A User's Guide to Reducing Echelle Spectra With IRAF

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Echelle spectra are generated by the use of a high angle (typically 63 deg) ruled grating usually cross-dispersed by a low dispersion grating, grism, or prism. The result is a high resolution, closely spaced array of side-by-side orders of large spectral coverage. The amount and nature of the data can be intimidating to observers to reduce and analyze. Fortunately some powerful tools have been written in IRAF to make this task manageable. This manual describes the use of these tasks.

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Contents

1 Introduction

Echelle spectra are generated by the use of a high angle (typically 63 deg) coarsely ruled grating usually cross-dispersed by a low dispersion grating, grism, or prism. The result is a high resolution, closely spaced array of side-by-side orders of large spectral coverage. Figure 1 shows a surface plot of a small section of a typical echelle spectrum viewed parallel to the orders. In addition to the well defined orders, numerous "cosmic ray" spikes are visible which will (hopefully) be "cleaned" out of the final extracted spectra by the tasks described here. As such, echelles produce excellent formats for two-dimensional arrays such as CCDs. However, the amount and nature of the data can be intimidating to observers to reduce and analyze. Fortunately some powerful tools have been written in IRAF to make this task manageable. This manual describes the use of these tasks, and is a supplement to the following manuals.

- *A User's Guide to CCD Reductions with IRAF* by Philip Massey (hereafter UGCRI)
- *A User's Guide to Reducing Slit Spectra with IRAF* by Massey et al. (hereafter UGRSSI)
- The main extraction task, **doecslit**, has rather lengthy parameter sets, and the document *Guide to the Slit Spectra Reduction Task DOECSLIT* by Francisco Valdes, should be at hand.
- For users new to IRAF, the document *A Beginner's Guide to Using IRAF* may be a good starting point.
- Help pages for tasks in the **echelle** package will also be useful.

This manual assumes that the user is familiar with IRAF, so in this sense it is not a cookbook. It is also assumed that the user has already made at least one pass with **ccdproc** (see UGCRI) to debias and trim the data. Flat-fielding requires special considerations and that is where this manual begins after a summary of the reduction process.

The preliminary reductions are done within the **noao.imred.ccdred** package; the actual echelle reductions are done using tasks in the **noao.imred.echelle** package.

An attempt is made to use different font types for IRAF tasks, parameters, and image names:

- a bold font is used for an **IRAF task name**
- an italic font is used for a *task parameter*
- a computer font is used for an `image name` or an `interactive cursor keystroke`

2 Overview of Reduction Process

1. Follow the first six steps as outlined in UGCRI, Section 3.1, to combine zeros and flats, and to trim and debias the data.

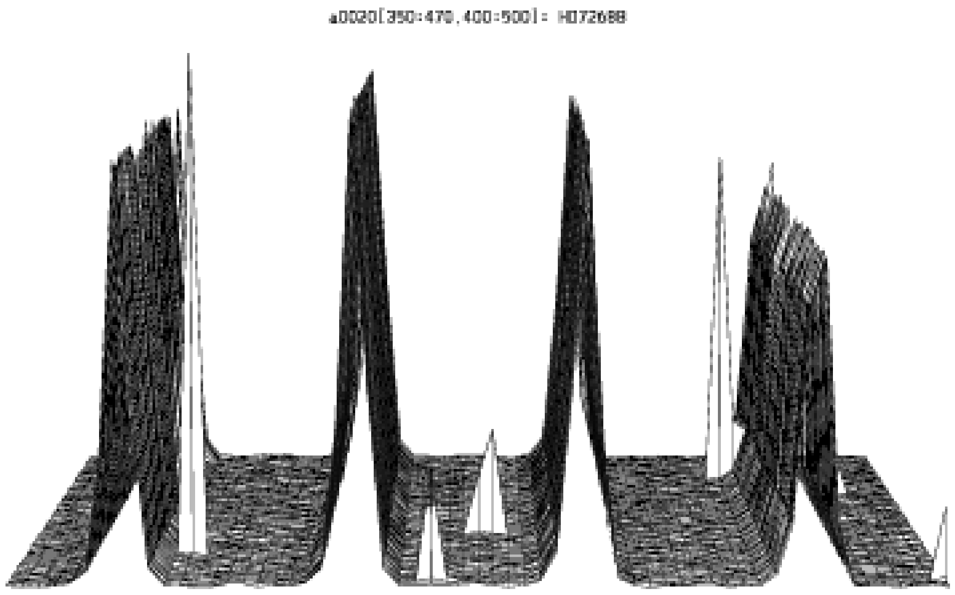


Figure 1: Surface plot of a small section of a typical echelle spectrum viewed parallel to the orders.

2. Create a normalized flat from your average flat with **apflatten**.
3. Run **ccdproc** again to flat-field the objects and comps.
4. Extract the data with **apall** (no wavelength calibration) or **doecslit** (with wavelength calibration). In the first case, wavelength calibration could be done subsequently with **ecidentify**, **ecreidentity**, **refspec**, **setairmass**, and **dispcor**. The output in either case will be a two dimensional image with as many lines as orders extracted.

3 Processing Details

We now go through the steps listed previously in detail, discussing the individual task parameters.

3.1 Initial CCD Processing

Only a few items will be mentioned here considering the wealth of detail given in UGCRI. One should **implot** a few raw biases and flats to check for any fluctuation in the overscan or the lamp. If the overscan is seen to vary by more than an ADU or two from one zero image to another, one may want to debias and trim the individual images before running **zerocombine** or **flatcombine**.

If flats are taken in more than one group, say 10 at the beginning and 10 at the end of the night, there may be a slight image shift on the CCD between the two groups. In this case it might be preferable to **flatcombine** each group separately to remove cosmic rays and then run **flatcombine** again without rejection or scaling to combine the group averages into one final average flat. Otherwise there may be very noisy edges on the average flat where the image shift caused excessive pixel rejection.

One item not discussed in UGCRI is how to fix bad columns or pixels by interpolation with **ccdproc**. First, one must decide which if any pixels are bad, or are not linear with flat-fielding. This may be a bit difficult to determine, but generally if a pixel drops to near bias level, it will not flat-field. A more empirical method might be used but depends upon obtaining a couple of groups of flats at different exposure levels. After de-biasing the flats and averaging each group with **flatcombine**, divide one average flat by the other with **imarith**. Any non-linear pixels should be obvious. One might also be able to determine the faulty pixels from the data itself after **imcopy**ing a test image and flat-fielding it. Cosmic rays may confuse the determination however.

After the bad pixels have been identified, create a bad pixel file by identifying them as rectangular sections, one to a line:

```
149   149   1     800
250   252   450   800
```

Here we have a short file identifying the region as column 149 and all rows (lines) of the CCD as bad. The second line designates the region between columns 250 and 252 and between lines 450 and 800 as bad. When **ccdproc** is run on the data, set the parameter *fixpix* to yes", and the parameter *fixfile* to the name of the file you have created, e.g., "badcols".

3.2 Creating a Normalized Flat

Flat-fielding is done mainly to remove individual pixel sensitivity variations, chip interference fringing (if any), and possibly the slowly varying grating blaze function. It is desirable that the flat-fielding process does not significantly change the intensity of the pixels or their relative values perpendicular to the dispersion. Otherwise, the spatial profile would be altered and optimal extraction and cosmic ray removal would not be as effective.

