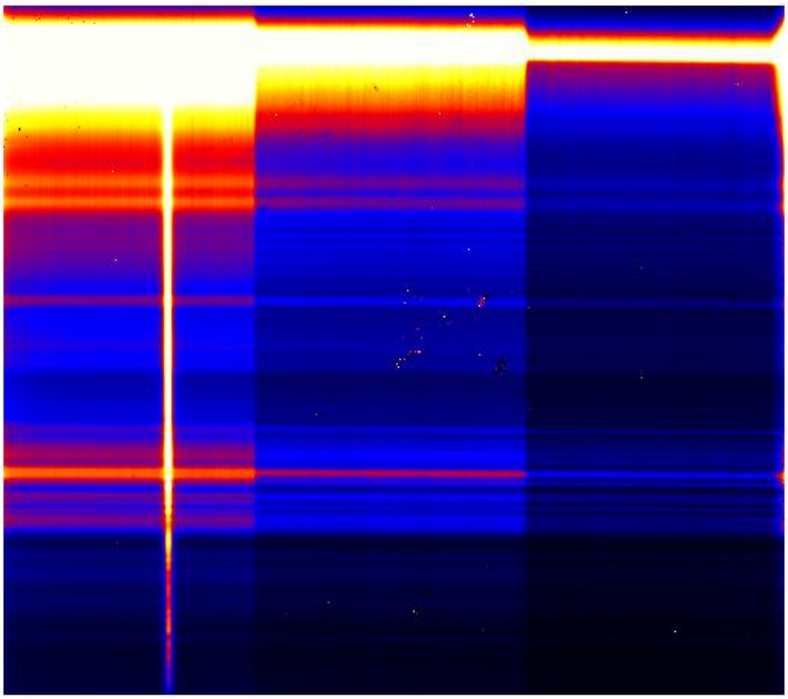
# Subaru Data Reduction CookBook: Grism Spectroscopic Observations with IRCS

— Version. 2.1.2e (December 10, 2008) —



*Based on the textbook in Japanese written by M. Imanishi*
*for Subaru Data Reduction School held in May, 2008 (Version 2.0)*

*Current Editor of English Version: R. S. Furuya*
*together with the combined effort of the past and current staff at Subaru Telescope*

# 1 Forward

This CookBook presents the typical procedure used to analyze infrared spectra. It is our expectation that a novice at grism spectroscopic observations using Infrared Camera and Spectrograph (IRCS) at Subaru Telescope will be able to produce a final infrared spectrum by him/herself. The focus of this CookBook is to describe how to analyze low-wavelength resolution infrared spectra having a moderate signal-to-noise (S/N) ratio. The targets of infrared low-resolution spectroscopy, like Subaru IRCS grism spectroscopic observations, are generally faint where the S/N ratio with respect to the continuum may be at most 10–30. On the other hand, high-dispersion spectroscopic observations are often carried out on bright objects, with an aim of achieving very high S/N ratios exceeding e.g., $\sim$100. Analysis of such high dispersion and high S/N ratio spectra requires a few more procedures where special care is needed in addition to the procedures described in the CookBook. As for the data handling of such spectra, we comment briefly on such additional procedures. Last but not least, we appreciate any feedback from the readers to help improve this CookBook.

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## Revision History

| Version | Date | |
|---|---|---|
| 2.1.0e | 2008 October 30 | First release based on the Japanese version [v.2.0 (2008 April 10)] by R.S.F. & M.I. |
| 2.1.1e | 2008 November 30 | Language correction for *Subaru Asia Winter School* by R.S.F. & A.H. |
| 2.1.2e | 2008 December 10 | Minor corrections after the school & changed the directory structure of the sample data by R.S.F. |

# Contents

# 2 Introduction to Spectroscopic Observations in the Near-Infrared

The basic concepts of near-infrared (NIR) spectroscopic observations are essentially the same as those at optical wavelengths. However, there are a few differences that characterize NIR spectroscopy, as described below:

1. Since CCDs used in the optical observations do not have sensitivity at the wavelength longer than 1$\mu$m, detectors with mercury cadmium telluride (HgCdTe) or indium antimonide (InSb) are generally used.

2. Compared to the optical wavelengths, thermal emission from the Earth's atmosphere and telescope itself is much higher (Fig. 1), making observations (e.g., calibration) difficult. This requires additional data handling processes[1]. In addition, the resultant signal-to-noise ratio (S/N) is degraded by Poisson noises from background emission. Furthermore, since infrared detectors cannot count numbers of photons exceeding a certain value (i.e., the full-well level, or simply full-well), one has to acquire data with a short integration time to prevent detector saturation. Acquiring data with such a short exposure time results in low observing efficiency, and produces a significant number of data frames (which occupies a large amount of hard disk space).

3. In general, calibration accuracy produced by infrared data reduction is lower than that for the optical regime. However, in the case of low-resolution infrared spectroscopy, our experience suggests that the quality of the final spectra is determined by the background noise rather than the calibration uncertainties.

Astronomical signal can be observed at all the optical wavelengths, whereas there exist some infrared wavelength ranges where the Earth's atmosphere is not transparent, as shown in Figure 2. Therefore, ground-based infrared observations are limited to the wavelength ranges where the

[1]The major noise sources associated with ground-based observations can be categorized into the following three sources: (1) signal from the astronomical object(s) itself becomes a major noise source, i.e., signal-limited. This effect is obvious especially in the high-dispersion observations toward very bright sourcesin the optical wavelength, (2) readout noise of the detector(s) generally becomes the major noise source in the case of the high-dispersion observations at infrared (readout-limited), and (3) Poisson noise of the background emission is generally the dominant noise source for the case of the low-dispersion observations in the infrared (background-limited). The degree of contributions from these noise sources depends on various parameters such as, e.g., source brightness, instrumental performance, wavelength resolution and/or atmospheric conditions. Therefore, we suggest that the user should always pay attention to which noise source most affects the quality of the data in order to select the best observing parameters.

