

# Computer exercises SPEX

High-Energy Astrophysics course 2009/2010

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## 1 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.

## 2 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 Exercise 1. 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?

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### 3 Basics of SPEX / Stellar Spectra

We examine a high resolution spectrum of a nearby star at a distance of 10 pc. The files `corona.spo` and `corona.res` contain the spectrum and instrumental response of this source. This spectrum has been simulated using a RGS-like response. We do not provide real data files, because of their size and because of the time constraints of the course. You can use `plot_rgs.com` for plotting.

1. Read the data into SPEX and plot it in unit Å. The data ranges roughly from 8 to 38 Å.
2. Determine the wavelength of the two strongest lines in the spectrum and use this table to identify them:  
[http://www.sron.nl/~kaastra/college2009/line\\_new.pdf](http://www.sron.nl/~kaastra/college2009/line_new.pdf)  
Can you give a rough estimate of the temperature (in keV) of the corona from the fact that you see these lines? Note: The temperatures listed in the line list are in log Kelvin ( $k_b = 8.617 \times 10^{-8} \text{ keV K}^{-1}$ ).
3. Load a model with just one component called CIE (`com cie`) which means Collisional Ionization Equilibrium. Fit the spectrum and calculate the error. Was your temperature estimate right? Note: Do not forget to issue the command `error dchi 1.` before calculating errors.
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 and the bias produced by  $\chi^2$  statistics (Humphrey, Liu & Buote, 2008). Because re-binning the spectrum obviously degrades the spectral resolution, we need another solution. In SPEX we can switch from  $\chi^2$  statistics to Cash statistics (Cash, 1979). This is accomplished by issuing the command `fit method cstat` before doing another fit.
6. Fit the spectrum using `fit method cstat`. 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, and 1000 (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 broadening (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. Remember to put the reference ion back to H before you set Fe to 0. Finally, SPEX can also provide a list with all the present ions: `asc ter 1 1 icon`.

Note: SPEX can provide a lot of information about the plasma or an absorber through the command `asc ter`. See the SPEX manual for more output options.

## 4 Clusters and Supernovae

### 4.1 Clusters

The temperature structure of the hot X-ray emitting gas in clusters of galaxies can be quite complicated, especially in cooling-core or merging clusters. The spectra that we obtain therefore contain spectral components originating from regions with different temperatures. Moreover, due to the extended nature of the source, lines are broadened in grating spectra. The temperature distribution is not exactly known and fitting all temperature components separately is rarely possible. The current approach is to assume a certain temperature distribution and reduce the number of variables of the distribution to two or three. A frequently used example of such a model is the `wdem` model. Here the Differential Emission Measure (DEM) as a function of temperature is assumed to be a power law. In addition, there is also a component to account for the spectral broadening due to the extent of the source, called `lpro`.

1. Load the spectrum in the file `cluster.spo` together with the `corona.res` response matrix. Set up a model containing a redshift (`reds`), absorption (`abs`), and WDEM (`wdem`) component. The cluster has a known redshift of  $z=0.05$  and the  $N_H$  is thought to be about  $7 \times 10^{20} \text{ cm}^{-2}$ . Fit the spectrum with a fixed power-law slope (`p`). Note: try to guess the value for the normalisation (`norm`) first by setting a value for it, calculate the model (`calc`), and see in the plot window whether the model is reasonably close to the data points.
2. It is clear that the lines in the spectrum are broader than the lines in the model. This is due to the grating spectrometer. Add the `lpro` component to your model to account for the broadening. In the data directory, there is a file called `vprof.dat`. This file contains the clusters' profile along the dispersion direction. Load this file in SPEX by issuing the command: `par 1 4 file av vprof.dat`. Does the fit improve? Adapt the scaling parameter of the `lpro` component if necessary.
3. Set the power-law slope (`p`) to `thawn` and fit again. Is the fit improving?
4. Free the abundances of O, Ne, Mg, and Si and set the reference atom to Fe. Fit again. Which of the abundances are well constrained? There are two ways to check: calculate the error on the abundances or estimate the uncertainty by changing the abundance by a factor of two and check the goodness of fit. The latter method is faster, but obviously also less accurate.

5. It would be interesting to see whether this multi-temperature approach is really necessary. Write down or remember the best fit `cstat` value. Remove the `WDEM` component with the command `com del 3` and add a CIE component. Do not forget to define the relations between the components again with `com rel`! Fit the spectrum again. Is it a good fit? Also if we fit the abundances?

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## 4.2 Supernovae

Up to now we have only fitted an object which was 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`.

1. Fit the spectrum with a CIE model. Is the fit acceptable?
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?
4. Now vary the pre-shock temperature. Does that make any difference?

## 4.3 Stellar DEM models

Many sources have a complicated multi-temperature structure, such as stars and clusters of galaxies. SPEX provides a number of model components that can model and fit multi-temperature plasma. The `wdem` component is an example of a Differential Emission Measure (DEM) model (see Exercise 2.1), but with this component we are limited to a power-law distribution. Fitting other kinds of distributions is possible with `pdem`.

For this exercise we consider a binary star system at a distance of 50 pc. The Hydrogen column density toward the source is  $9 \times 10^{20} \text{ cm}^{-2}$ .

1. Load the spectrum `stardem.spo` with the supplied response matrix and set up a model containing two CIE components. Fit the spectrum. Make sure that  $N_H$  is fixed to the value of the column density.
2. Free the abundances that may cause the fit to be unacceptable and fit again. Is the fit acceptable now?

3. In this case, the spectrum contains multiple temperatures. To estimate the contribution of every temperature we can run a `dem` model. Unfortunately, abundance fitting is not possible with this advanced model. Delete the CIE components and load the `dem` component. Do not forget `com rel`.
4. In order to initialize the DEM model, we first need to set the grid parameters. By default, DEM creates a logarithmic grid. Set the lower temperature (start temperature) to 0.1 keV and the highest temperature (end temperature) to 10 keV. Set the number of bins to 21. Then we have to create a DEM library with the command `dem lib`. Every time we change the model parameters, this command has to be issued!
5. There are several methods to do DEM fitting. We first try out the clean method. This method is best for spiky DEM distributions. Give the command `dem clean` and look at the dem distribution by changing the plot type to `plot type dem`. The plot may need some rescaling. Set the Y-axis to log (`plot y log`) and draw a line between the points (`plot line disp true`). Is the  $\chi^2$  value reported on the command line acceptable? How many discrete temperatures do you see?
6. For more continuous distributions, there is also the polynomial DEM. Issue the command `dem poly 6` (6<sup>th</sup> order polynomial). What do you see in the DEM plot? Try out higher orders, like 7, 8, and 9. Does the fitted DEM distribution change?

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## 5 Relativistic lines

The file `agnrel.spo` contains a spectrum of an AGN at 1 Mpc distance. The response matrix can be found in `rgs.res`. 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.

## 6 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. We set the distance to the source to 1 Mpc and the  $N_H$  to  $1 \times 10^{20} \text{ cm}^{-2}$ . Response file: `corona.res`.

1. This spectrum is too complicated to fit in one run. Therefore start fitting with just an absorbed power-law 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 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?
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:  $\xi = \frac{L_X}{nr^2}$ . 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.

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