Observational Astrophysics

Practice 4: Spectroscopy

1 Introduction

The object of this practice is the reduction and analysis of images obtained with a spectrograph. From them we have to extract spectra calibrated in wavelength and flux. The images to work with have been obtained with the 50 cm. telescope of the Aras de los Olmos Observatory. The work will be done by using the IRAF software package.

2 Image calibration

To initialize IRAF, click on the corresponding icon in the applications of the Linux virtual desktop Ubuntu. A terminal will open with the "command language" cursor:

```
ecl>
```

First, type the instruction:

```
set stdimage=imt2048
```

Next, go to the working directory and open a graphical window to view the images:

```
!ds9 &
```

We see that spectroscopic images have a very different appearance than the direct focus images. It is important to understand the content of each image before moving on to the subsequent processing.

As always when working with astronomical images, the first step is the removal of the instrumental signature, through the process we call calibration. In the images of this practice, the calibration consists of the subtraction of the polarization current ("bias"), the dark current ("dark") and the sensitivity correction ("flat field"). We will do all this with the "ccdproc" tool. To invoke it we move to the directory where it is located:

```
noao
imred
ccdred
```

First we have to check that the system is able to recognize the main characteristics of our images, such as the type of image corresponding to each file. To do this we type:

```
setinstrument direct
<ctrl>+d
<ctrl>+d
```

And then we list the images, to check that the assigned types are correct:

```
ccdlist
```

by answering "*" to the image name.

For bias correction, we first create a mean bias image with:

```
zerocombine
```

Next we subtract the bias using a first pass through "ccdproc". To do so we edit its parameter file,

```
epar ccdproc
```

and configure it by entering the value "yes" in "zerocor", and "no" in the rest of the actions; in the parameter "zero" we enter the name of the mean bias image Zero.fits. We execute the instruction:

```
ccdproc
```

by answering "*" to the image name.

We repeat the process for dark correction. We first create the master dark file with

```
darkcombine
```

and configure it by entering the value "yes" in "darkcor", and "no" in the rest of the actions; in the parameter "dark" we enter the name of the master dark image Dark.fits. We execute ccdproc again.

Next, we create a flat field master image using flatcombine. Before running it, we must edit its parameter file:

```
epar flatcombine
```

and indicate the values for the gain and readnoise, which for the CCD used (Starlight Xpress SXV-H9) are 0.45 e^-/ADU and 5.0 e^- respectively. We must also make sure that the process parameter is set to "no".

In the case of spectroscopic data, we cannot expect the flat field master image to contain a more or less uniform distribution of illumination, as in the case of the direct images we have used for photometry. On the one hand, the light from the thermal lamp used for the flat field is not evenly distributed over all wavelengths, and on the other, the sensitivity of the CCD also varies with the energy of the incoming radiation. Therefore, we can expect that the illumination will vary along the spectral direction. This can be verified by analyzing the master image, Flat.fits, with "imexamine". If we sample along a row with the "l" command, we will obtain something similar to that shown in Fig. 1.

If we were to divide the "flat" image by its mean value, as in the case of direct images, the "flat field" correction would depress the central region along the spectral direction, and increase the extremes, thus distorting the image to be calibrated. Therefore, with spectroscopic images we cannot proceed in the same way as with direct images.

In the case of spectroscopic images, what we are trying to do is correct for high-frequency sensitivity differences in the spectral direction. In other words, smoothing out the variation in illumination along that direction, which as we see in Fig. 1, is not a smooth curve but rather presents a noticeable degree of noise. We also intend to correct the differences in sensitivity along the spatial direction.

To achieve this, instead of dividing the "flat" image by its mean value, we divide it by a function fitted along the spectral direction. We fit this function with the "response" tool, which is located in the noao/twodspec/longslit