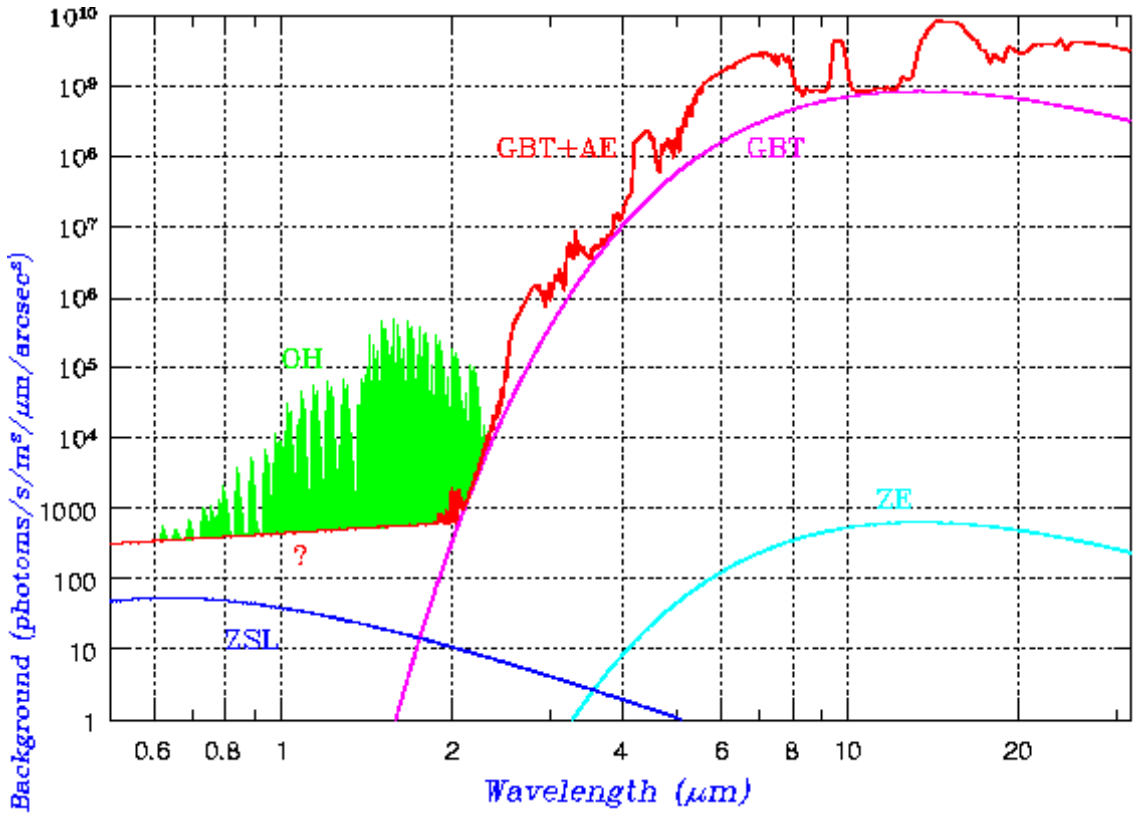



Figure 1: A typical spectrum of the background emission between the optical and the infrared wavelengths where one finds that the noise level will increase significantly $\lambda \gtrsim 2\mu$m. Here, AE denotes thermal radiation from Earth's atmosphere (220 – 273 K), GBT : thermal emission from telescope, OH : OH airglow, i.e., OH vibration-rotation bands, ZSL : scattered light from the Sun due to dust in zodiacal plane, ZE : thermal emission from such dust. The plot is from *Astronomy Lecture Notebook* (in Japanese) by Prof. Iwamuro at Kyoto University (http://www.kusastro.kyoto-u.ac.jp/~iwamuro/LECTURE/OBS/).

atmospheric transparency is at a reasonable level (ideally close to unity). Such a wavelength range is often referred to as a band.

# 3 IRCS

IRCS (Infrared Camera and Spectrograph) at Subaru Telescope offers both imaging and spectroscopic observational capability in the infrared. For further information, please visit the IRCS web page, `http://www.naoj.org/Observing/Instruments/IRCS/index.html`. Spectroscopic observations using IRCS can be categorized into low-dispersion (i.e., low wavelength-resolution) single-order observations and the high resolution cross-dispersion (such as the HDS in the case of the Subaru

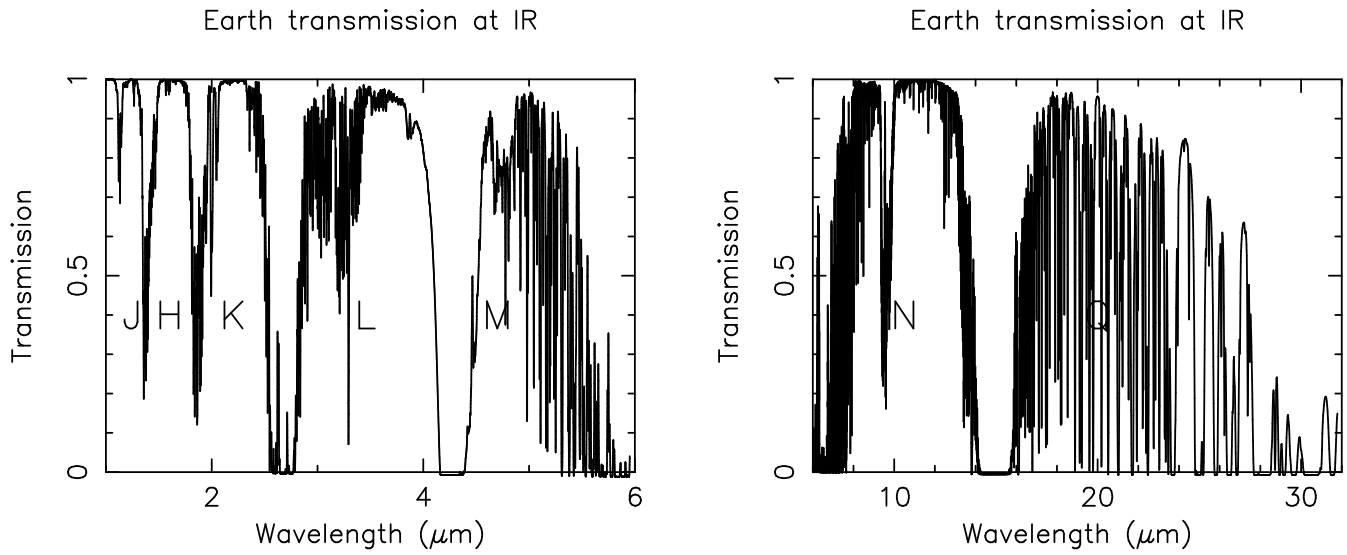



Figure 2: A plot of Earth's atmospheric transmission, i.e, infrared wavelength window (`http://www.jach.hawaii.edu/UKIRT/astronomy/utils/atmos-index.html`). Ground-based infrared observations are limited to the (wavelength) bands where the Earth's atmosphere is transparent. These bands are referred to as $J, H, K, L, M, N$, and $Q$. The Earth's atmospheric opacity is highly time variable with several conditions. In particular, it is known to be sensitive to the total column density of water vapor above the telescope site. The illustrated transmission curve is the good conditions case (i.e., the water vapor level is low). As water vapor level rises, the transmission level degrades at all wavelength. Such an effect is especially prominent at wavelength whose transmission is intrinsically low. See Figure 11 for a magnified view of the $L$ band transmission curve.