We therefore need to normalize the average flat by fitting its intensity along the dispersion by a first or higher order fit, while setting all points outside the order aperture to 1. The task **apflatten** can be used to do this; a typical parameter set is shown in Figure 2. The parameters are set after examining the particular flat to be used. In this case we are using a flat from the echelle/grism setup at the 2.1m coude spectrograph as shown in Figure 3. **Apflatten** uses parameters from **apdefault**, **apfind**, **aprecenter**, **apresize**, **apedit**, and **aptrace**, so check these also. Many of these individual tasks have parameters that are redundant with those in **apflatten** and only the ones specific to that task need be set. The other important parameter set is the echelle package parameters. Type **epar echelle** and check the *dispaxis* parameter. For orders (roughly) parallel to rows, set *dispaxis* = 1, and for orders parallel to columns, set *dispaxis* = 2. You may also want the *verbose* parameter set to "yes" in order to see on the screen all the information on the extraction that is sent to the logfile.

Notice that even though there is some scattered light present ($\sim 3\%$), we have *background* set to "none" as we are more interested in the variations in the flat orders than their exact level. If your version of IRAF is earlier than V2.10.2, the *gain* parameter should be set to 1. A bug in earlier versions causes the output spectrum to be multiplied by the gain. This will generally not affect the result as cleaning will already have been done during **flatcombine**. If your version of IRAF is V2.10.2 or later, this should not be a problem.

Running **apflatten**,

```
apflatten Flat NFlat
```

will first enter the aperture editor (Figure 3) where all the relevant apertures can be marked, if not already, and the aperture widths checked. You may want to set the width of the apertures using the **y** key during **apedit** for a more consistent aperture size than given by the auto-resize when in the presence of a varying background. When satisfied with the aperture selections, type **q** to enter the **aptrace** phase where all of the selected apertures can be traced interactively or at least their traces examined one after another, as described in UGRSSI, Section 3.3.2.

The **icfit** routine is used here to map closely the position of the aperture along the dispersion axis (Figure 4). If the initial fit does not follow the points to the desired closeness the following parameters can be adjusted:

1. The fit order can be increased (`:o n`, where n is the order number)
2. Deviant points deleted (`d` with cursor on point)
3. The number of fit iterations increased (`:niterate n`, n=number of iterations)
4. The high and low rejection sigmas (`:hi n, :lo n`, n=value of cutoff)

First time users may wish to review the discussion in UGRSSI, Section 3.3.2.

When the tracing has been finished, another **q** begins the fitting of the 1-dimensional aperture sum (intensity) along the dispersion to fit the general spectral shape of the flat field light. The fit parameters can be adjusted here just like for the **aptrace** phase. Figure 5 demonstrates how closely the fit can be made to the shape of the spectrum. In the far red fringing will be significant, and only the envelope of the spectrum can be fit. Alternatively, a first order legendre or chebyshev polynomial may be used if the shape of the flat is to be preserved.

After running **apflatten** you may want to plot the output image to see the bizarre result. You should see alternating smooth and noisy sections if plotting perpendicular to the dispersion (as in Figure 6) and a normal looking plot along an order. All values should be near 1.0. The regions between the orders have been set to 1, and the data inside the aperture have been normalized to 1 with the large scale fluctuations removed. If a first order function was fit to the light distribution, then the flat will have the same shape with an average value of 1.

```
                              IRAF
                 Image Reduction and Analysis Facility

PACKAGE = echelle
   TASK = apflatten

input   =                Flat  List of images to flatten
output  =                NFlat List of output flatten images
(referen=                    ) List of reference images

(interac=                 yes) Run task interactively?
(find   =                 yes) Find apertures?
(recente=                 yes) Recenter apertures?
(resize =                 yes) Resize apertures?
(edit   =                 yes) Edit apertures?
(trace  =                 yes) Trace apertures?
(fittrac=                 yes) Fit traced points interactively?
(flatten=                 yes) Flatten spectra?
(fitspec=                 yes) Fit normalization spectra interactively?

(line   =               INDEF) Dispersion line
(nsum   =                  20) Number of dispersion lines to sum
(thresho=                 20.) Threshold for flattening spectra

(backgro=                none) Background to subtract
(pfit   =               fit1d) Profile fitting type (fit1d|fit2d)
(clean  =                  no) Detect and replace bad pixels?
(skybox =                   1) Box car smoothing length for sky
(saturat=               INDEF) Saturation level
(readnoi=                   6) Read out noise sigma (photons)
(gain   =                 2.6) Photon gain (photons/data number)
(lsigma =                  4.) Lower rejection threshold
(usigma =                  4.) Upper rejection threshold

(functio=             spline3) Fitting function for normalization spectra
(order  =                   1) Fitting function order
(sample =                   *) Sample regions
(naverag=                   1) Average or median
(niterat=                   3) Number of rejection iterations
(low_rej=                  3.) Lower rejection sigma
(high_re=                  3.) High upper rejection sigma
(grow   =                  0.) Rejection growing radius
(mode   =                  ql)
```

Figure 2: Typical parameters for the **apflatten** task.

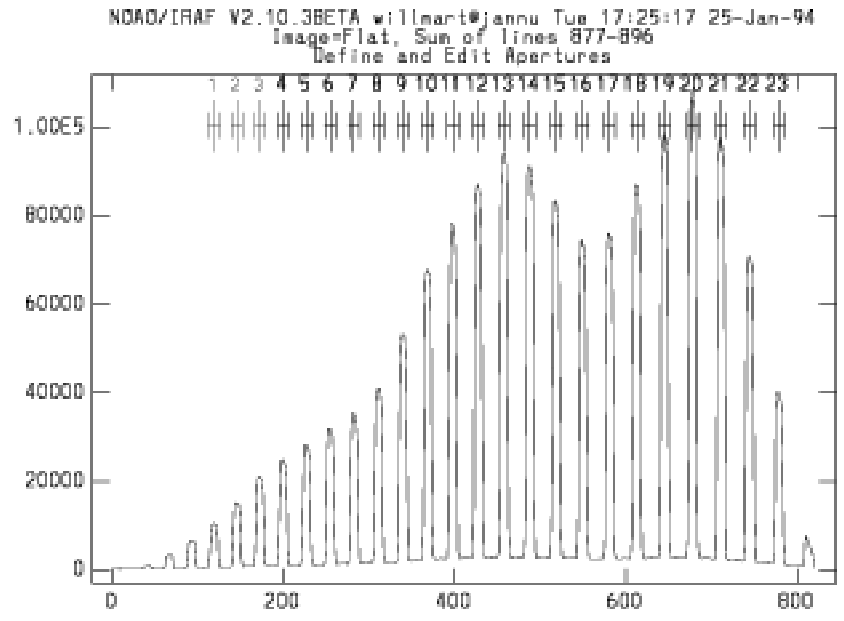


Figure 3: A flat from the echelle/grism setup at the 2.1m coude spectrograph with the orders and apertures marked.