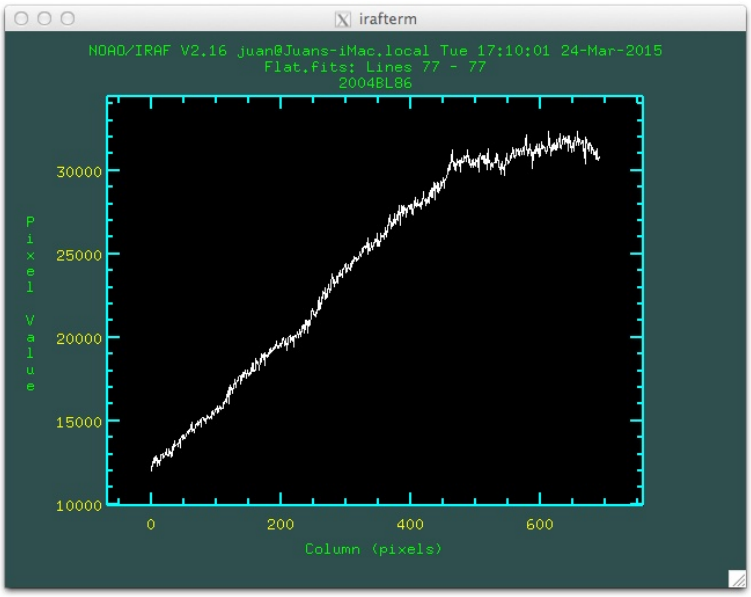

Figure 1: Sampling of the Flat.fits image along the spectral direction.

directory. To move to it from the noao/imred/ccdred where we are, we do:

```
bye
bye
twodspec
longslit
```

We execute the "response" task. It will ask us a series of questions, which we answer as follows:

Longslit calibration images (): Flat.fits
Normalization spectrum images (): Flat.fits
Response function images (): Flat0.fits
Fit the normalization spectrum for Flat.fits interactively (): yes

A graph like the ones shown in Fig. 2 will appear. In it we see the image collapsed along the spectral direction as a continuous line, and the fit as a dashed line. Above the graph we see the fitting function used and the order of the fit, along with other information.

If the fit is not satisfactory, we can modify it using a different function or a higher order fit. To do so, type ":", and then "order n" to change the order of the fitting (e.g. :order 3) or "function FUNCTION" for different fitting functions (e.g. :function spline3). The possibilities are spline1 (linear spline), spline3 (cubic spline), legendre or chebyshev. The program that performs the fit is called "icfit", and we can find more information by typing

```
help icfit
```

Each time we change the order or the fitting function we type "f" to make the new fit, and we check whether it is better than the previous one by visual inspection of the graph and the RMS. Once we are satisfied with the fit we exit the program by typing "q". The fit in Fig. 2, rifgt panel, has been obtained with a spline3 function and order 15.

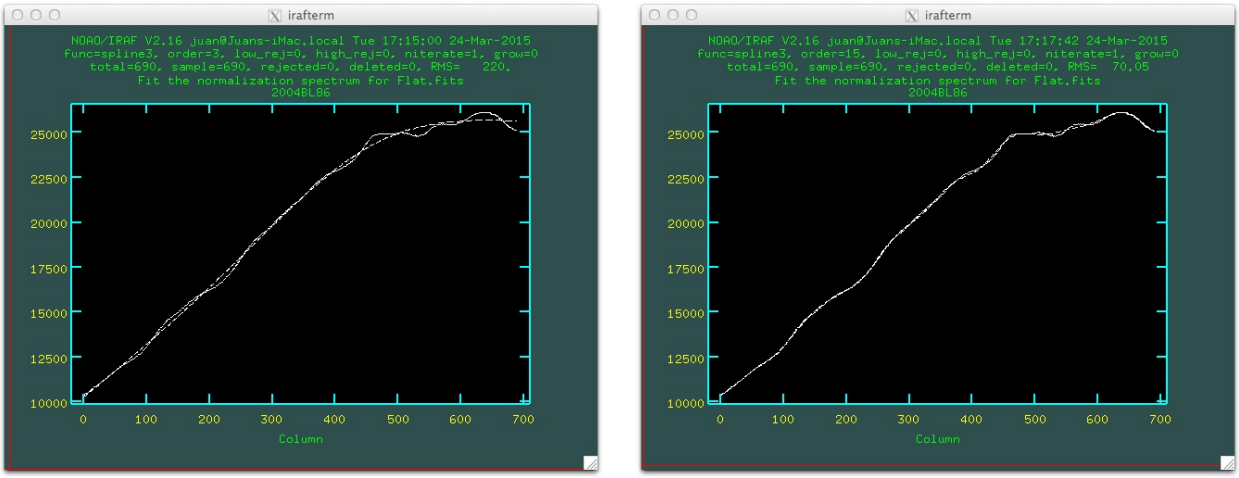

Figure 2: Fit to the illumination function of the flat field image with `response`. Left: first fit with an order 3 cubic spline. Rigth: final fit with an order 15 cubic spline.

