

# SPEX exercises

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The data files needed to do these exercises can be found at the following website:  
<http://www.sron.nl/files/HEA/SPEX/tutorial/tutorial-data.tar.gz>.

## A Powerlaw

The spectrum in the files `power1.spo` and `power1.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? If yes, do it.
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.

## B Powerlaw with a 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  $\chi^2$  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..`. 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 A. What is the difference between absorbed and unabsorbed flux? Find out which of the columns (above the  $\chi^2$  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  $F_\lambda$  is the photon flux of the line in unit photons  $\text{s}^{-1}$  and  $F_c$  is the flux of the continuum at the energy of the line in unit photons  $\text{s}^{-1} \text{keV}^{-1}$ )
4. Calculate the errors on all free parameters. What is the error in the equivalent width you calculated?

## C The spectrum of IGR J16318-4848

Last year a new highly absorbed X-ray source was discovered in the direction of the galactic center by ESA's INTEGRAL satellite. Soon after the discovery XMM-Newton performed a follow-up observation of the source. The files `igr_pn.spo` and `igr_mos2.spo` contain the spectra from two different instruments aboard XMM-Newton (EPIC MOS2 and EPIC pn). Both spectra also have their own response files.

1. Load the two spectra into SPEX and plot them (as before) using the file `plot.com`. Ignore the energy intervals which do not contain useful data and rescale the x-axis accordingly. (You have to tell SPEX which frame in the plot should be rescaled: `plot frame 1` changes the mode to change the upper frame and `plot frame 2`, the lower one with the residuals). Rebin the spectrum with a factor which is optimal with respect to the resolution of each instrument ( $\sim \frac{1}{3}$  FWHM of the lines). How many (significant) lines do you see?
2. If we assume that the source is located in our own galaxy. Can you give a rough estimate of the distance? You can put your estimate in SPEX with the `dist` command.
3. Try to fit the spectrum with an absorbed powerlaw plus 3 Gaussian lines. From the line positions we expect emission from Fe  $K\alpha$  ( $\sim 6.4$  keV), Fe  $K\beta$  ( $\sim 7.0$  keV) and Ni  $K\alpha$  ( $\sim 7.5$  keV). Set up this model in SPEX and fit the spectra. Is the fit acceptable?
4. Calculate the error of  $N_H$  and the powerlaw index  $\gamma$ . Why are the errors large?
5. The powerlaw component in SPEX also has the possibility to base the normalization on the luminosity over a certain energy range (parameters `type`, `elow`, `eupp` and `lum`). Set the energy range to 6–10 keV and calculate the error on the luminosity. Do the same for 1.0–4.0 keV. What happened to the relative error?
6. The theoretical line ratio between the line strengths of Fe  $K\alpha$  and Fe  $K\beta$  is about 0.14. Calculate the errors on the normalization of the Gaussians. Does the fit confirm this line ratio?
7. The line centroids of K lines depend slightly on their ionization level. Calculate the errors on the line energies. In the PS file below is a table with line energies for different ionization states:  
<http://www.sron.nl/divisions/hea/spex/version1.10/trpb04c.ps.gz>  
Is the material which is emitting these lines ionized?
8. Do you have an idea about the nature of this source?

## D Fitting a thermal spectrum

We will examine a high resolution spectrum of a nearby star at a distance of 10 pc. Like the sun, most stars have an X-ray emitting corona. The files `corona.spo` and `corona.res` contain the spectrum and response of this source. This spectrum has not been recorded with just a CCD, as before, but using a high resolution X-ray grating. The light is dispersed by the grating and falls on a CCD. The position of the photon on the detector has a linear dependence on wavelength. Therefore, we plot these kind of spectra in unit  $\text{\AA}$ .

1. Read the data into SPEX and plot it in unit  $\text{\AA}$ . The data ranges roughly from 8 to 38  $\text{\AA}$ . What is the bandwidth in keV?

2. Determine the wavelength of the two strongest lines in the spectrum and use this table to identify them:  
[http://www.sron.nl/divisions/hea/spex/version1.10/line/line\\_new.ps.gz](http://www.sron.nl/divisions/hea/spex/version1.10/line/line_new.ps.gz)  
 (more information about the origin and units used in this table can be found in:  
<http://www.sron.nl/divisions/hea/spex/version1.10/line/index.html>)  
 Can you give a rough estimate of the temperature (in keV) of the corona from the fact that you see these lines ( $k_b = 8.617 \times 10^{-8} \text{ keV K}^{-1}$ )?
3. Load a model with just one component called CIE (`com cie`) which means Collisional Ionization Equilibrium (more information will follow during the lectures). Fit the spectrum and calculate the error. Was your temperature estimate right?
4. There is one line that is not fitted correctly. Use the line table from exercise 2 to see which element is emitting this line. Set this element to `thawn` and fit again. Is the fit better?
5. Now you can also free the iron and oxygen abundance and fit the spectrum again. What are the values for the abundance? The values in the fit are relative to solar abundances (more details can be obtained with the command `asc ter 1 1 abun`). Calculate the errors. Are the fitted abundances consistent with solar abundances?  
  
