because the short newbin time allows us to notice changes over a broad range of frequencies, but the trade-off is that we lose some precision.

In scenario (b), with a longer newbin time of 0.03 seconds (which is 10 times longer than in scenario a), we see clearer lines, and the frequencies we observe are more focused, ranging from about 0.003 to 11 Hz. The longer newbin time gives us more precision, especially at lower frequencies, but we might miss some changes happening at higher frequencies.

Task 16:

Save the model fitted PDS. Make a table for all model fitted parameter with errors and c2 value with degrees of freedom.





Parameter No.	Parameter	Value	Unit
1	LineE	3.95547	keV
2	Width	9.34935	keV
3	Norm	2.75113×10^{-3}	No unit
4	LineE	0.327811	keV
5	Width	5.17875×10^{-4}	keV
6	Norm	1.14555×10^{-3}	No unit
7	LineE	0.89112	keV
8	Width	0.169894	keV
9	Norm	1.57277×10^{-3}	No unit
10	LineE	6.83201×10^{-18}	keV
11	Width	1.28783	keV
12	Norm	3.59657×10^{-2}	No unit

Chi-square value of my model is= 150.07
Degrees of freedom are= 56
Reduced chi-square value is= 2.71

Task 17:

What is the frequency of QPO (LC value)? The significance of the QPO is defined by Q-factor (ratio of the centroid frequency with width of the peak). Calculate the Q-factor.

The peak of the second Lorentzian is significant, and I will use its parameters for subsequent calculations. The QPO's frequency matches the LineE parameter of the Lorentzian model in XSPEC, and it is determined to be 0.327811. The LC value, representing the inverse of the LineE value in Hz, is calculated as 1/LineE, resulting in 3.0505383. The Q-factor is derived by taking the ratio of LineE to the Width value of the same Lorentzian component. Therefore, the Q-factor is calculated as (0.327811/5.17875 x 10^-4), yielding a value of 632.9925.