The use of "response" creates the image "Flat0.fits", suitable for the "flat field" calibration of the spectroscopic images. To perform the calibration with "ccdproc" we return to the noao/imred/ccdred directory, and edit the "ccdproc" parameter file. We write "yes" in the "flatcor" parameter, and "no" in the other actions. In the "flat" parameter we write the file Flat0.fits, generated with "response", instead of the Flat.fits generated with "flatcombine".

After running "ccdproc" with these parameters we already have the calibrated images ready for astronomical exploitation.

3 The extraction of the spectra

To extract the spectra we will use the "apall" tool, located in the directory noao/imred/ctioslit. We type "apall" followed by the name of one of the images that contains the spectrum of a star:

```
apall image_name
```

We answer the questions as follows:

Find apertures for nombre_imagen? (yes): yes
Number of apertures to be found automatically: 1
Resize apertures for nombre_imagen? (yes): yes
Edit apertures for nombre_imagen? (yes): yes

The profile of the star along the slit appears in the spatial direction, with the spectrum and sky extraction intervals marked, as shown in Fig. 3. We can modify both the extraction aperture and the background extraction area.

If the profile and the extraction area appear too narrow, we can zoom in on the graphic. To do so, we place the cursor on the lower left limit of the region we want to select, and press "w" and then "e". Next, we move

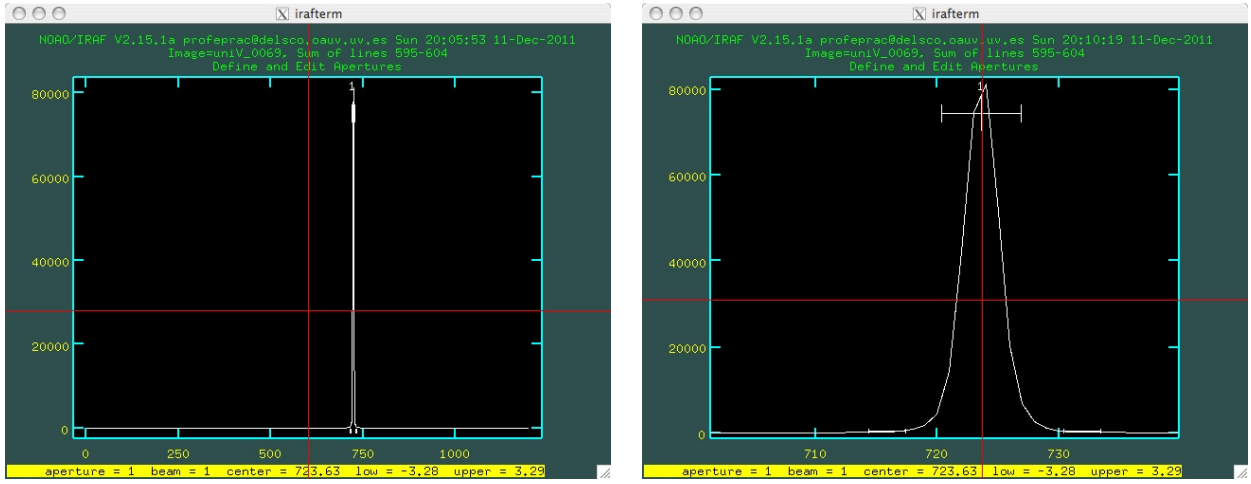

Figure 3: Extraction of the spectrum with "apall"

the cursor to the upper right limit, and press "e" again. We can repeat this operation for a deeper zoom, until we see the star profile and the selection intervals correctly, as also shown in Fig. 3, right panel. If we want to return to the initial image before zooming in, we press "w" and then "a".

In general, the extraction parameters proposed by the program are adequate, and we can accept them without further ado. However, we have the possibility to modify them, using the following options:

- Modify the width of the extraction aperture by changing its upper and lower limits (e.g. `:upper n1, :lower n2`). n1 and n2 represent the number of pixels from the center of the aperture. n2 must be a negative integer.
- We can define the limits of the aperture with the cursor. To do so, move the cursor and type "y". The selected aperture will be the intersection of the horizontal axis of the cursor with the profile of the line.
- We can also delete the selected aperture to start over. To delete it, type "d". We define a new aperture by positioning the vertical axis of the cursor and typing "n". The width of this new aperture can be modified as explained in the previous points.