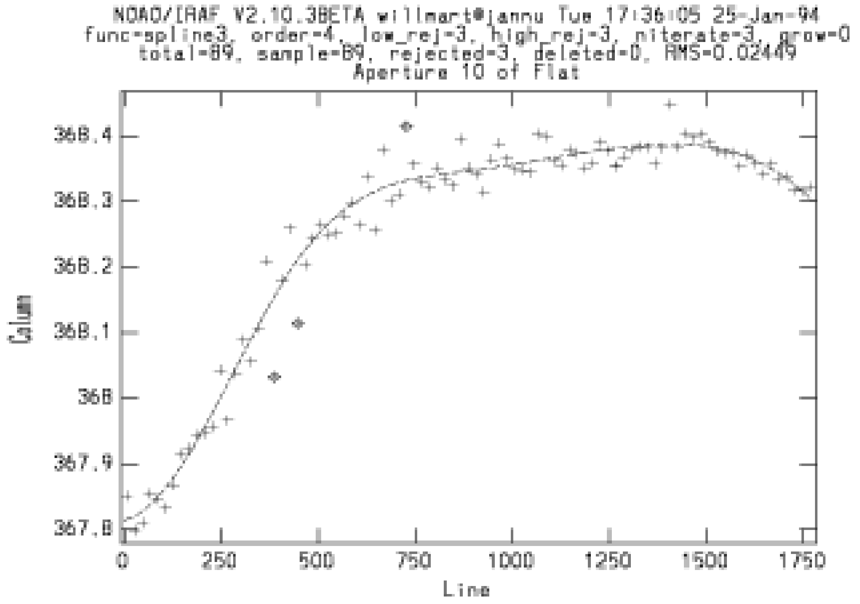


Figure 4: Position of an aperture along the dispersion axis. The line represents the fit to the data points. The fitting information is at the top of the plot.

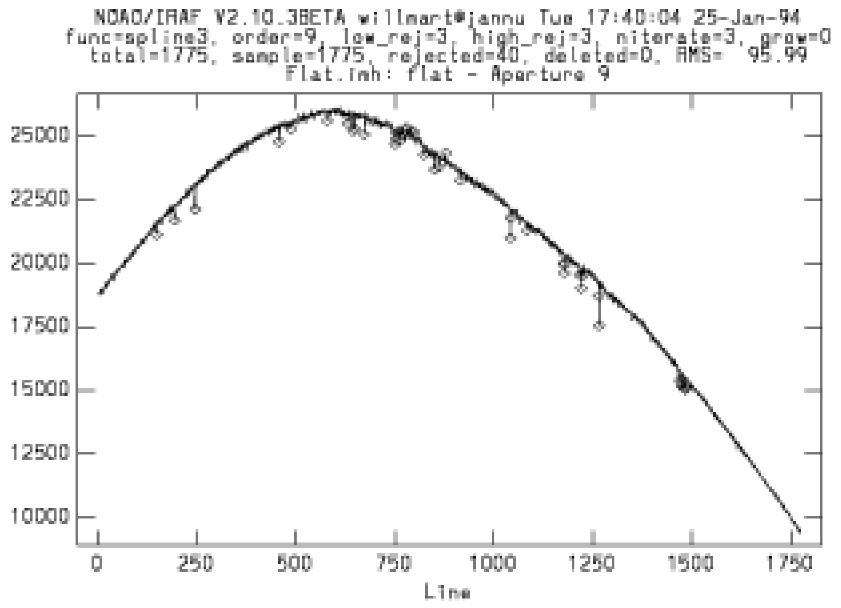


Figure 5: Fit along the dispersion of the general spectral shape.

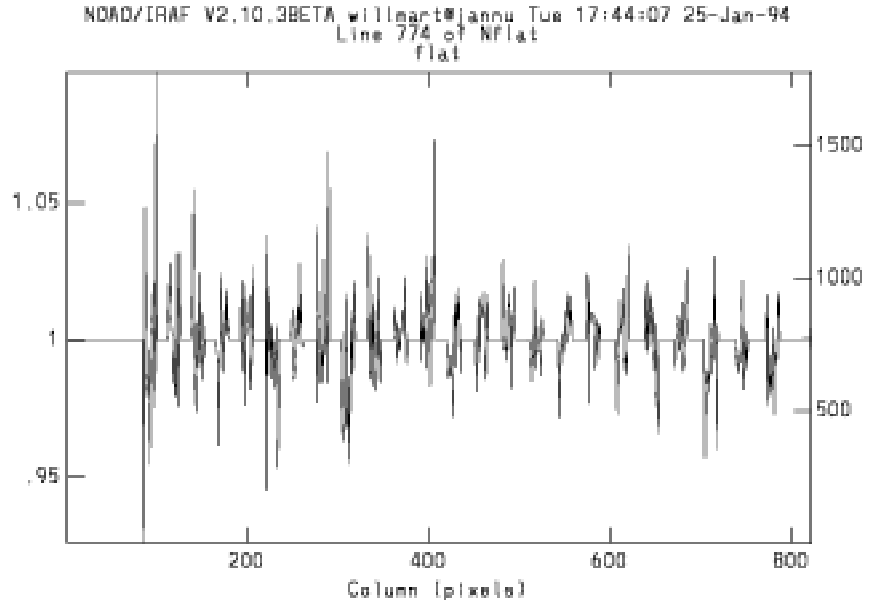


Figure 6: A plot of the output image from **apflatten** perpendicular to the dispersion. The regions between the orders have been set to 1; the data inside the apertures have been normalized to 1 with the large scale gradients removed.

The last step in preparing the flat is to reset the value of CCDMEAN in the header to 1. This parameter is added to the header during **flatcombine** for subsequent use in **ccdproc**. If the value of CCDMEAN is not changed, the object spectra would be multiplied by some large number and then divided by a flat whose value is roughly one resulting in spectra with counts many times higher than in the original data.

```
hedit Flat ccdmean 1.0
```

In IRAF versions V2.10.3 and later **apflatten** will reset CCDMEAN to 1 automatically.

3.3 Flat-fielding the Data

Now that we have our normalized flat we can proceed to flat-fielding the spectra with **ccdproc**. Trimming, overscan subtraction, and zero subtraction can also be done now if not previously. With **ccdproc** parameters set as before,

```
ccdproc @objects flatcor+ flat=NFlat
```

or **epar ccdproc** to set the parameters. Process the comps in the same manner.

3.4 Extraction of the Orders—doecslit or apall

Generally one will want wavelength scales on the spectra so **doecslit** is the task to use. **Apall** can be used otherwise or if one just wants to do it step-by-step. **Doecslit** has the advantage of extracting each comparison spectrum with exactly the same aperture as the object. Prospective users should read the IRAF document *Guide to the Slit Spectra Reduction Task DOECSLIT* by Francisco Valdes. Since **apall** is just a subset of **doecslit**, its use will not be discussed here, but all of the details except wavelength calibration, extinction correction, and flux calibration are applicable.

A careful examination with **implot** of a typical object image is useful to determine values for setting task parameters. These include the base width of the orders, order separation, maximum signal level, number of orders to be extracted, and scattered light and/or sky background levels.