Telescope). However, for the novice, we will focus on describing on how to reduce the former. If you are interested in reducing data from cross-dispersion spectroscopy, we suggest reading "A User's Guide to Reducing Echelle Spectra with IRAF" (Daryl Willmarth and Jeanette Barnes, 1994 May; `http://iraf.noao.edu/docs/spectra.html`).

# 4 A Standard Procedure of Infrared Spectroscopic Observation

In this section, we describe a standard procedure for data reduction of infrared spectroscopic observations. For simplicity's sake, we limit our discussion only to observations of a point-like source.

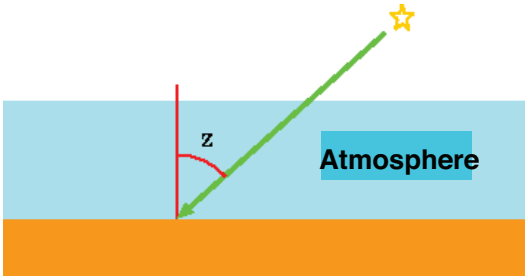



Figure 3: A sketch illustrating a concept of airmass. Airmass is defined by $\sec(z) = 1/\cos(z)$ where $z$ is the zenith angle. As is clear from the definition, it takes a minimum (= 1.0) at zenith. The degree of the attenuation of the signal is proportional to the distance in the atmosphere that the photon has traveled, i.e., proportional to the airmass. One should plan to observe target sources at an airmass as small as possible: less than $\sim$2.0 (image courtesy: Prof. Iwamuro as the same URL for Figure 1).

1. Observing an object at two positions (hereafter named `A` and `B`) along a slit — Configure non destructive readout (NDR)[2], of the detector and the numbers of exposure at each position (`COADD`) accordingly. Keep in mind that each exposure should be completed within a reasonable timescale comparable to (or less than) the characteristic time scale of the Earth's atmospheric variation.

2. Taking several sets of data with an `ABBA` dithering sequence

3. Observing bright standard star (a main-sequence G star in many cases) before and after observing the science target(s) — We suggest observing such a standard star at an airmass difference (Fig.3) of less than 0.1 with respect to the target object. Recall that atmospheric transmission in the infrared will vary significantly with weather conditions and observing wavelength(s). One can correct for the variation of the Earth's atmospheric transmission through dividing the target spectrum by that of the standard star whose intrinsic spectrum (i.e., the spectrum free from the absorption by the Earth's atmosphere) is well-known.

Given the above observing procedure, we will describe a typical procedure to reduce low-dispersion infrared spectroscopic data.

[2]Contrary to the CCDs used in the optical, infrared detectors can read out the accumulated electric charge many times without destruction (Non Destructive Readout; NDR), allowing us to reduce read-out noise. The maximum number of NDRs is given by the read-out speed and the exposure time. The default setting at IRCS is configured to maximize the NDR numbers. In the case of $L$-band ($\lambda = 2.8-4.2\,\mu$m) low-resolution spectroscopy such as the sample data used as an example in this CookBook, Poisson noise from the background would overcome the read-out noise. Therefore, instead of using the default setting at IRCS, you have to wisely optimize the numbers of NDRs, because unnecessarily large number of NDRs reduce the observing efficiency.

# 5 A Standard Procedure of Infrared Spectroscopic Data

## 5.1 *First fact*

Listed below are the typical steps required for the analysis of infrared spectroscopic data.

1. Subtracting data taken at a slit position from those at another, i.e., `A-B`
2. Correcting for bad pixels
3. Dividing by a spectroscopic flat frame
4. Extracting the signal, then combining `A` and `B`
5. Correction for non-linearity (we will skip this procedure for the sample data.)
6. Wavelength calibration
7. Airmass correction (we will skip this procedure for the sample data.)
8. Binning the obtained spectra (if necessary)
9. Dividing the object spectrum by a standard star spectrum
10. Multiplying the intrinsic spectrum of the standard star
11. Flux calibration
12. Obtaining the final spectrum

Due to difficulty in the long-wavelength infrared observations described above, the number of successful observations is clearly smaller than those at the short wavelength. The smaller number of observation yields less feedbacks from the data reduction process as compared to shorter wavelengths. We, however, believe that it will not be so difficult to learn data reduction of the shorter wavelength observations once you have familiarized yourself with relatively long wavelength data. In this CookBook, we will use the already published $L$-band ($\lambda = 2.8 - 4.2$ $\mu$m) spectroscopic data toward the ultra-luminous infrared galaxy IRAS 00188−0856 (Imanishi et al. 2006 ApJ 637 114).

## 5.2 Data Reduction: *the Details*

We will utilize the widely used multi-purpose data reduction package — the Image Reduction and Analysis Facility (IRAF) distributed and maintained by the National Optical Astronomy Observatory (NOAO) of the United States. See `http://iraf.noao.edu/` for getting further information. At `http://iraf.noao.edu/docs/spectra.html`, you will find a helpful guide book "A Beginner's Guide to Using IRAF (IRAF Version 2.10) by Jeanette Barnes (1993 August).

If you are looking for a document focusing on single-order spectroscopy, we suggest reading "A User's Guide to Reducing Slit Spectra with IRAF" by Phil Massey, Frank Valdes, and Jeanette Barnes (1992 April; `http://iraf.noao.edu/docs/spectra.html`).