Once we are satisfied with the spectral extraction aperture, we select the extraction area of the sky. To do so, we type "b". We enter a graphic window different from the previous one, in which the background level is marked as a horizontal line. This line must be at the level of the background that we see in the image on the sides of the star. If it is not, we have to modify the background extraction regions. We first delete the previous selection by typing "t". We select a new extraction zone to the left of the spectrum with the vertical axis of the cursor, typing "s" to mark the beginning of the interval, and again "s" at the end. We do the same to select another zone at the right side of the star. We type "f" to see the fit to the background, and if we are satisfied, again "q" to return to the aperture editor.

If everything is OK, we type "q" again and answer "yes" to all questions. A new graph appears, showing the fit model to the spectrum (dotted line), and its difference from the center of the line along the entire spectral direction (crosses), see Fig. 4. If the fit is not satisfactory, we can modify it using a higher order fit (e.g. :order 3) or different fitting functions (e.g. :function spline3), just as we did with the fit to the flat field in the previous section.

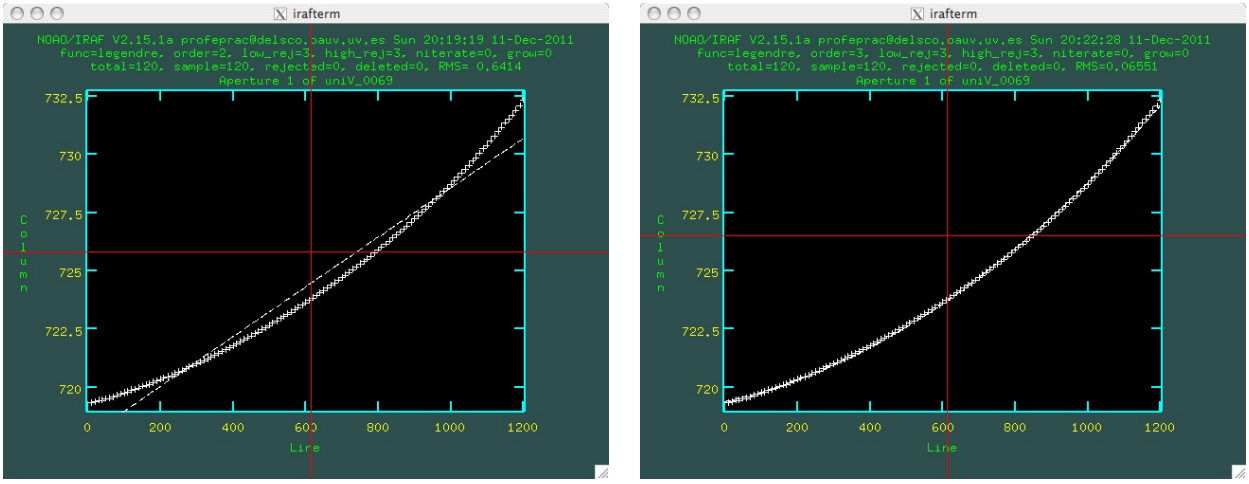

Figure 4: Fit to the spatial variation of the stellar image center. Left: first fit proposed by the software. Right: Final fit of order 3.

We type "f" for a new fit, and check if the RMS is better than the previous one. Once we are satisfied with the fit, we first note the lines occupied by the spectrum along the spatial direction on the CCD ($\sim$ 720 to 730 in the example in Fig. 4), which will be used to extract the spectrum of the lamp for calibration in wavelengths. Next we exit the program by typing "q" and answering affirmatively to the questions. At the end we see the extracted spectrum. We press "q" again to return to the command line.

We can see the spectrum again with the instruction

```
splot image_name.ms
```

Which shows us the extracted spectrum.

4 Wavelenght calibration

For wavelength calibration we will use a spectrum of a discharge lamp, also called a spectral arc. To proceed with wavelength calibration, we first represent the spectrum with:

```
identify lamp_image_name section='line l1 l2'
```

Where l1 and l2 are the lines in the spatial direction between which we will extract the lamp spectrum, that we have noted in the last step of "apall" before extracting the corresponding stellar spectrum. We see that an emision line spectrum appears, as represented in Fig. 5. We select each line with the vertical axis of the cursor, and type "m". Next, we type the wavelength of that line, which we find in the atlas presented in Fig. 6. Note that the spectrum to be calibrated is inverted with respect to that of the map (i.e., decreasing wavelengths from left to right). Once the wavelengths have been selected, we press "f" to obtain the fit.

A graphical representation of the fit appears again, with information about the order, the fitting function and the dispersion. Again, this fit is made with "icfit", and so, as in the previous cases, we can vary these parameters, and obtain a new fit by typing "f" again.

