Spectral fitting in SPEX

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January 12 2021

1 Powerlaw

The spectrum in the files `powerl.spo` and `powerl.res` was recorded from a source at 6 kpc distance.

1) Load the spectrum into SPEX and plot it. Is it necessary to rebin the spectrum?
2) Set up an absorbed powerlaw model and fit the spectrum. Is it a good fit?
3) Calculate the errors on all free parameters and save your results in a text file.

1.1 Loading, plotting and rebinning the spectrum

After successfully installing the SPEX software onto my personal computer and adding the path to the initializing script to the `.bashrc` file, I could finally run the SPEX program by simply typing `spex` in the command line. The spectrum file `powerl.spo` and corresponding responses `powerl.res` were loaded via command `data powerl powerl`. For plotting purposes, I used modified `plot.com` script from the AHEAD High-Resolution X-ray Astronomy School[1], which was executed by command `log execute plot`. The data were restricted to the $0.2 - 10$ keV energy range and rebinned to contain at least 10 counts per bin (Figure 1):

```
SPEX> ignore 0.:0.2 unit keV
SPEX> ignore 10.:100. unit keV
SPEX> bin 0.2:10.0 10 unit keV
```

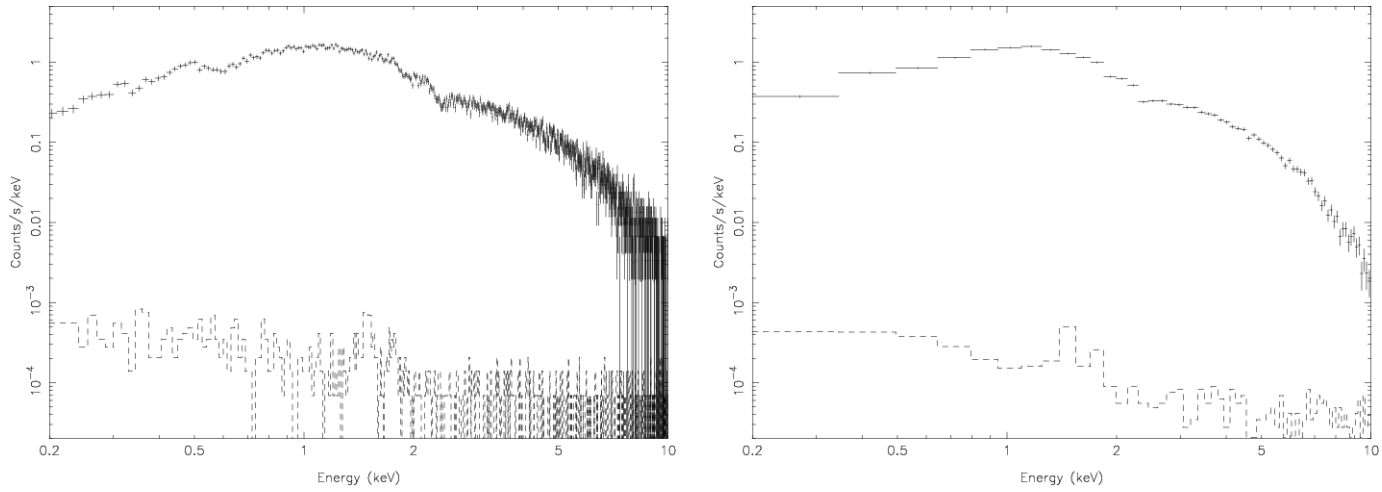

Figure 1: Raw (left) and rebinned (right) data (crosses) and corresponding background (dashed line) plotted in the $0.2 - 10$ keV energy range.

[1] http://personal.sron.nl/ jellep/ahead/

1.2 Setting up and fitting the model

The distance to the source was set via command `distance 6. kpc`. To create individual model components (absorption and powerlaw) and to set up the relation between them I used the following commands:

```
SPEX> comp absm
SPEX> comp pow
SPEX> comp relation 2 1
```

and then performed the fit. The final fit statistic is $\chi^2 = 78.58$ with 62 degrees of freedom.