In this CookBook, we describe a method to reduce spectroscopic data on the basis of the recipes already available in these documents. We believe that the basic concept of data handling is essentially the same as those used in many references, although some optimizations will be required in order to reduce the sample data.

### 5.2.1 Getting Started: Setting up Your IRAF

We assume that you have a Linux/Unix machine where IRAF is available. If not, please consult with your local experts. The PC-IRAF web page
`http://iraf.noao.edu/projects/pc-iraf/pc-iraf.html` would also help you when you have trouble [3]. To start IRAF, go to any directory where you will work with IRAF, e.g., "`ircs_sp`" in the case of the sample data described in §5.2.2, type "`mkiraf`". You may have to answer some questions with `y` and `xgterm`.

```
ana03 /home/imanshms/ircs_sp> mkiraf
Initialize uparm? (y|n): y
-- initializing uparm
Terminal types: xgterm,xterm,gterm,vt640,vt100,etc.
Enter terminal type: xgterm
A new LOGIN.CL file has been created in the current directory.
You may wish to review and edit this file to change the defaults.
```

[3] If some IRAF commands do not work on your computer, your version of IRAF may not be compatible with those commands.

This will create an ASCII text file named `login.cl` which defines your IRAF environment. Open the file with your favorite editor (e.g., `vi`, `emacs`, etc) and find the line:

```
#set    imtype          = "imh"
```

We suggest modifying this line to (don't forget to remove # at the beginning),

```
set    imtype          = "fits"
```

This tells IRAF that your default image format is FITS rather than the IRAF one.

Type "`xgterm &`" from any Linux/Unix command line, then type `cl` in the xgterm window. You will get an IRAF environment with the following message.

```
NOAO Sun/IRAF Revision 2.12.1-EXPORT Wed Jul 10 13:33:04 MST 2002
This is the EXPORT version of Sun/IRAF V2.12 for SunOS 4 and Solaris 2.8

Welcome to IRAF.  To list the available commands, type ? or ??.  To get
detailed information about a command, type 'help command'.  To run a
command or load a package, type its name.  Type 'bye' to exit a
package, or 'logout' to get out of the CL.  Type 'news' to find out
what is new in the version of the system you are using.  The following
commands or packages are currently defined:

  apropos     guiapps.    lists.      plot.       system.
  color.      guidemo.    mscred.     proto.      tables.
  dataio.     images.     noao.       softools.   utilities.
  dbms.       language.   obsolete.   stsdas.

cl>
```

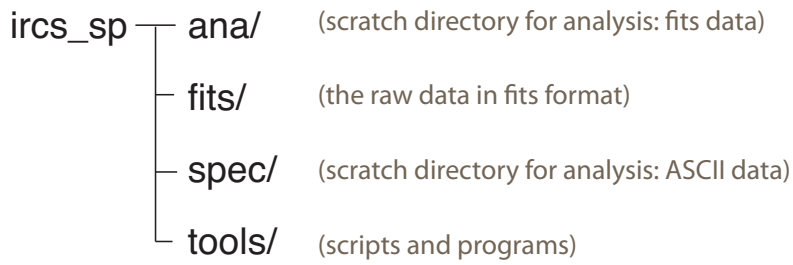
Here `cl>` is the IRAF prompt. To work on your data, you also need to start an image viewer `ds9` (or `saoimage`). Type "`ds9 &`" to start it.

### 5.2.2 The Sample Data and Initial Data Inspection

We assume that you were able to download the archive of sample data as well as some scripts and programs, `ircs_sp.tar.gz`, from
`http://optik2.mtk.nao.ac.jp/subaru_red/IRCS/files/ircs_sp.tar.gz`. To extract the the tar archive, type

```
tar zxvf ircs_sp.tar.gz
```

You have a directory named `ircs_sp` which has the four sub-directories as shown below. Although name of the directory is arbitrary, we suggest that the users follow our nomenclature used in this CookBook. Both the `ana` and `spec` directories are empty at this stage because they are the directories where we will store the FITS and ASCII text format data created in the data reduction steps.




You will find a series of data files in FITS format under the `fits` directory. If you are curious to see more information, pick one of the FITS files to see its header by typing "`more IRCA00070351.fits`", you will see the basic parameters of the data such as object name, observing date, observing mode, and integration time.

```
OBJECT  = 'HR72              ' /

DATE-OBS= '2002-08-19        ' / UT date of Observation (yyyy-mm-dd)
```

Let's go back to the working directory, "`ircs_sp`", by typing "`cd ..`" (from the `fits/` directory) to see the raw data. In the case of sample data, sequential FITS files, IRCA00070351 – IRCA00070362, are the data of a standard star. To inspect the raw data, we use the task `display`. Optimize several input parameters to show the image accordingly. See below.

```
cl> epar display

                                    I R A F
                     Image Reduction and Analysis Facility
PACKAGE = tv
   TASK = display

image   =    IRCA00070351.fits  image to be displayed
frame   =                   1  frame to be written into
(bpmask =                 BPM) bad pixel mask
(bpdispl=                none) bad pixel display (none|overlay|interpolate)
(bpcolor=                 red) bad pixel colors
(overlay=                   ) overlay mask
(ocolors=               green) overlay colors
(erase  =                 yes) erase frame
(border_=                  no) erase unfilled area of window
(select_=                 yes) display frame being loaded
(repeat =                  no) repeat previous display parameters
(fill   =                  no) scale image to fit display window
(zscale =                  no) display range of greylevels near median
(contras=                0.25) contrast adjustment for zscale algorithm
(zrange =                  no) display full image intensity range
(zmask  =                   ) sample mask
(nsample=                1000) maximum number of sample pixels to use
(xcenter=                 0.5) display window horizontal center
(ycenter=                 0.5) display window vertical center
(xsize  =                  1.) display window horizontal size
(ysize  =                  1.) display window vertical size
(xmag   =                 0.5) display window horizontal magnification
(ymag   =                 0.5) display window vertical magnification
(order  =                   0) spatial interpolator order (0=replicate, 1=linea
(z1     =                   ) minimum greylevel to be displayed
(z2     =                   ) maximum greylevel to be displayed
(ztrans =              linear) greylevel transformation (linear|log|none|user)
(lutfile=                   ) file containing user defined look up table
```

```
(mode   =                    ql)
```

Here, we have modified the default parameters to `xmag = 0.5, ymag = 0.5, zscale = no,` and `zrange = no`. The first two parameters display the whole area of the image using 1024×1024 pixels. The third and fourth parameters manually control the display range of the data, i.e., the intensity scale. You can leave all the remaining default parameters as they are. To modify the parameters, bring your cursor to the desired line and put the parameter value, and type "`:q`" to quit the input interface. If you want to change (or erase) a variable, just hit the `SPACE` key on that parameter. To initialize all the parameters to the default values, issue "`unlearn display`" at IRAF command line (i.e., `cl> unlearn display`).