If we are satisfied with the fit, we exit the program by typing "q" twice, and answering affirmatively to the

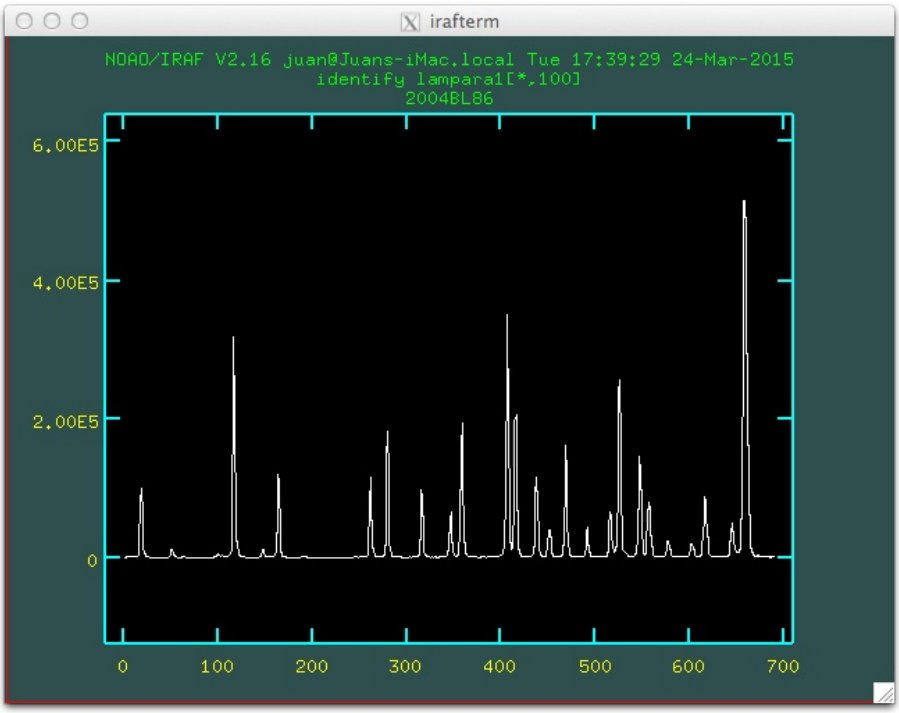

Figure 5: Calibration lamp spectrum.

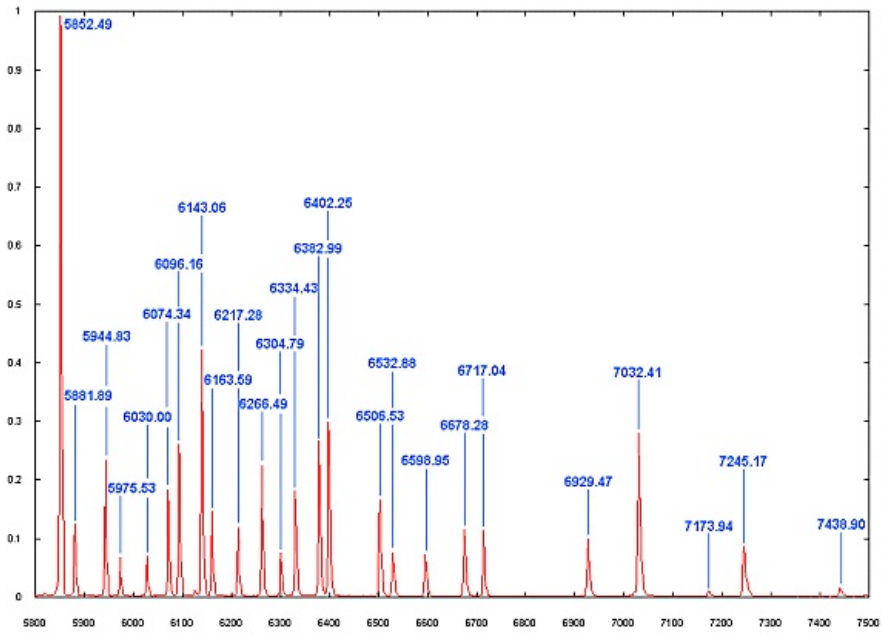

Figure 6: Neon lamp atlas.

question

Write feature data to the database (yes)?

The output of the program is a file created in the "database" directory and called `idname`.