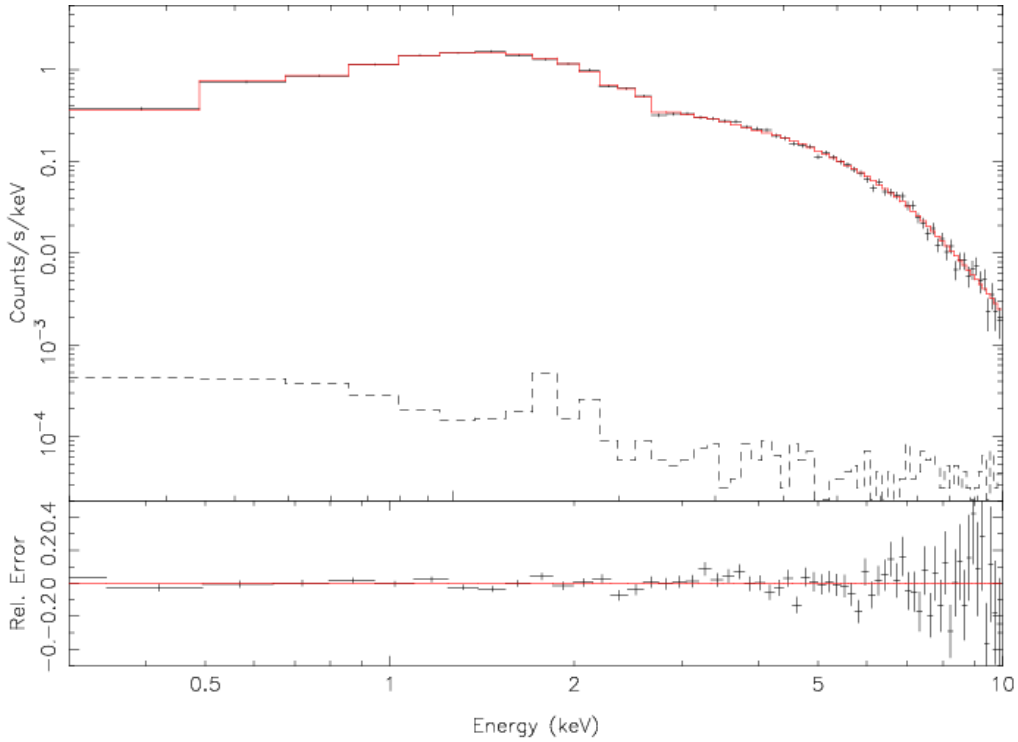

Figure 2: Binned data (black crosses) plotted together with the fitted model (red stepped line) and the relative error.

1.3 Calculating the errors

The standard output can be written to a chosen file (`errors.out`) using command `log output errors` and at the end the output is saved via `log close output`. After performing the fit, errors are obtained simply by typing `error #component parameter` (eg. `error 1 nh`). The final values and errors are listed in Table 1.

Parameter	Value
$n_{\rm H}$ $[10^{21}$ cm$^{-2}]$	1.45 ± 0.03
norm $[10^{44}$ ph/s/keV$]$	0.250 ± 0.003
photon index Γ	1.78 ± 0.01

Table 1: Fitted parameters of the absorbed powerlaw model with corresponding uncertainties.

2 Powerlaw with Gaussian line

The files `powgaus.spo` and `powgaus.res` contain an absorbed powerlaw spectrum with a Gaussian line. From an optical observation of the source we know that this source has a redshift of $z = 0.0345$.

1) Load the spectrum into SPEX, plot it using `plot.com` and rebin the spectrum properly. Set up a model with the right components (a gaussian is added with the command `com gaus`) and fit the spectrum.
   You can find the absorbed and unabsorbed fluxes and luminosity just above the χ^2 value. The energy limits can be changed by the command elim. To change the energy range over which the fluxes are calculated, type `elim 0.2:10.0`. This changes the range to 0.2–10 keV.

2) What is the 2–10 keV luminosity of the source? Compare it with the value you got in Exercise 1. What is the difference between absorbed and unabsorbed flux? Find out which of the columns (above the χ^2 value) is absorbed.