After setting all the parameters, try the command,

```
cl> display fits/IRCA00070351.fits 1 z1=0 z2=30000
```

You will see the standard star data (the very bright one) taken at the slit position `A` as shown in the left panel of Figure 4 where the dispersed signal is seen in the vertical direction. On the other hand, it would be difficult to identify the signal from the targets as they are generally faint. In the figure, you can recognize that the data consists of three parts split in the horizontal direction; they represent data taken with the different slit widths (each section corresponds to a slit width of 0.″9, 0.″6, and 0.″3 from the left). It should be noted that the data having the wider slit width have the higher background signal level as the total power of the incident radiation is proportional to the slit width. In the case of the sample data, the standard star can be recognized in the left-hand portion of the data, i.e., on the 0.″9 width slit.

In general, slit width should be selected on the basis of the stellar image size (i.e., seeing) during observations. Considering scientific goals as well, you may have to select an appropriate slit width to achieve the highest S/N ratios. If you select a narrow slit width, you reduce the background noise level, but also you may lose signals under poor seeing conditions (because of slit loss). Such a degradation may also occur if the tracking accuracy of telescope is poor. Needless to say, you should be able to get an excellent data set with a narrow slit under excellent seeing conditions.

```
cl> display fits/IRCA00070352.fits 1 z1=0 z2=3000
```

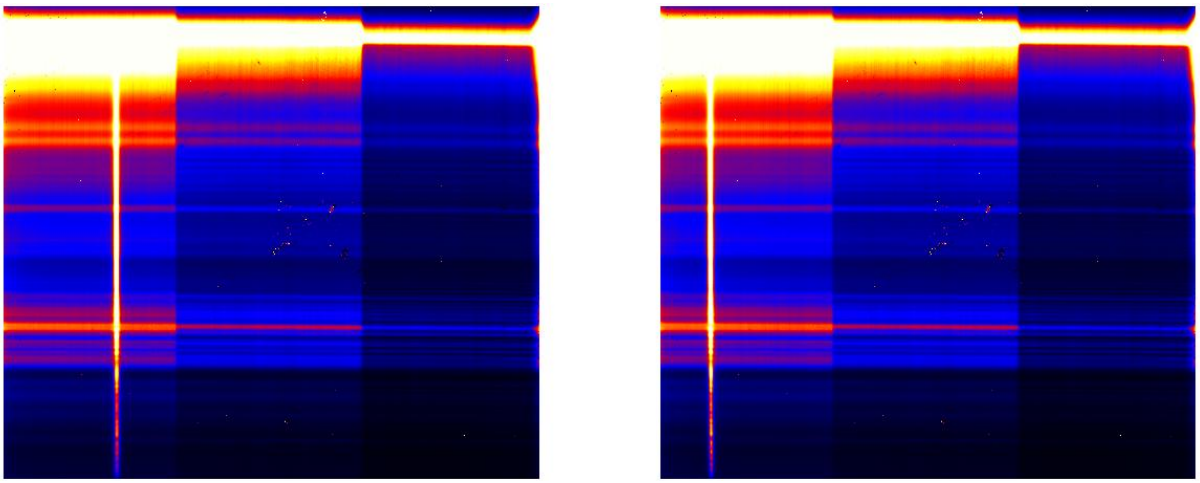


Figure 4: An image of the standard star without any calibration (i.e., the raw data). The left and right panels, respectively, show the image taken at the slit positions `A` and `B`.

Check quality of the data taken at the position `B` using the above command. You will see an image shown in the right-hand panel of Figure 4 where you should verify that the location of the signal of the standard star has moved to the left.

### 5.2.3 Subtraction: `A` − `B`

The raw image, of course, contains not only the desired target signal but also the background emission which is usually very strong in the $L$-band. To better visualize signals from the star, we can simply subtract the background emission, namely, making an image through `A-B`. Issue the following IRAF commands,

```
cl> imarith fits/IRCA00070351 - fits/IRCA00070352 ana/HR72_351_352

cl> display ana/HR72_351_352 1 z1=-1000 z2=1000
```

You will see an excellent spectroscopic (the resultant subtracted) image for the standard star as shown in Figure 5 left. Here, `ana/HR72_351_352` is the name of the output image which can be arbitrary. It would be wise of you to establish your own naming convention for file names. As seen above, IRAF recognizes a file name without its extension (e.g., `.FITS`) as we have defined in §5.2.1. Also try to see how the images will be displayed with different `z1` and `z2` values.

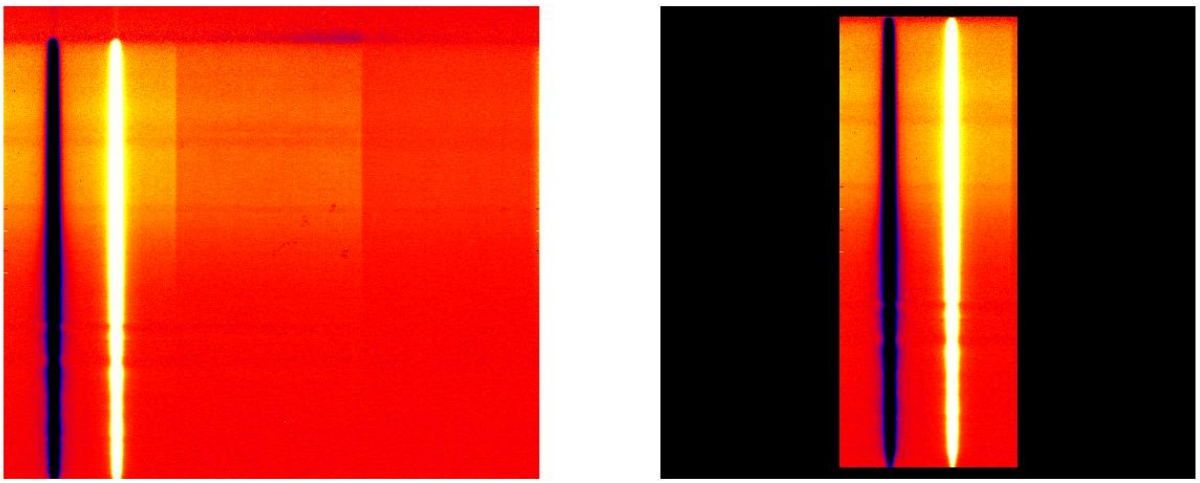


Figure 5: (Left) – Spectroscopic data of the standard star obtained from `A-B`. The mean value for the source-emission-free region ideally should have zero count within the errors. (Right) – The same as the left panel, but a sub-image containing only the source of interest; the sub-image has been obtained by truncating the original.

