Computer exercises SPEX

High-Energy Astrophysics course 2020

SRON/Leiden University

Note: First read carefully the document "A short introduction to SPEX" before making the first exercise. The time you need for exercises can vary. If you have time left over, try to start already with the next exercise, even if it is for the next time!

September 8th, 2020

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.

2. The calibration of the instrument is not very accurate for energies below 0.3 keV and above 10 keV. Ignore those parts of the spectrum.

3. How many data bins do you have in the spectrum? Now try to apply optimal binning to the spectrum. How many bins are left?

4. Set up an absorbed powerlaw model. Do not forget to set the distance to the source.

5. Next step: fit the spectrum. Is it a good fit?

6. Calculate the errors on all free parameters and save your results in a text file.

7. It may be wise to save the commands that you entered in SPEX to a command file, so you can repeat the analysis where needed. Try to make such a command file.

Learning goals:
After having done this spectrum, you should know:

- how to read a spectrum in SPEX

- use the basic plot functionalities

- how to ignore parts of the spectrum

- how to rebin a spectrum

- how to set-up a simple spectral model

- how to do spectral fitting

- how to determine errors on parameters

- how to save your commands & results

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 $z = 0.0345$. There is also Galactic foreground absorption. The source has been observed with the same instrument as exercise 1.

1. Load the spectrum into SPEX, select the proper energy range 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.

2. You may want to fit first with the line flux set to zero (freeze or fix some parameter of the line, make a fit, and then fine-tune the line by releasing the relevant parameters.

   You can find the absorbed and unabsorbed fluxes and luminosity just above the fit statistics. 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.

3. What is the 2–10 keV luminosity of the source? What is the difference between absorbed and unabsorbed flux? Find out which of the columns in the table (listed above the fit statistic values) is absorbed.

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

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

Learning goals:
After having done this spectrum, you should know:

- How to make complex spectral models

- How to freeze or thaw parameters

- How to obtain fluxes & luminosities

- How to calculate the equivalent width of a line

3 Statistics, binning and more

The files `nustar.spo` and `nustar.res` contains the observed (not simulated!) spectrum of the pulsar PSR J1813-1246 as observed by the NuSTAR satellite. You can adopt a distance of 2.5 kpc to this source. You can assume that the spectrum is a simple power law with Galactic foreground absorption.

1. Load the spectrum into SPEX, and rebin the spectrum properly. No need to ignore any data here.

2. Define the proper model and make a fit.

3. We will make a few alternative fits. Make a table and note down the following numbers for each fit starting with your current one: the best-fit parameters and their error bars of the three free parameters of your model; the correlation between these parameters; and the fit statistic with its expected values; your current fit is model A.

Model	A	B	C	D
Norm				
Γ				
Luminosity				
corr norm-Γ				
corr norm-n_{H}				
corr $n_{\mathrm{H}} - \Gamma$				
C-stat or χ^2				
Exp. C-stat or dof				

4. Same as before, but now use the 3-80 keV luminosity as free parameter instead of the norm (change "type" for the power law model and the status of some parameters). This is model B.

5. as above, but now instead the 3-20 keV luminosity (model C)

6. as above, but now change the fit statistic from C-stat to χ^2 (model D). Be shocked by the bias in fit parameters that you will see!

   Learning goals:

After having done this spectrum, you should know:

- How to change from normalisation to luminosity

- See the importance of "pivot" point for the luminosity / normalisation

- Understand the danger of using χ^2-fitting.

4   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, but it is more instructive and easier to plot manually!

1. Read the data into SPEX and plot it in unit Å. The data ranges roughly from 8 to 38 Å. Hint: you may issue successively the commands `plot set all` and `plot line disp t` to get a connecting line through the data for better visibility.

2. Determine the wavelength of the two strongest lines in the spectrum and use this table to identify them:
   http://www.sron.nl/~kaastra/leiden2020/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 ($k_b = 8.617 \times 10^{-8}$ 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?