3) What is the energy of the centroid of the line? Calculate the equivalent width of the line (by hand). (equivalent width is the ratio $\frac{F_\lambda}{F_c}$, where F_λ is the photon flux of the line in unit photons s^{-1} and F_c is the flux of the continuum at the energy of the line in unit photons s^{-1} keV^{-1})

4) Calculate the errors on all free parameters. What is the error in the equivalent width you calculated?

2.1 Adding gaussian line to the powerlaw model

For fitting the `powgaus.spo` data I used very similar model to that used in Section 1 - to the absorbed powerlaw model I added an additional Gaussian component to describe the emission line (Figure 3). In this case the data were binned to contain at least 5 counts per bin, despite it had fewer counts than `powerl.spo`, so the emission line is well resolved and it is possible to fit also the width of the emission line (FWHM).

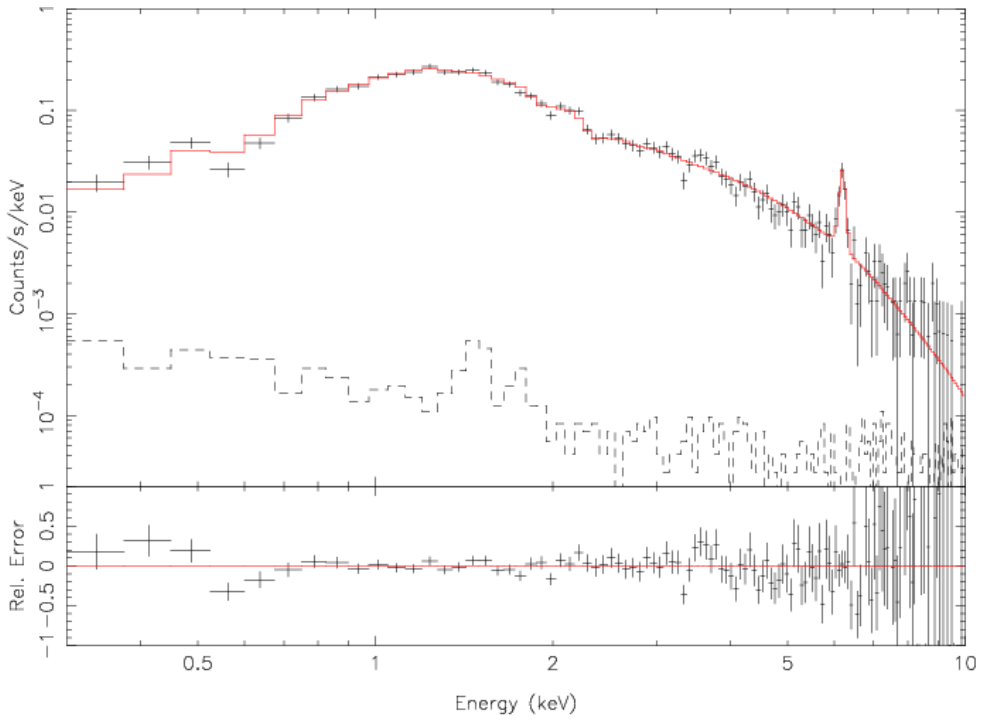

Figure 3: Data points (black crosses) fitted with absorbed powerlaw model with additional Gaussian component (red stepped line).

2.2 Luminosities and fluxes

Luminosities of the model components were calculated during the fit – the energy range for which the luminosities were estimated was set to $2-10$ keV. The resulting luminosities are $6.68 \cdot 10^{42}$ erg/s for the powerlaw component and $4.91 \cdot 10^{41}$ erg/s for Gaussian component. In the previous Section the luminosity of the powerlaw component was estimated to $9.00 \cdot 10^{34}$ erg/s – although this source has higher count rate it's distance is significantly smaller than the distance to the source with the Gaussian line, which is the reason why the luminosity of the second source is much higher.

Unabsorbed flux is the original flux of additive components (powerlaw or Gaussian), like if there is no absorption in the vicinity of the source or in the Galaxy and it is expressed in the fit as the normalization or luminosity of the component. The absorbed flux is the flux of these components after being absorbed by the obscuring material (desribed by `absm` multiplicative component) and is stated right above the fit statistics.