There is generally a few percent (compared to order maxima) of scattered light present in echelle spectra. It is often helpful to average 50–100 rows or columns perpendicular to the dispersion to see a more accurate view of the nature of the scattered light, as in Figure 7. Here we find about 60 ADUs of inter-order light with some structure compared to order maxima of around 4700 ADUs. We can only assume (conveniently!) the scattered light under an order is continuous with the inter-order light, and a smooth fit between the orders will be representative. Comparison exposures generally have negligible scattered light.

There is more than one way to subtract scattered light, but the most rigorous method does it during extraction with **doecslit** (or **apall**). This is recommended as only here is the noise of the background taken into account for cosmic ray cleaning and optimal extraction. Since the scattered light is highest near the peak intensity of an order, the background noise

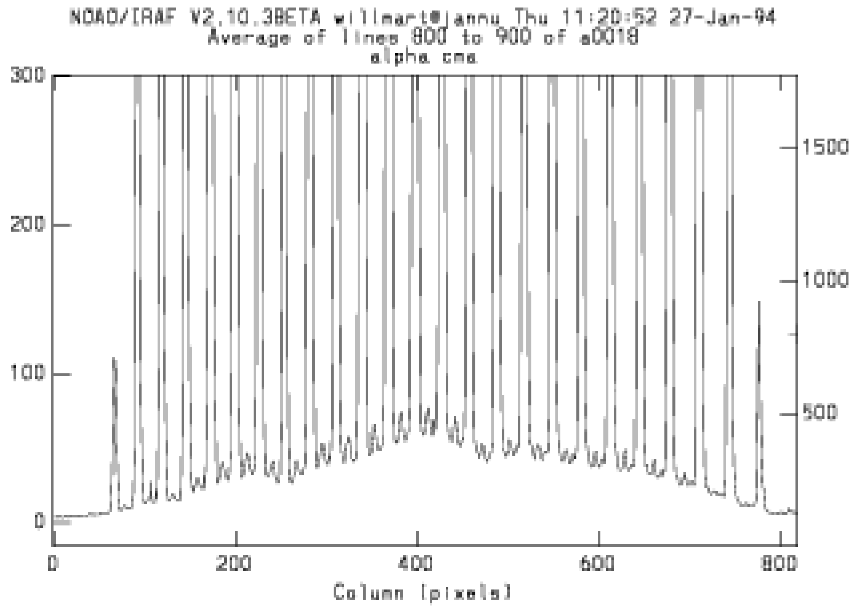


Figure 7: A plot perpendicular to the dispersion showing the scattered light.

is also higher here; in other words there is a variable background noise level. There are several methods for subtracting the background within **doecslit**, and the **doecslit** guide can be consulted for details. Here also the distinction can be made between scattered light and true background from the sky. Sky background will usually not be significant at the f-ratio of the coude feed telescope, but could be with the 4-m echelle. If scattered/background light is to be removed in **doecslit**, it is important to do a careful job of normalizing the flat in **apflatten**. Fitting a constant to the flat to preserve its spectral shape won't do as this flat would change the values of the object spectra compared to the inter-order regions where they are divided by 1.

A method to subtract scattered light before extraction involves using **apscatter** where apertures are defined, sized, and traced. The area between the apertures is then fit (with deviant pixel rejection) perpendicular to the dispersion and then these fits are smoothed in the orthogonal direction. This is the most time consuming method, and can be shortened by not smoothing the fits, usually without too much loss of accuracy. This would be similar to using the task **background**, except there apertures are not defined. With **background** the orders are rejected by setting the parameters *low_reject* and *high_reject* to low values like 1 or 2. **Apscatter** can also be invoked from within **doecslit** but the noise values will not be remembered during weighted extraction.

Typical parameters for **doecslit** are shown in Figure 8. Note that it has a "nested" parameter set; that is the parameter *sparams* is actually another parameter set. It can be edited either by typing `:e` on that line or with **epar sparams**. One of the groups of parameters in

sparams (see Figure 9) concerns the manner in which the comparison spectra are assigned to each object spectrum. This is a very flexible part of the reductions and can assign and weight comparison spectra based on the relative time between the object and comparisons, the position in the sky, or even the date, to mention a few of the possibilities. The default in **doecslit** is to run the tasks **setjd and setairmass** on all spectra to compute and add the header parameters for the Julian Date (JD), the local Julian Date (LJD), universal time (UTMIDDLE), and the air mass at the middle of the exposure. This allows the reduction of more than one night of data by using LJD to group the data with the correct comparison spectra, and UTMIDDLE to assign the correct spectra within a given night. Using other criteria for assigning comparison spectra may involve adding new header keywords and computing values for them. The help pages for **refspectra** describe these options in detail and give several examples.

What the last paragraph infers is that **doecslit** is *header* driven—certain keywords are expected to be in the image headers. See the help pages for **setairmass** and **setjd** for more information. The image header keyword IMAGETYP must also be present in the image headers; possible values are "object", "OBJECT", "comp" or "COMPARISON". Data that are not from NOAO may need to be modified with **hedit** or **asthedit** before **doecslit** will run properly on the data.

3.4.1 Aperture and Background Definition

Having more or less characterized our images we can now run **doecslit**:

```
doecslit @imagelist
```

It is good practice to review the apertures initially found for the reference object and subsequent images. Occasionally an aperture width will not be wide enough due to asymmetry of the profile or a local peak. In these cases, the **y** key or the `l` and **u** keys can be used to resize the aperture. Check for proper numbering of the apertures which should be increasing or decreasing monotonically. The numbering should also be consistent with any skipped orders; the desired orders are numbered as if all were there. A useful option can be used by toggling the **all** key: if set, other commands will perform the same operation on all the apertures. For example the **y** key discussed above would resize all the apertures to the same vertical height instead of just the aperture near the cursor.

Of the various options available for background subtraction, one will probably want to use methods that eliminate cosmic rays and take the additional background noise into account. Global scattered light fitting (**apscatter**) does the former but not the latter. It is also very slow. The other method involves the definition of background regions on each side of the order by specifying a buffer distance from the edge of each aperture and a range of pixels. The background regions are set automatically by the program but can be changed interactively during the background review as discussed below. By using either the "fit" or "median" options of *background*, cosmic rays can be eliminated and the background noise values will be taken into account. If sky background is not a factor and just scattered light is present, boxcar smoothing of the background may be useful. Check the present value while in the

```
                              IRAF
                Image Reduction and Analysis Facility
PACKAGE = echelle
   TASK = doecslit

objects =              a0024 List of object spectra
(apref  =             a0018) Aperture reference spectrum
(arcs   =            @comps) List of arc spectra
(arctabl=                  ) Arc assignment table (optional)
(standar=                  ) List of standard star spectra

(readnoi=                 6) Read out noise sigma (photons)
(gain   =               2.6) Photon gain (photons/data number)
(datamax=             25000) Max data value / cosmic ray threshold
(norders=                24) Number of orders
(width  =                7.) Width of profiles (pixels)

(dispcor=               yes) Dispersion correct spectra?
(extcor =                no) Extinction correct spectra?
(fluxcal=                no) Flux calibrate spectra?
(resize =               yes) Resize object apertures?
(clean  =               yes) Detect and replace bad pixels?
(trace  =               yes) Trace object spectra?
(backgro=               fit) Background to subtract
(splot  =               yes) Plot the final spectra?
(redo   =                no) Redo operations if previously done?
(update =                no) Update spectra if cal data changes?
(quicklo=                no) Approximate quicklook reductions?
(batch  =               yes) Extract objects in batch?
(listonl=                no) List steps but don't process?

(sparams=                  ) Algorithm parameters
(mode   =                ql)
```