In the following steps, we will work on the `A-B` image, but we will use solely the left-hand portion of the image where the star of interest is visible. Therefore, it would be good idea to get rid of the remaining two-third portion on the right-hand side to save disk space. Another reason is that these region may contain "jumped" pixel counts (i.e., showing an extraordinary high count) that may not be handled correctly. For this purpose, let us truncate the left portion using the following command:

```
cl> imcopy ana/HR72_351_352[1:340,40:900] ana/HR72a
```

where the first two values in the square brackets are the $x$-coordinates and the last two are the $y$-coordinates for the image to be clipped. After clipping, make sure that you have selected the desired portion of the image by,

```
cl> display ana/HR72a 1 z1=-1000 z2=1000
```

We assume that you have an `A-B` image, like the right-hand panel of Figure 5, that will be reduced in the following manner. In practice, almost all the observers repeat the observing sequence of `A`

and B. Namely, we have more than one pair of A and B images that should be combined after making A-B images from adjacent sequences. Since the standard star, HR 72, has been observed before and after observing the target galaxy, we have 12 frames from IRCA00070351 through IRCA00070362 (giving 6 sets of A-B) and 8 frames from IRCA00070413 through IRCA00070420 (giving 4 sets of A-B). In this CookBook, let us use the former set of data.

To make subtracted-images, execute the IRAF task imarith, as follows:

```
cl> imarith fits/IRCA00070351 - fits/IRCA00070352 ana/HR72_351_352
cl> imarith fits/IRCA00070354 - fits/IRCA00070353 ana/HR72_354_353
cl> imarith fits/IRCA00070355 - fits/IRCA00070356 ana/HR72_355_356
cl> imarith fits/IRCA00070358 - fits/IRCA00070357 ana/HR72_358_357
cl> imarith fits/IRCA00070359 - fits/IRCA00070360 ana/HR72_359_360
cl> imarith fits/IRCA00070362 - fits/IRCA00070361 ana/HR72_362_361
```

Consequently all the six images should be combined into an image in order to improve the S/N. For this purpose, we decided to sum up the images straightforwardly. To combine the images, you can also take another approach that calculates the mean. Notice that both methods should essentially work the same from our point of view; the resultant images created from summation and averaging only have a difference in their scale factors.

Open a blank ASCII file typing "emacs HR72_list &" on the Unix/Linux command line. The file should contain the following lines:

```
ana/HR72_351_352.fits
ana/HR72_354_353.fits
ana/HR72_355_356.fits
ana/HR72_358_357.fits
ana/HR72_359_360.fits
ana/HR72_362_361.fits
```

Note that you may omit the ".fits" extension. Use the ASCII text file as an input file to sum up the 6 images,

```
cl> imsum @HR72_list ana/HR72_351_362
```

Did you get an improvement of the S/N ratio for the standard star image? If you are happy with the results, it would be prudent to throw away the unnecessary region by issuing the following command:

```
cl> imcopy ana/HR72_351_362[1:340,40:900] ana/HR72_1
```

Just for your knowledge, we do not need to subtract dark-current images, as we are going to reduce the `A-B` images (in fact, the dark current and bias level stay at a negligible level for the majority of the $L$-band observations).

If you are familiar with IRAF scripts, you may want to skip some steps that are often repeated such as "`subsum_fits.cl`", which is found in "`ircs_sp/tools`". To use the IRAF script, follow below:

```
cl> task subsum_fits = tools/subsum_fits.cl

cl> subsum_fits IRCA0007 351 362 HR72

cl> imcopy ana/HR72_351_362[1:340,40:900] ana/HR72_1
```

Here, you may see a write permission warning for the output files. In this case, delete the files before using the script:

```
cl> imdel ana/HR72_1
```

The script will help you to increase your work efficiently. We hope that you will be able to write such scripts after familiarizing yourself with IRAF. However, if you consider yourself as being a novice, we suggest repeating each command and inspecting all the results by eye.

Subsequently, let us apply the same procedure[4] on the target ultra-luminous infrared galaxy IRAS 00188−0856. Although we have a full set of data set (file number = IRCA00070368 through IRCA00070407), we are going to use the subsets of the files here i.e., between IRCA00070368 and IRCA00070387 for illustrating how to make a subtracted (= `A-B`) file that will be named `IR00188_368_387.fits`[5] After that, we will clip only the area in the same fashion as applied to the HR 72 image (see Figure 6).

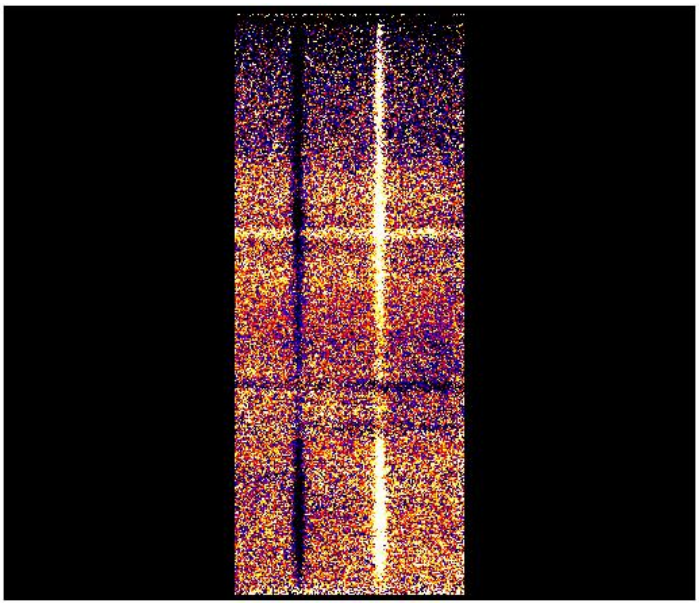


Figure 6: An example of spectroscopic raw data generated by `A-B` for the target source. The image shown here is the clipped sub-image. Compared with Figure 5, the image toward the infrared galaxy image is noisier than that of the standard star.