2.3 Energy and width of the line

The energy of the centroid of the line was fitted to 6.196 keV (with 0.004 keV FWHM). To estimate the fluxes of the line and the continuum at the energy of the line I restricted the energy range used for luminosity calculation to the centroid of the line ± line's FWHM ($6.192 - 6.200$ keV). After fitting the model I obtained the photon rates of individual components in chosen energy range: $F_{\mathrm{Gauss}} = 4.31 \cdot 10^{49}$ ph/s, $F_{\mathrm{Pow}} = 4.59 \cdot 10^{47}$ ph/s. And from these values I calculated the corresponding equivalent width of the line as follows:

$$\frac{F_\lambda}{F_\mathrm{c}} = \frac{F_{\mathrm{Gauss}}[\mathrm{ph/s}]}{F_{\mathrm{Pow}}[\mathrm{ph/s}]/\mathrm{FWHM}[\mathrm{keV}]} = \frac{4.31 \cdot 10^{49}}{4.59 \cdot 10^{47}/0.004} = 0.376 \text{ keV}.$$

(I couldn't figure out how to do this differently or how to get the continuum flux at energy of the line. I noticed I could get these values in proper units directly from the fit, but the fitted normalization of the powerlaw component is expressed only for the whole range. And restricting the energy range by ignoring the remaining energies in the fit didn't seem to me as a good idea. Or should I have just divided the normalizations? - This would result in equivalent width ≈ 0.01 keV.)

2.4 Calculating the errors

The uncertainties of parameters were calculated and outputted similarly as in the Subsection 1.3. The final values and errors are listed in Table 2.

Parameter	Value
n_{H} $[10^{21}$ cm$^{-2}]$	4.84 ± 0.15
$\mathrm{norm}_{\mathrm{Gauss}}$ $[10^{49}$ ph/s$]$	4.9 ± 0.7
$\mathrm{e}_{\mathrm{Gauss}}$ [keV]	6.196 ± 0.012
$\mathrm{FWHM}_{\mathrm{Gauss}}$ [keV]	$0.004^{+0.043}_{-0.004}$
$\mathrm{norm}_{\mathrm{Pow}}$ $[10^{51}$ ph/s/keV$]$	4.86 ± 0.18
photon index Γ	2.43 ± 0.04

Table 2: Fitted parameters with corresponding uncertainties for the absorbed powerlaw + Gaussian line model.

3 AGN winds

In many cases the emission from the central region around the black hole is partly absorbed by the disk and/or wind. In the file `agn.spo` we have a spectrum showing a lot of absorption lines. We set the distance to the source to 1 Mpc and the $N_{\rm H}$ to 1×10^{20} cm^{-2}. Response file: `corona.res`.

1) This spectrum is too complicated to fit in one run. Therefore start fitting with just an absorbed powerlaw model to get the slope and normalization right.

2) Identify the absorption lines near 17.7 Å, 18.6 Å, 19.0 Å and 21.6 Å using the SPEX line list.

3) Now add a component called `slab` to your model and free the ions which you identified in 2). You might want to increase the column density per ion to about 10^{20} (Note: the parameter in `slab` is logarithmic). Do the same for the ions C VI and N VII. Is it a good fit?

4) Near 15 Å there are a lot of lines associated with iron. Free the column density of Fe XIV to Fe XVII and fit again. Is the fit acceptable yet?

5) You can obtain a table with the optical depth of all the lines with the following command: `asc ter 1 3 tran` (replace 3 in this command with your component number for `slab`). Write down the optical depth of the O VII and O VIII edge or save the output. Where are the O VII and O VIII edge in the plot? Also save or write down the column densities of O VII and O VIII. You need those later.

6) Remove the slab component from your model and add a component called xabs, which is a more physical model. Fit the spectrum again.

7) If we zoom in on the lines, we see that they are blueshifted. Fit the parameter `zv`. Provide a reasonable starting value for `zv` first. What is the speed of the absorber?

8) Create the table with optical depths again with the command `asc ter 1 3 tran` and `asc ter 1 3 col` to get the column densities for every ion. Do you see differences with the slab model?