Figure 8: Typical Parameters for **doecslit**.

```
                              IRAF
                Image Reduction and Analysis Facility

PACKAGE = echelle
   TASK = sparams

(line   =               INDEF) Default dispersion line
(nsum   =                  20) Number of dispersion lines to sum
(extras =                  no) Extract sky, sigma, etc.?

                               -- AUTOMATIC APERTURE RESIZING PARAMETERS --
(ylevel =                0.05) Fraction of peak or intensity for resizing

                               -- TRACE PARAMETERS --
(t_step =                  20) Tracing step
(t_funct=             spline3) Trace fitting function
(t_order=                   2) Trace fitting function order
(t_niter=                   3) Trace rejection iterations
(t_low  =                  3.) Trace lower rejection sigma
(t_high =                  3.) Trace upper rejection sigma

                               -- BACKGROUND AND SCATTERED LIGHT PARAMETERS --
(b_funct=            legendre) Background function
(b_order=                   2) Background function order
(b_naver=                  -5) Background average or median
(b_niter=                   5) Background rejection iterations
(b_low  =                  3.) Background lower rejection sigma
(b_high =                  1.) Background upper rejection sigma
(buffer =                  2.) Buffer distance from apertures
(apscat1=                    ) Fitting parameters across the dispersion
(apscat2=                    ) Fitting parameters along the dispersion

                               -- APERTURE EXTRACTION PARAMETERS --
(weights=            variance) Extraction weights (none|variance)
(pfit   =               fit1d) Profile fitting algorithm (fit1d|fit2d)
(lsigma =                  4.) Lower rejection threshold
(usigma =                  4.) Upper rejection threshold
```

Figure 9: Typical parameters for **sparams**.

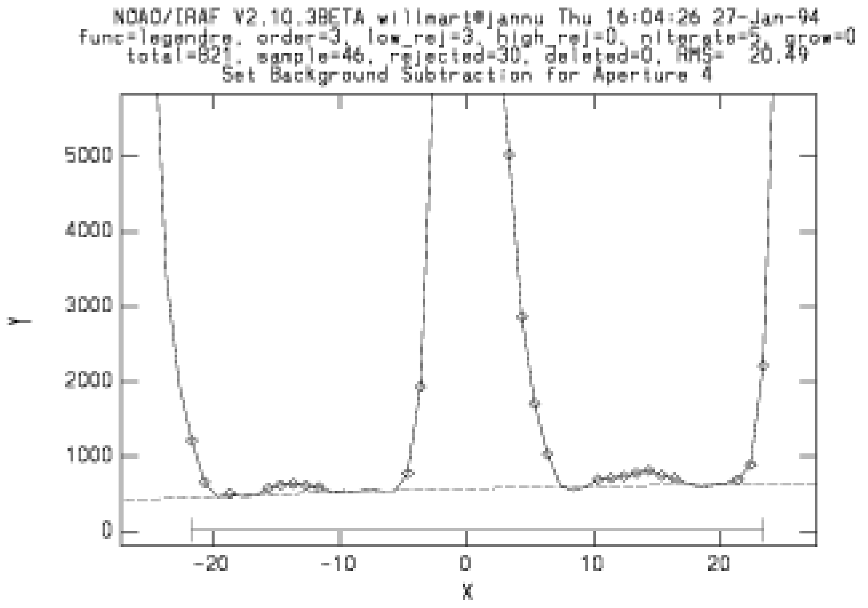
```
                               -- ARC DISPERSION FUNCTION PARAMETERS --
(coordli=  linelists$thar.dat) Line list
(match  =                 0.1) Line list matching limit in Angstroms
(fwidth =                 3.5) Arc line widths in pixels
(cradius=                  5.) Centering radius in pixels
(i_funct=            legendre) Echelle coordinate function
(i_xorde=                   3) Order of coordinate function along dispersion
(i_yorde=                   3) Order of coordinate function across dispersion
(i_niter=                   3) Rejection iterations
(i_low  =                  3.) Lower rejection sigma
(i_high =                  3.) Upper rejection sigma
(refit  =                 yes) Refit coordinate function when reidentifying

                               -- AUTOMATIC ARC ASSIGNMENT PARAMETERS --
(select =              interp) Selection method for reference spectra
(sort   =                  jd) Sort key
(group  =                 ljd) Group key
(time   =                  no) Is sort key a time?
(timewra=                 17.) Time wrap point for time sorting

                               -- DISPERSION CORRECTION PARAMETERS --
(lineari=                 yes) Linearize (interpolate) spectra?
(log    =                  no) Logarithmic wavelength scale?
(flux   =                 yes) Conserve flux?

                               -- SENSITIVITY CALIBRATION PARAMETERS --
(bandwid=                 10.) Bandpass widths
(bandsep=                 10.) Bandpass separation
(s_inter=                 yes) Graphic interaction to examine/define bandpasses
(s_funct=             spline3) Fitting function
(s_order=                   1) Order of sensitivity function
(fnu    =                  no) Create spectra having units of FNU?
(mode   =                  ql)
```

Figure 9: Typical parameters for **sparams**—cont.



```
NOAO/IRAF V2.10.3BETA willmart@jannu Thu 16:04:26 27-Jan-94
func=legendre, order=3, low_rej=3, high_rej=0, niterate=5, grow=0
total=821, sample=46, rejected=30, deleted=0, RMS=  20.49
Set Background Subtraction for Aperture 4
```

Figure 10: An expanded plot of an echelle order examining the background regions.

apedit stage with `:skybox`, or set it to the desired value with `:skybox 50`, for example. If background subtraction is turned on, check the regions for each order by typing `b` with the cursor centered on the order. An expanded plot will be drawn which you may need to expand vertically (and horizontally) with `w` and `e` as in Figure 10 to see the lower levels of the signal accurately. It might be easiest to start at the order with the largest separation (usually the red end). The sample region need not omit the order itself since the sigma rejection or medianing will eliminate the region within the order. The existing sample region can be deleted with `z` if necessary, and new ones defined with the `s` key. If the `a`(ll) key is set, all other orders will now have the same size region centered on them. Typing `f` will fit the background and show the rejected points.

3.4.2 Aperture Tracing

Once the apertures and background regions have been satisfactorily defined, type `q` to enter the aperture tracing phase. Here one can interactively fit the curve defined by the center of each order at points along the order specified by the parameters *nsum* and *t_step*. An initial aperture trace is displayed, after which the order of the fit may be changed (`:o n`) or points deleted (`d` with cursor at point) and the curve refit by typing `f`. The function type itself may also be changed (`:func chebyshev,legendre,spline1`, or `spline3`) and the curve refit. A spline3 function has been found to work well for the aperture curves with a different number of pieces for various orders. When a satisfactory fit is obtained as in Figure 4, typing `q` will display the next order for fitting.