To associate the wavelength calibration with our spectrum we have to introduce the keyword "REFSPEC1" in its file header, and associate it with the file that contains the results of the fit. We do so with:

```
hedit spectrum_name.ms REFSPEC1 "lamp_image_name" add+
```

And then we apply the wavelength calibration:

```
dispcor spectrum_name.ms new_name.ms
```

To see the spectrum wavelength calibrated we type:

```
splot new_name.ms
```

We follow the procedure outlined in the last two sections to extract and wavelength calibrate all spectra of interest.

5 Continuum normalization

To normalize the continuum to the unit we also use the "splot" task:

```
splot new_name.ms
```

We type "t", and then "/". Next we have to select the regions of the continuum to be fitted, which are the areas where no line appears. We place the cursor so that the vertical line is at beginning of the first of these areas, and press "s". We move the cursor up to the end of the area to be selected, and press "s" again. We repeat this operation as many times as intervals of the continuum we want to use for the fitting.

To finish we press "f", and the fitting function and fit parameters appear at the top of the graphic window. If the fit does not satisfy us we can change the function or the order, as we have done previously. If we want to choose the regions of the continuum again, we press "t" and proceed as we have just described.

Once the fit is satisfactory, press "q" to finish, and the normalized spectrum shows up. To save it, press "i", and the program asks for a name for the normalized spectrum. We write the name, and exit by pressing "q".

Once we have obtained the final spectrum, we can convert it to ASCII format, to work with it using a spreadsheet, graphic program, etc. We do this with the instruction:

```
noao
onedspec
wspectext name.ms name.txt
```

6 Line parameters analysis

The "splot" program also allows us to determine the fundamental parameters of the lines, from spectra already calibrated in wavelength and with normalized continuum.

6.1 Line flux and equivalent width

We call the program with:

```
splot file_name.ms
```

We carefully place the cursor on a point on the continuum, at the left side of the line to be analyzed, and press "e". We then move the cursor to another point on the continuum at the right of the line, and press "e" again. The program calculates the position of the center of the line, its equivalent width (note that for emission lines the equivalent width is negative), the level of the continuum and the flux over the continuum. We can repeat the process using different points on the continuum, to estimate the error of each of these values.

6.2 Line profile fitting

We can fit different analytical functions to the profile of a spectral line. This can also be done with "splot". Once the line is represented, we carefully place the cursor on the continuum at the left of the line, and press "k". Next we move the cursor to a point on the continuum at the right of the line, and press "g" to obtain a Gaussian fit, "l" for a Lorentzian fit, or "v" for a Voigt profile. The fit appears superimposed to the spectrum, and we are also presented with the values of the center of the line, the equivalent width, and the width at the half-height, relative to the fitted function.

Once the fit is made, we can subtract it from the spectrum, to see the residuals of the line on the average profile. To do so, we position ourselves again at a point on the continuum at the left of the line, and press "-". We move the cursor to a point at the right, and press "-" again.

In the case of lines with several components, we can simultaneously fit several profiles to the line. To do so, we should first zoom in on the region where the line is located. We do this as we have already done with "apall", placing the cursor on the lower left limit of the region we want to select, and press "w" and then "e". We then move the cursor to the upper right limit, and press "e" again.

We then place the cursor on the continuum, at the left of the line, and press "d". We then place it at the right, and press "d" again. We now move the cursor until the vertical line coincides with the center of one of the components we want to adjust. Once positioned, press "g" for a Gaussian fit, or "l" or "v" for a Lorentzian or Voigt fit, respectively. We repeat the operation for each of the components of the line we want to adjust. When they are all there, press "q".

The program asks us a series of questions:

- Fit positions (fixed, single, all, quit)

  It asks us if, for the adjustment, we keep the centers of the lines we have marked fixed (fixed), or allow the program to consider them as free parameters of the adjustment (all). The "single" option adjusts them keeping the distance between them fixed. Press "f", "s" or "a" according to the option you prefer, or "q" to finish.

- Fit Gaussian widths (fixed, single, all, quit).

  The same, with the same meanings, for the widths at the half-height of the adjustment functions.

- Fit background (no, yes, quit)

  The option is whether to fit the level of the continuum ("y") or enter it manually by pressing "d" on the continuum ("n").

- Overplot (total, components, both, none)

  We choose between representing the global fit ("t"), the individual fits to each component ("s"), both ("b") or none ("n").

Once the fit is finished, the parameters of the first fitted function appear on the bottom line. We can press "+" or "-" to move over the list of components and see the fits to each of them. We exit the process with "q".