9) The ionization parameter `xi` is defined as follows: $\xi = \frac{L_{\rm X}}{nr^2}$. Determine the luminosity ($L_{\rm X}$) of the source ($L_{\rm X}$ is the luminosity between 1 and 1000 Rydberg, where 1 Rydberg = 13.6 eV) and calculate the density (n) if the wind is at 1 pc from the source. Take care of units and logs.

   Usually the density is estimated from variability arguments, which then allow one to put a limit on the distance of the absorber.

10) The impact of the outflow on its environment can be assessed as follows. Assume that the outflow has constant velocity v (measured from your spectrum). The outflow is not fully spherical. Usually people assume that the solid angle sustained by the outflow $\Omega \sim 1$.

    Then the total mass loss is $\dot{M} = \Omega m_{\rm H} n r^2 v$ and the kinetic energy carried away per second is $L_{\rm K} = \frac{1}{2} v^2 \Omega m_{\rm H} n r^2 v$.

    Calculate the kinetic energy carried away and compare to the ionising luminosity (you should do this offline from SPEX, but use the numbers from your fit). Is the kinetic energy significant compared to the radiated energy?

3.1 Pre-fitting with absorbed powerlaw

After visual inspection of the data, the spectrum was restricted to $0.33 - 2$ keV energy range. Since we want to fit the absorption lines properly, the data were not binned because it would lead to decrease of energy (or wavelength) resolution. The spectrum was firstly fitted only with an absorbed powerlaw model (Figure 4).

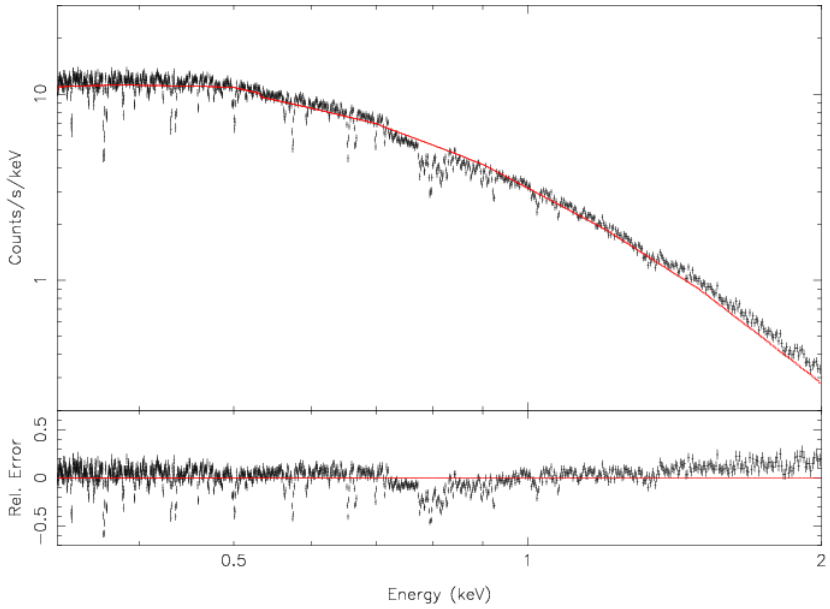

Figure 4: Spectrum of AGN wind fitted with simple absorbed powerlaw model.

3.2 Line identification and fitting `slab` component

For the purpose of better line identification I re-ploted the spectrum as a function of wavelength (in units of Ångström) as can be seen on Figure 5. To identify individual absorption lines I used the new SPEX list of lines (version 2.0[2]).

Wavelength [Å]	Ions
17.688, 17.714	Fe XIX
18.605	Fe XVIII
18.971, 18.977	O VIII
21.602, 21.607	O VII, O VI

Table 3: Identified absorption lines near wavelengths 17.7 Å, 18.6 Å, 19.0 Åand 21.6 Å.

After line identification the model was extended by the `slab` component, which describes absorption lines, and identified lines stated in Table 3 as well as C VI and N VII lines were freed. And subsequently were added even other absorption lines of Fe XIV and Fe XVII (Figure 6). The final fit statistics is listed in Table 4.