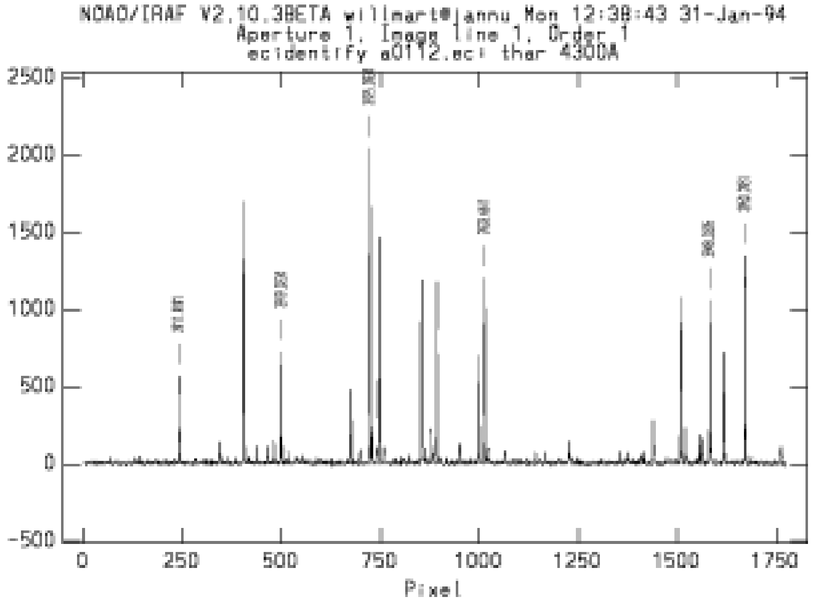


Figure 11: A plot of the comparison spectrum for the first order.

3.5 Comparison Identification and Wavelength Solutions—ecidentify

After q is typed for the last aperture trace of the reference spectrum, the first comparison image will be extracted based on the apertures just defined for the reference image. The first plot will be of the first aperture of the comparison spectrum (Figure 11). It is assumed that an appropriate file is specified for the parameter *coordlist* ("linelist$thar.dat" by default). The trick now is to identify a few lines in each of an order near the first, middle, and last apertures. In other words, you needn't identify lines in all the apertures or necessarily in the first aperture, but at least three apertures should have identifications. It can be sometimes difficult to make the initial line identifications, and perhaps one of the object spectra with known lines can help to pin down the rough area. With the help of an appropriate atlas of the comparison lamp (e.g., *A CCD Atlas of Comparison Spectra: Thorium-Argon Hollow Cathode*) set the cursor on a known line, type m (mark) and type in the wavelength. Usually entering to the nearest tenth of an Ångstrom is sufficient to match a line in the linelist. Mark several lines across the order and then move to a new aperture with the j, k or o key. Knowing the wavelength of one order will enable one to predict wavelengths in other orders with a table of central order wavelengths such as in the *KPNO Coude Spectrograph Manual*. Do not type f (fit) until the three or more apertures have had lines marked. Otherwise, the derived fit may not be accurate enough to automatically find additional lines from the linelist. Occasionally there will be one or more intense lines in the plot which scale the plot such that few other lines are distinguishable. In these cases rescaling the plot with w and e will help to see the lower intensity lines.

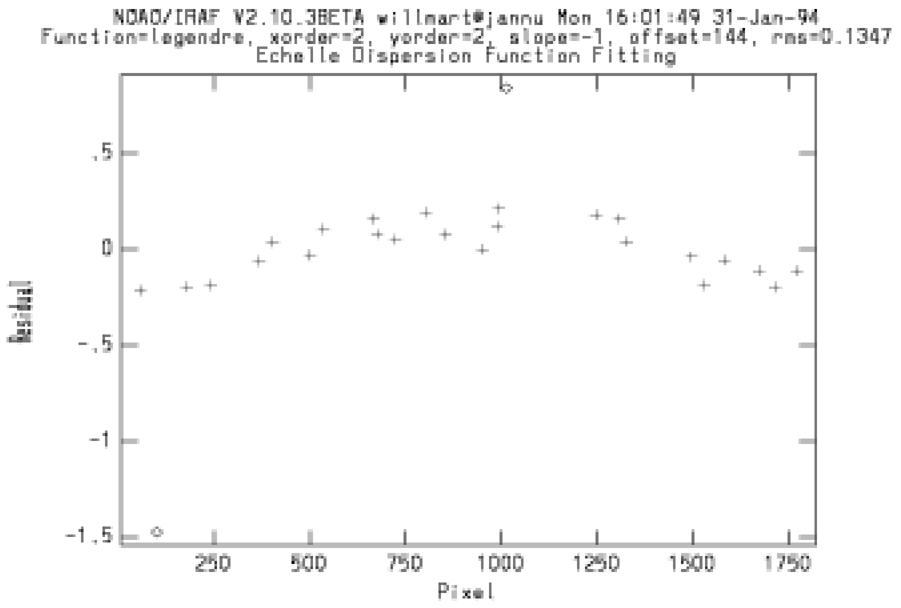


Figure 12: Initial wavelength fitting for an echelle spectrum with residuals versus pixel number shown. The fitting parameters are listed at the top of the plot.

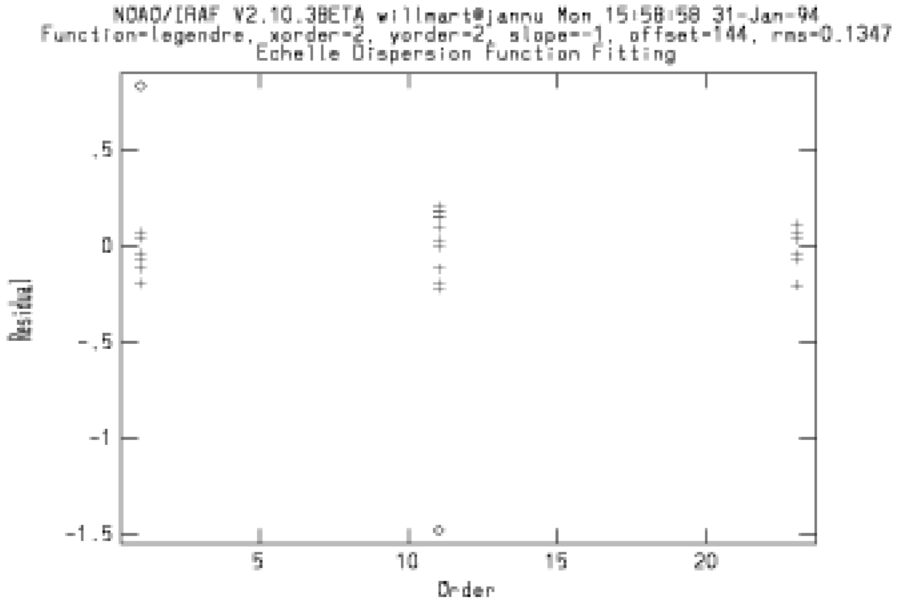


Figure 13: Initial wavelength fitting for an echelle spectrum with residuals versus order number shown. This is the same data shown in Figure 12 —just plotted differently.