### 5.2.4 Dividing with Spectroscopic Flat

Ideally, both the standard star and the target should be observed at the identical slit positions. However, in practice, it is difficult to match exactly the position of the standard star and the

[4]The task `subsum_fits` requires a rather large amount of memory, making the system unusually slow. When you attempt to combine large numbers of images using a computer with a limited amount of memory and encounter such a problem, try to reduce the number of images being combined.

[5]Since the observations were carried out by repeating the sequence of `ABBA`, the FITS file numbers of IRCA00070368 and IRCA00070369 correspond to the slit positions `A` and `B`, respectively. The sub-data sets ends with IRCA00070387 which is taken at `A`.

source(s). Moreover, we cannot exclude the possibility that slit width varies with slit position and/or that the transmission is not uniform over the entire IRCS optics system along the slit. In order to eliminate these artifacts, we correct for the transmission along the slit using an image obtained by observing spatially uniform incident light. We have to make a differential image by subtracting the reference lamp ON (i.e., the light from the lamp plus thermal emission of the system) from OFF (the system thermal emission only). Hence, the subtraction should give an image that contains the spatially uniform incident light emanated from the lamp.

Since we now have the five sets of lamp ON (IRCA00070227 – IRCA00070231) and OFF (IRCA00070247 – IRCA00070251) images, we should make a differential image for each pair.

Here, you may see an error when running `imcombine` command in IRAF. This error is due to improper writing of the FITS header by IRCS (unfortunately this has not been fixed yet). Please check if the header parameter `CTYPE2` is `LINEAR`. If this is the case, an extra step to modify the header information is needed.

Creat files named "`flaton`" and "`flatoff`", using an editor. The file of `flaton` contains:

```
fits/IRCA00070227.fits
fits/IRCA00070228.fits
fits/IRCA00070229.fits
fits/IRCA00070230.fits
fits/IRCA00070231.fits
```

The file of `flatoff` contains

```
fits/IRCA00070247.fits
fits/IRCA00070248.fits
fits/IRCA00070249.fits
fits/IRCA00070250.fits
fits/IRCA00070251.fits
```

Let's see and modify the input parameters for the `hedit` task:

```
cl> epar hedit

images  =              @flaton  images to be edited
fields  =               CTYPE2  fields to be edited
value   =           DEC---TAN  value expression

cl> hedit

cl> epar hedit

images  =             @flatoff  images to be edited
fields  =               CTYPE2  fields to be edited
value   =           DEC---TAN  value expression

cl> hedit
```

The `hedit` task asks you many questions at each step. If this is annoying, you can select the silent mode by changing `verify` to `no`. Parameter editing can be done with `epar hedit`.

Subsequently, we will subtract the OFF files from each corresponding ON file, then extract a region that contains the target object (i.e., left portion of the detector). For combining the data, our experience suggests adopting the so-called "`median`" filtering rather than averaging one (the option "`average`"). This is because, cosmic rays may hit during an exposure, causing pixels whose counts are enormously high. The presence of such pixels would skew the resultant average value improperly, while the "`median`" filtering avoids such cases.

```
cl> imcombine @flaton ana/flaton_227_231 comb=median

cl> imcombine @flatoff ana/flatoff_247_251 comb=median

cl> imarith ana/flaton_227_231 -  ana/flatoff_247_251 ana/flat1

cl> imcopy ana/flat1[1:340,40:900] ana/flat2
```

After getting spectroscopic flat data, it would be convenient to normalize its intensity scale, although this is not a strict requirement as the result of not normalizing is just an image that is scaled by a constant value.

```
cl> epar imstat

                    Image Reduction and Analysis Facility
PACKAGE = imutil
   TASK = imstatistics

images  =             ana/flat2) List of input images
(fields = image,npix,mean,midpt,stddev,min,max) Fields to be printed
(lower  =                 INDEF) Lower limit for pixel values
(upper  =                 INDEF) Upper limit for pixel values
(nclip  =                     0) Number of clipping iterations
(lsigma =                   3.) Lower side clipping factor in sigma
(usigma =                   3.) Upper side clipping factor in sigma
(binwidt=   1.0000000000000E-5) Bin width of histogram in sigma
(format =                   yes) Format output and print column labels ?
(cache  =                    no) Cache image in memory ?
(mode   =                    ql)
```

Add `midpt` to the `fields` parameter, and edit `image,npix,mean,midpt,stddev,min,max` as shown above.

```
cl> imstat ana/flat2

      IMAGE      NPIX      MEAN     MIDPT    STDDEV       MIN       MAX
ana/flat2      292740     1440.     1520.     365.3      -58.      2459
```

Editing the parameters as shown above, you now are ready to normalize the frame with its median value (= MIDPT).

```
cl> imarith ana/flat2 / 1520.0 ana/flat
```

Although you should learn by trial and error, we suggest that a small value of `binwidt` (i.e., the width for each bin of the histogram) will give a reasonable median value.

The next step is to divide the object and the standard star frames by the normalized spectroscopic flat.

```
cl> imarith ana/HR72_1 / ana/flat ana/dHR72_1

cl> imarith ana/IR00188_1 / ana/flat ana/dIR00188_1
```

Here, the `IR00188_1.fits` should be created from the data set described in p.19 with the same as for the standard star. In practice, final IRCS spectra that have been divided by spectroscopic flat do not differ significantly from final IRCS spectra that have not been divided by spectroscopic flat. We strongly encourage readers to verify the results of with and without spectroscopic flat-fielding.