Fitted lines	C-stat	Chi Squared
no lines	11124/1178	13233/1167
O VI-VIII, Fe XVIII-XIX	6526/1178	7305/1167
+ C VI, N VII, Fe XIV, Fe XVII	5495/1178	6074/1167

Table 4: Comparison of fit statistics for simple absorbed powerlaw model (no lines), model with only Oxygen and some Iron lines and model with added also other absorption lines of Carbon, Nitrogen and Iron.

The optical depths for all the fitted lines were obtained by command `asc ter 1 3 train` and the output was written into text file. The optical depths of O VII and O VIII lines are 0.150 and 0.049, respectively. The column densities for these lines were fitted to $6.18 \cdot 10^{21}$ m^{-2} and $4.95 \cdot 10^{21}$ m^{-2}. The oxygen edge is probably the little shift in the spectrum near 17 Å.

[2]https://sron.nl/ jellep/spex/line_new.pdf

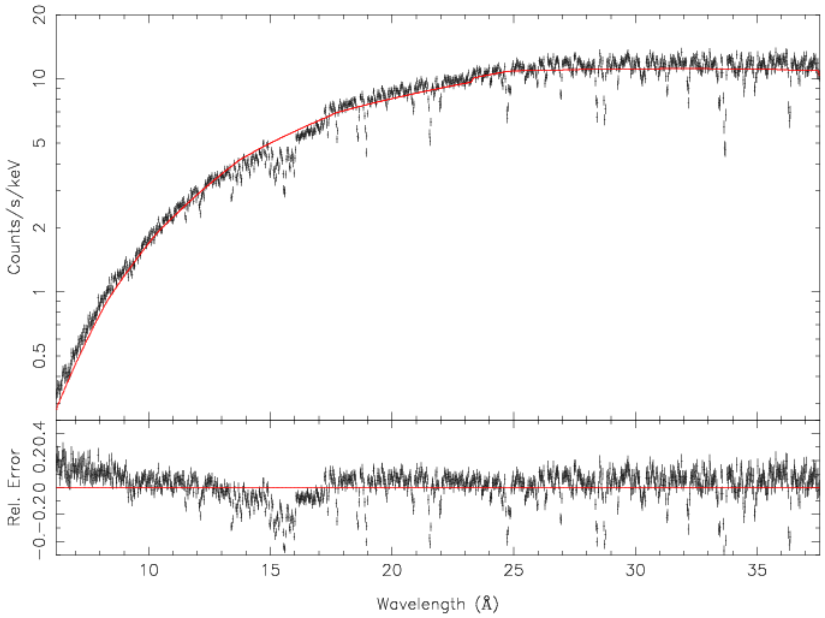

Figure 5: AGN spectrum fitted with absorbed powerlaw model re-plotted as a function of wavelength.

3.3 Using better absorption model

The absorption line `slab` component was replaced by more sophisticated `xabs` component. Abundances of all elements were fixed to Solar and the only fitted parameters for the `xabs` component were the hydrogen column n_{H}, the ionization parameter $\log \xi$ and the average systematic velocity. The average systematic velocity was fitted to $v = -504 \pm 7$ km/s. The final fit statistics for C and χ^2 statistic are 1203/1178 and 1208/1167, respectively. The fitted model is shown in Figure 7.

The optical depths and column densities of ions were obtained similarly as in the case of `slab` component. The values for Oxygen ions (O VII, O VIII) are compared in Table 5.

Ion	τ_{slab}	τ_{xabs}	$n_{\mathrm{H,slab}}$ [10^{21} m^{-2}]	$n_{\mathrm{H,xabs}}$ [10^{21} m^{-2}]
O VII	0.150	0.140	6.18	5.77
O VIII	0.049	0.066	4.95	6.78

Table 5: Comparison of optical depths τ and column densities n_{h} for `slab` and `xabs` components.

To estimate the X-ray luminosity L_X the energy range used for luminosity calculations was restricted to $0.0136 - 13.6$ keV ($1 - 1000$ Rydberg). The density of the wind was then calculated as $n = \frac{L_X}{\xi r^2}$, where r is distance of the wind from the source (we assume distance 1 pc). The X-ray luminosity was fitted to $L_X = 1.11 \cdot 10^{34}$ W and the ionization parameter to $\xi = 5.53 \cdot 10^{-8}$ Wm. The resulting density of the wind is $n = 210.5$ cm^{-3}. The kinetic power (kinetic energy carried away per second) was calculated from the formula $L_{\mathrm{K}} = \frac{1}{2} v^3 \Omega m_{\mathrm{H}} n r^2$, where v is the systematic velocity of the wind and Ω is the solid angle sustained by the outflow ($\Omega \sim 1$). The total kinetic power was estimated to $L_{\mathrm{K}} = 2.09 \cdot 10^{31}$ W, which is approximately 10^{-3} times the X-ray luminosity power.