When sufficient lines have been identified, type `f` to fit the default function to the spectrum. Now a plot of deviations from the fit vs. pixel number is displayed and interactive fitting may be done. Figure 12 shows an example of this initial fit using the default function and orders. One can see a couple rejected points, probably misidentifications, and a noticeable curve indicating a higher order is needed. It may be a little more useful to display the plot with residual vs. order number (Figure 13) by typing `x` and `o`. This will make it easier to find a bad identification than just having all the lines displayed as pixel number. Other options are also shown when typing `x`. When satisfied with the initial fit, type `q` to return to the line identification mode. One can now mark additional lines in other orders to test the fit or type `l` to locate and mark all the possible lines falling within the acceptance criteria. If some likely looking candidates are not marked, they may be close blends or the *maxfeatures* parameter may not be set to a large enough value. Type `f` again to enter the two-dimensional fitting routine (Figure 14) and type `d` to delete points that fall outside of whatever value you feel is acceptable. The "good" lines generally are pretty tightly clumped about small residual values. Note the value of the order "offset" shown at the top of the residuals plot; if the value does not reflect the true order of the aperture, it can be adjusted with the `o` key. Type `q` when satisfied with the fit and `q` again when you are satisfied with the whole comparison identification and fitting process. Figure 15 shows the residuals from the final fit with a Legendre function having `xorder` = 5, and `yorder` = 6. Order values higher than these did not improve the fit significantly.

3.6 The Rest of the Story

Unless flux calibration is to be done, the rest of the extraction will be done without interaction. Then you are queried whether to plot the final spectra or not (*splot* = yes). You may wish to look at least at the first image to check the results. The line/aperture number will be queried for, followed by the "band" number. If the parameter *extras* is "yes", the output image will be 3 dimensional, with "band" number referring to the following sets of apertures:

band	image type
1	cleaned, weighted, extracted spectra
2	uncleaned, unweighted spectra
3	background spectra
4	estimated sigma spectrum

Band 1 is what we are really after, but the others may be of interest to insure the cleaning and background subtraction did what we thought it should. The keys `)` and `#` can be used to move around from order to order, while a different band will be used only if `%` is typed. Since this poking around is just **splot**, it will all work the same after the reductions are finished.

3.7 Flux Calibration

Flux Calibration of echelle spectra is problematic due to the short pieces of spectra and the large bandpasses of most standard star data. An order containing or near a hydrogen

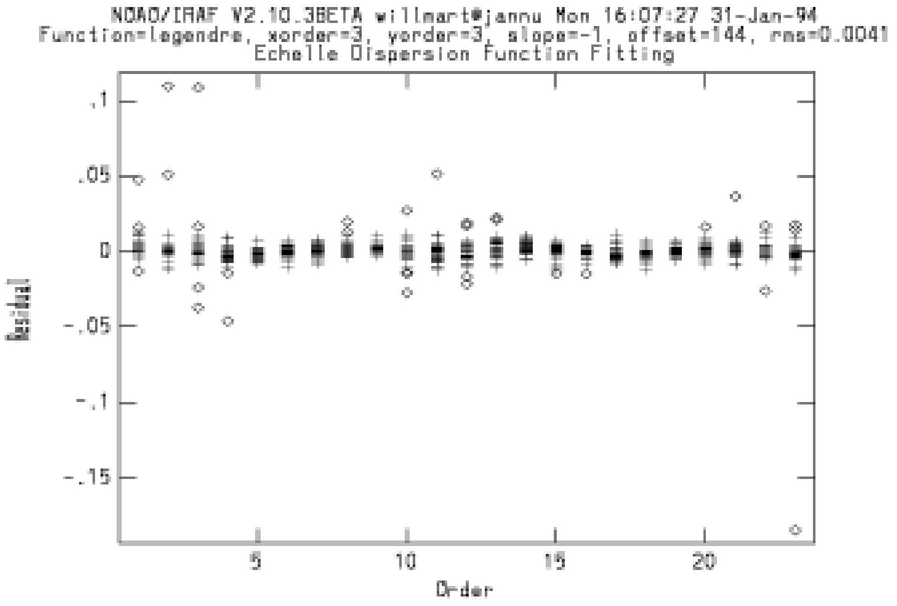


Figure 14: A second pass through the fitting of the dispersion function for echelle comparison data—more lines have been added to the solution and the fitting parameters have been adjusted.

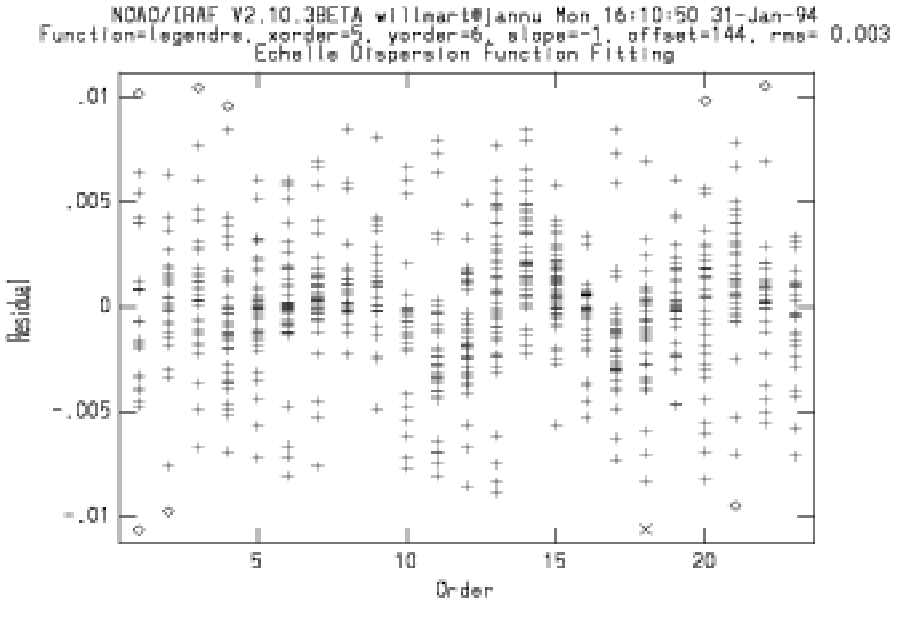


Figure 15: The final fit.

line is especially difficult in the early type stars. Velocity differences between the object and standard can change the bandpass enough to cause significant errors in the presence of steep line gradients. Unless the observations of the objects and standards are made with the spectrograph slit at the parallactic angle, significant throughput differences will exist between the extreme orders. In regions of the spectra not containing H-lines however, flux calibration may be a useful way of flattening the rather peaked echelle blaze function. For this purpose alone though, one may want to consider using the **continuum** task, as it allows more direct interaction with the spectrum itself.

Flux calibration in **doecslit** is accomplished through the tasks **standard**, **sensfunc**, and **calibrate**. An extinction correction is also applied during the **calibrate** phase based on header parameters.

Standard allows an interactive definition of bandpass regions starting with the initial values found in the sensitivity calibration parameters, or uses those from the calibration file if *bandwith* and *bandsep* are set to "INDEF". Unless the orders span a wavelength interval of about 100Å or more, it will probably work better to specify the above paramaters as 5 or 10Å. Since the smallest bandwidths in the standard calibration files are 16Å (onedstds$spec16cal), smaller bandwidth values will allow more points along the order. The standard calibration data is interpolated to the bandpasses specified or defined graphically. Figure 16 shows an order with 5Å interpolated bandpasses. If editing of bandpasses is selected, you may add (**a**) or delete (**d**) bandpasses. The final bandpasses selected for each aperture remain in effect for subsequent images, so there is no need to edit each time.