 These kind of spectra (with a low continuum) often produce wrong abundances because of the low S/N of the continuum. Because rebinning the spectrum obviously degrades the spectral resolution, we need another solution. Instead of using the errors on the data we can use the expected error from the value of the model in the  $\chi^2$  equation for  $\sigma$ . In this way we give less weight to low S/N data points. In SPEX we can do this by issuing the command `fit weight model` before doing a fit. Because the expected errors can change when the model changes, this command has to be given a few times between fits to get the real minimum.
6. Fit the spectrum using `fit weight model`. Are the abundances the same as before? Calculate the errors. Are the new values consistent with solar abundances?
7. The values for the abundance are relative to the solar hydrogen abundance by default. But as there are no hydrogen lines in this spectrum, we can use another element as a reference (iron for example). Set the reference atom to iron, fix the iron abundance and calculate the error on oxygen. Is the fit better?
8. Fix all abundances and free the ion temperature. Fit the spectrum and calculate the error on the ion temperature. Is it well constrained? Find out what the ion temperature does with the lines for values 1, 10, 100 (change the value in the model and calculate the model by typing `ca`. Do not fit!). What happens?
9. Plot the spectrum from 21 Å to 23 Å. These lines are called the oxygen triplet. The lines depend strongly on electron density. Play around with the electron density in the same way as you did with the ion temperature. What happens with these lines? Calculate the error. Can you give an upper limit for the density of the plasma?
10. There are a lot of lines in this spectrum. You can learn also which lines belong to a certain element by putting its abundance to 0 and calculate. Do this for O, Ne and Fe. If you like, you can also try it out for other elements. Finally, SPEX can also provide a list with all the present ions: `asc ter 1 1 icon`.

## E Infalling group of galaxies

We observe a cluster of galaxies at a redshift of  $z = 0.03$ . In X-rays the emission is dominated by hot thermal plasma which usually has a temperature (kT) of the order of 1 keV. For this exercise we assume that all elements have the same abundance relative to solar abundances (so the overall metallicity can be different from 1!). The spectrum is in the file `cluster.spo` and the response is the same as `corona.res`.

1. Fit the spectrum with a cie model (including redshift and absorption). The  $N_H$  is of the order of  $2 \times 10^{20} \text{ cm}^{-2}$ .

The fit is obviously not correct. In an image of the source we see the presence of a blob of soft X-ray emission associated with a group of galaxies which is falling into the cluster.

2. Assume that the soft emission from the group of galaxies is also thermal and add an extra thermal cie component to your model. Remember, the group probably has a relative velocity with respect to the cluster! Fit the spectrum. (Caution: the fit might try out a temperature which is too low and may subsequently crash the program. Set the range of allowed temperatures to something like 0.01 to 10., in SPEX language `par 1 t range 0.01 10.`)
3. What is the infall velocity along the line of sight of the group? Is it falling toward us or away from us?
4. Let us assume that the cluster is a homogeneous sphere with constant density and a radius of 300 kpc. The group of galaxies has a radius of 100 kpc. Calculate the mass of the cluster and the group of galaxies in solar masses using the normalization. (The number density ratio of  $n_e/n_H$  can be obtained with the command `asc ter 1 1 plas`)

## F Non-equilibrium spectra

Up to now we have only fitted objects which are in collisional ionization equilibrium (CIE), but when there are plasma shocks in a (low density) medium, equilibrium might not be reached yet. This is often the case in supernova remnants. We will illustrate this with the following spectrum: `nei.spo`. Again the response is the same as `corona.res`. The source is not redshifted.

1. Fit the spectrum with a CIE model. Is there a big difference?
2. With the parameter `rt`, which is the ratio between the temperature in ionization balance and spectral temperature, we can obtain a better fit. Set the parameter to `thawn`, but be aware that this ratio is not allowed to get too close to 0! Is the fit acceptable?
3. In SPEX there is also a component which can fit a non-equilibrium spectrum called `nei`. The most important parameter is  $U$ . It is defined as follows:  $U = \int_{t_0}^{t_n} n_e dt$ . When  $U$  is big, it means the ionization is in equilibrium. Fit the spectrum with `nei`. What is the temperature after the shock?

## G Relativistic lines

The file `agnrel.spo` contains a spectrum of an AGN at 1 Mpc distance. The two features that are visible in the spectrum are the O VIII  $L\alpha$  and N VII  $L\alpha$  lines. Because the emission from the disk is influenced by general relativistic effects, the lines appear to be broad and

asymmetric. In SPEX we can model these lines by convolving a delta line with a so-called Laor profile (`com laor`) and learn a lot about the geometry of the system.

In this exercise we fix the  $N_H$  to  $1 \times 10^{20} \text{ cm}^{-2}$ . The continuum emission can be well described with a powerlaw. The response file is `corona.res` (see previous exercise).

1. Set up a model using the components `pow`, `delt` and `laor` and fit the spectrum. In the `laor` component you can free the parameters `r1`, `r2`, `q` and `i`. You can find the line energies of the oxygen lines in the SPEX line list. Is the fit acceptable? Look at the residuals of the fit and check whether the lines are well fitted. If not, try to find out which parameter of the `laor` component should be altered.
2. If the fit is acceptable, then calculate the angular momentum of the black hole. (Hint: use the formula for the inner stable orbit,  $r_{ms}$ )
3. Vary the parameters `r1`, `r2`, `q` and `i` to see how they influence the line profile.

## H Photoionized absorption in AGN

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. Again we set the distance to the source to 1 Mpc and the  $N_H$  to  $1 \times 10^{20} \text{ cm}^{-2}$ . Responsefile: `corona.res`.

1. This is a complicated spectrum! 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 21.5 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 command `asc ter 1 3 tran`. 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?
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`. What is the speed of the absorber?
8. Create the table with optical depths again with the command `asc ter 1 1 tran` and `asc ter 1 1 col` to get the column densities for every ion. Do you see differences with the `slab` model?
9. The ionisation parameter `xi` is defined as follows:  $\xi = \frac{L_X}{nr^2}$ . Determine the luminosity ( $L_X$ ) of the source ( $L_X$  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.