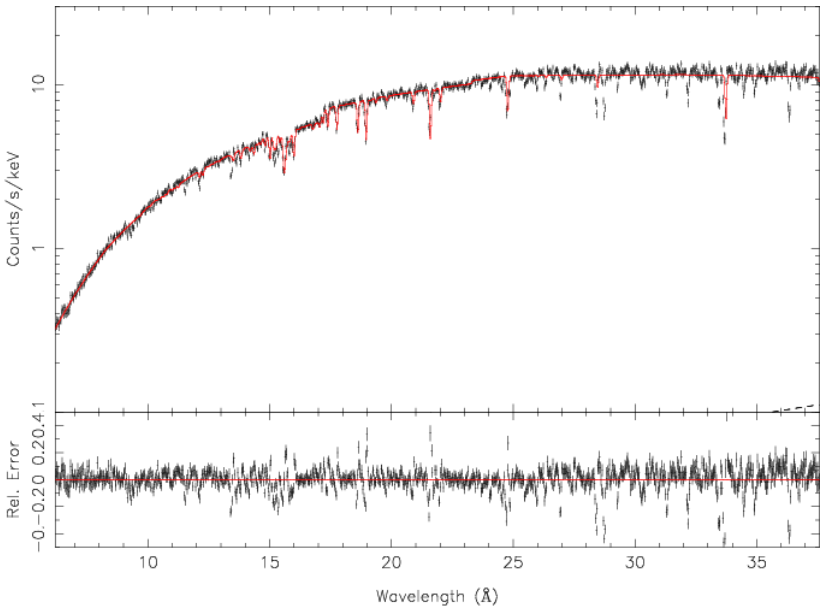

Figure 6: Absorbed powerlaw model with additional `slab` component with freed Oxygen (O VI–VIII), Carbon (C VI), Nitrogen (N VII) and Iron (Fe XIV, XVII–XIX) absorption lines.

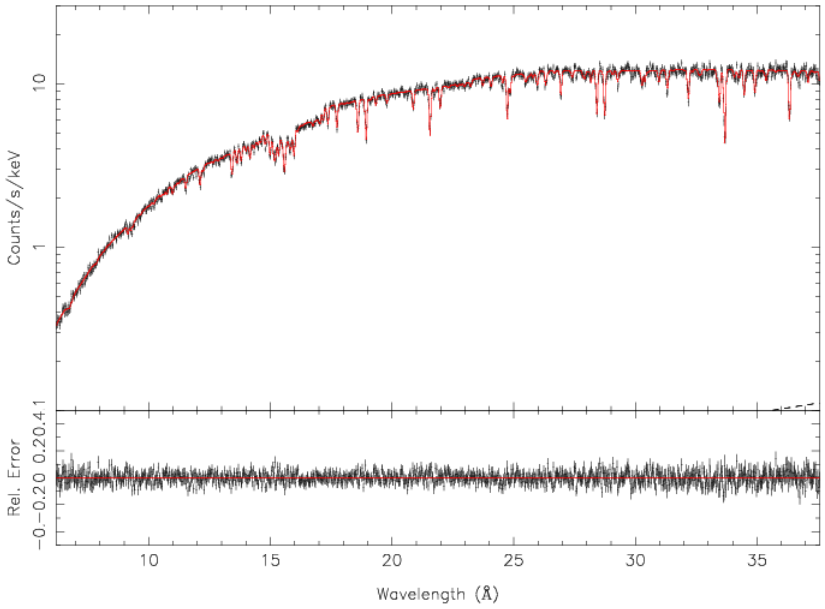

Figure 7: AGN spectrum fitted with absorbed powerlaw model with additional `xabs` absorption line component.