After all the bandpasses for each aperture have been defined, a curve fitting phase is entered (**sensfunc**) where the flux values for each order are fit to a smooth curve to relate system sensitivity to wavelength for each aperture. Figure 17 shows the default plot for an aperture. Points may be deleted, the fitting function type or order changed, and curves may be shifted (grey shift), to name a few of the options available. See the help pages for this and the previous task for details.

Finally, the task **calibrate** applies both an extinction correction and the derived calibration curves for each aperture to produce the final flux calibrated spectra. This phase is non-interactive.

4 Looking at the Reduced Data

The **splot** task can be used to examine the extracted and calibrated spectra. If you are new to this task read the help page since **splot** offers many different options for plotting and manipulating the data.

4.1 Other Tasks

Other tasks are also available for extracting, plotting, and combining orders. Some of these are listed below.

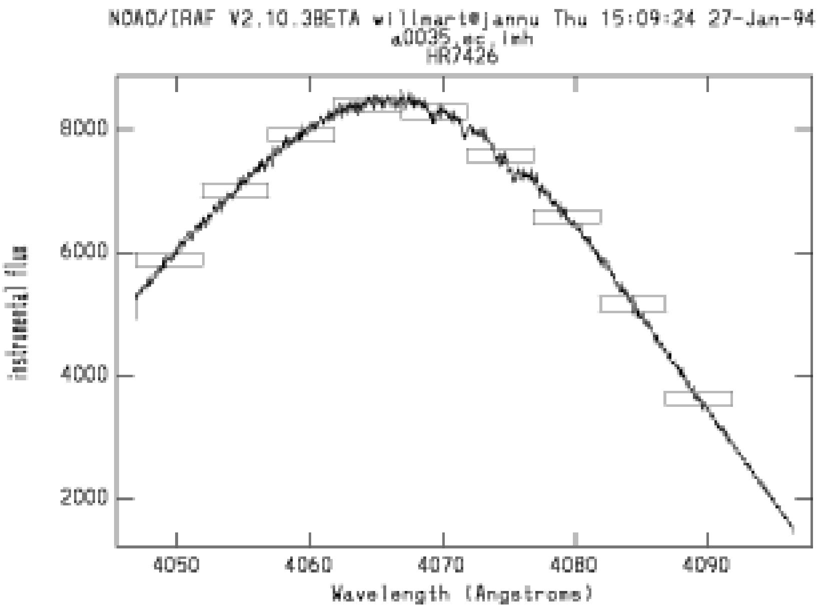


Figure 16: A plot of an order with 5Å interpolated bandpasses marked using the task **standard**.

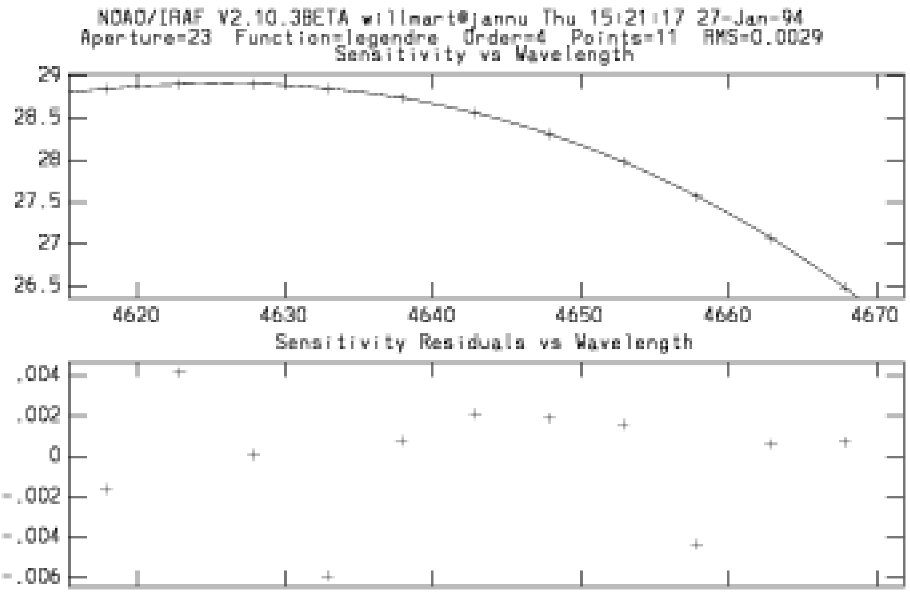


Figure 17: The interactive phase of the task **sensfunc**. The units on the left axis are in magnitudes.

```
    bplot - Batch plots of spectra
continuum - Fit the continuum in spectra
 deredden - Apply interstellar extinction corrections
   dopcor - Doppler correct spectra
   sarith - Spectrum arithmetic
 scombine - Combine spectra
    scopy - Select and copy apertures in different spectral formats
    slist - List spectrum header parameters
 specplot - Stack and plot multiple spectra
specshift - Shift spectral dispersion coordinate systems
```

4.2 Image Headers

The IRAF image headers are updated throughout the reduction process, and by the time the echelle reductions have been completed there are a whole spectrum of new keywords added to the image header. These keywords can vary slightly depending on which version of IRAF you are using.

A partial image header of a reduced echelle spectrum is presented below, using IRAF Version 2.10.3. Note that the wavelength information for each order is stored in the WAT* keywords. For a complete description of the headers for spectral data see **phelp onedspec.specwcs** (IRAF Version 2.10.3 or later) or **phelp onedspec.package** (in earlier versions).

```
BANDID1 = 'spectrum - background none, weights variance, clean no'
BANDID2 = 'raw - background none, weights none, clean no'
BANDID3 = 'sigma - background none, weights variance, clean no'
WCSDIM  =                    3
CTYPE1  = 'MULTISPE'
CTYPE2  = 'MULTISPE'
CTYPE3  = 'LINEAR  '
CD1_1   =                   1.
CD2_2   =                   1.
CD3_3   =                   1.
LTM1_1  =                   1.
LTM2_2  =                   1.
LTM3_3  =                   1.
WAT0_001= 'system=multispec
WAT1_001= 'wtype=multispec label=Wavelength units=Angstroms
WAT2_001= 'wtype=multispec spec1 = "1 113 0 4955.0239257812 0.06515394896268
WAT3_001= 'wtype=linear
WAT2_002= '56 0. 23.22 31.27" spec2 = "2 112 0 4998.9482421875 0.06753599643
```

```
WAT2_003= '3 256 0. 46.09 58.44" spec3 = "3 111 0 5043.6640625 0.06996016949
WAT2_004= '2 256 0. 69.28 77.89"
DCLOG1  = 'REFSPEC1 = demostddemoarc.ec'
DC-FLAG =                    0
STD-FLAG= 'yes     '
EX-FLAG =                    0
CA-FLAG =                    0
BUNIT   = 'erg/cm2/s/A'
```