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 χ^2 statistics (Humphrey, Liu & Buote, 2008). In SPEX we can switch from C-statistics to χ^2 statistics to test this. This is accomplished by issuing the command `fit stat chi` before doing another fit.

6. Fit the spectrum using `fit stat chi`. Are the abundances the same as before? Calculate the errors. Are the new values consistent with solar abundances? Switch back to C-statistics after this step.

7. 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?

8. 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?

9. 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`.

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.

Learning goals:

After having done this spectrum, you should know:

- How to plot a spectrum in wavelength units

- How to identify spectral lines

- How to get physical parameters from a thermal X-ray spectrum

- How to measure abundances from an X-ray spectrum

- How to measure electron density from an X-ray spectrum

- How to use the "asc" command in SPEX

5   Supernova remnants

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`. Adopt a source distance of 3 kpc, and fix the Galactic foreground absorption to 5×10^{24} m^{-2}. Define your spectral model.

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 `neij`. 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 `neij`. What is the temperature after the shock?

4. Now vary the pre-shock temperature. Does that make any difference?

5. In order to see the effect of Non-Equilibrium Ionisation (NEI), make the parameter "U" of the `neij` model 10 times smaller and 10 times larger than your best-fit value (leave all other parameters the same!), calculate the spectrum using the "calc" command (no fitting here!) and plot the spectrum. You will see large differences.

Learning goals:
After having done this spectrum, you should know:

- How to check your data for Non-Equilibrium Ionisation (NEI) effects by using the parameter RT

- How to use proper NEI models and get a basic understanding of these spectra

6 Relativistic lines

The file `agnrel.spo` contains a spectrum of an AGN at 1 Mpc distance. The response matrix to be used is `rgs.res`. The two features that are visible in the spectrum are the O VIII Lα ($\lambda = 18.969$ Å) and N VII Lα ($\lambda = 24.781$ Å) 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$_\mathrm{H}$ to 1×10^{20} cm^{-2}. The continuum emission can be well described with a powerlaw. The response file is `rgs.res`.

1. First start with the most simple model components: `pow` and Galactic foreground absorption. Plot the data. Hint: it may be useful to plot the flux as counts/m^2/s/Å versus wavelength in Å. Try first to get a reasonable model spectrum for the continuum. You may do this by ignoring the part of the spectrum where you see lines.

2. Set up next the full model by adding lines with `delt` and relativistic broadening by `laor`. Do not forget to use all data again, and it may be wise at this stage to freeze the parameters for the continuum (but do not forget to thaw them for your final fits).

3. Fit the spectrum. Hint: do not thaw all parameters at the same time, but step by step.

   In the `laor` component you can free the parameters `r1`, `r2`, `q` and `i`. You can find the line energies of the oxygen and nitrogen lines also in the SPEX line list. Is the fit acceptable? Look at the residuals of the fit and check wether the lines are well fitted. If not, try to find out which parameter of the `laor` component should be altered.

4. The inner radius of the disk `r1` tells you immediately the spin of the black hole. A non-spinning black hole has $r_1 = 6$, a maximally spinning black hole has $r_1 \to 1$. What can you tell about the spin of the black hole?

5. Vary the parameters `r1`, `r2`, `q` and `i` to see how they influence the line profile (give them manually a different value and issue the "calc" command followed by the "plot" command).

Learning goals:
After having done this spectrum, you should know:

- How to create a complex model with relativistic emission lines

- The usefullness of freezing parameters or omitting initially parts of the spectrum to get a first-step estimate of the spectrum

- How X-ray spectra tell you something about spinning black holes

7 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_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 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 may 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 ter1 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. 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 $\dot{M} = \Omega m_H n r^2 v$ and the kinetic energy carried away per second is $L_K = \frac{1}{2} v^2 \Omega m_H n r^2 v$.

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?

Learning goals:
After having done this spectrum, you should know:

- How to use models for photo-ionised plasmas

- How you can get more info out of SPEX by using the "asc" commands

- Some basic parameters of black hole winds that can be derived from X-ray spectra