### 5.2.5 Eliminating Bad Pixels

It is known that some of the pixels within the 1024×1024 IRCS detector arrays do not behave as expected. Some of them permanently do not work. They always generate enormously high pixel counts (i.e., hot pixel) or no-signal (i.e., dead pixel). Contrary to these "bad" pixels, the majority of the working pixels — "good" pixels — generate output signals whose levels are proportional to the numbers of the incident photons. As we described in the previous section, even "good" pixels sometimes may return extremely high counts after being hit by cosmic rays. Clearly, data from these pixels should not be used in any data reduction process. In the following, we describe how to identify and eliminate such bad pixels. Let's go back to `IRCA00070351.fits` (see Figure 4 left) for the purpose of inspecting pixel behavior.

```
cl> display fits/IRCA00070351 1 z1=0 z2=30000
```

You may recognize that there are a few compact white points around the image center. Moreover, one can identify a distinct white point (i.e., showing a very high count value compared to its surrounding pixels) both on the left and right portions of the image. Accordingly we should correct for (i.e., replace) these bad pixels with the appropriate ones, by extrapolating from the surrounding pixel values. For this purpose, a general approach is to replace the bad pixel values with either the mean or the median of the adjacent 8 pixels. We believe that this approach works for many cases. But, if you have a preference, try an alternative approach.

In principle, you can identify bad pixels by eye by typing the following command:

```
cl> display ana/dHR72_1 1 z1=-1000 z2=1000
```

Ideally, bad pixel correction should be done on each individual frame. However, it will be tedious to inspect very large numbers of the frames because, in general, frame rates of infrared observations are high. Here, we will apply bad pixel corrections onto the data set combined from several frames.

We will use the IRAF task, `cosmicrays` on `dHR72_1.fits` to identify and correct for the bad pixels that have elevated values compared to their surrounding pixels. The task is implemented in the `crutil` package under `noao/imred`:

```
cl> noao

no> imred

im> crutil

cr> epar cosmicrays

(interac=                    no) Examine parameters interactively?
```

This allows you to use the task `cosmicrays`[6].

[6]For your knowledge, once you have executed `cosmicrays` at `cr>`, you can issue the command from any prompt. Namely, not only at the `cr>` prompt, but also at the e.g., `cl>` and `no>` prompts.

```
cr> cosmicrays ana/dHR72_1 abc
```

Notice that `cosmicrays` command is designated solely to find bad pixels having positive values. You may want to find the negative bad pixels as well, e.g., in the case of the `A-B` image. For this purpose, just multiply $-1$ to the image before running `cosmicrays`, as shown below.

```
cr> imarith abc * -1 abc1

cr> cosmicrays abc1 abc2

cr> imarith abc2 * -1 ana/cHR72_1
```

Comparing the original `dHR72_1.fits` with the corrected `cHR72_1.fits`, you will see that the latter image has smaller numbers of bad pixels than the former. The task `cosmicrays` has succeeded in eliminating almost all the bad pixels. If you are not satisfied with the results, you can perform further bad pixel corrections by hand using the task `fixpix`. The following shows how to accomplish this:

```
cr> imcopy ana/cHR72_1 ana/fHR72_1

cr> fixpix ana/fHR72_1 badHR72_1
```

The first line just makes a copy of the original data as `fixpix` overwrites the original image. The second operation corrects the count values of the pixels whose coordinates are given in the `badHR72_1` file, which should contain pixel coordinates:

```
18 18 97 97
23 24 67 69
```

This tells `fixpix` that count values for the pixel located at $(x, y) = (18, 97)$ and (23 to 24, 67 to 69) should be replaced with those extrapolated from their surroundings.

If you want to give a specific value to replace the bad pixel, instead of using extrapolation, the task `epix` allows you to do this:

```
cl> epix ana/fHR72_1 18 97

              17       18       19
      96 -39.0465 -7.45007  44.8567
      97  2.20168 -51.8033 -30.5948
      98 -17.9674 -55.1241 -52.4665
median -30.59483, mean -23.04381, sigma 32.69519, sample 9 pixels
new value for pixel (-51.8033): 5.0
```

The above example replaces the count at (X, Y) = (18, 97) with 5.0.

Last, don't forget to apply the bad pixel corrections to the target data (i.e., `dIR00188_1.fits` to make `cIR00188_1.fits` and `ana/fIR00188_1.fits`.

### 5.2.6 Extracting Signals and Combining Data taken at Different Slit Positions

We assume that you have successfully completed all the calibration steps so far. Now we are ready to extract spectra of the standard star and the target galaxy. The extraction can be done with the task `apall` in IRAF.

If you want to learn the detail on how `apall` works on single-order spectroscopic data, we suggest reading "A User's Guide to Reducing Slit Spectra with IRAF" by Phil Massey, Frank Valdes, & Jeanette Barnes (1992 April; `http://iraf.noao.edu/docs/spectra.html`).

```
cl> noao

no> twodspec

tw> apextract
```

ap> apextract.dispaxis=1 (This is just to make sure that the vertical axis represents the wavelength dispersion.)

ap> epar apall

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = apextract
   TASK = apall

input   =          ana/fHR72_1  List of input images
(output =                     ) List of output spectra
(apertur=                     ) Apertures
(format =            multispec) Extracted spectra format
(referen=                     ) List of aperture reference images
(profile=                     ) List of aperture profile 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 the traced points interactively?
(extract=                  yes) Extract spectra?
(extras =                   no) Extract sky, sigma, etc.?
(review =                  yes) Review extractions?

(line   =                  400) Dispersion line
(nsum   =                   20) Number of dispersion lines to sum or median

                               # DEFAULT APERTURE PARAMETERS

(lower  =                  -5.) Lower aperture limit relative to center
(upper  =                   5.) Upper aperture limit relative to center
```

```
(apidtab=                    ) Aperture ID table (optional)

                               # DEFAULT BACKGROUND PARAMETERS

(b_funct=            chebyshev) Background function
(b_order=                    1) Background function order
(b_sampl=        -40:-30,30:40) Background sample regions
(b_naver=                   -3) Background average or median
(b_niter=                    0) Background rejection iterations
(b_low_r=                   3.) Background lower rejection sigma
(b_high_=                   3.) Background upper rejection sigma

(b_grow =                   0.) Background rejection growing radius

                               # APERTURE CENTERING PARAMETERS

(width  =                   5.) Profile centering width
(radius =                  10.) Profile centering radius
(thresho=                   0.) Detection threshold for profile centering

                               # AUTOMATIC FINDING AND ORDERING PARAMETERS

nfind   =                    1  Number of apertures to be found automatically
(minsep =                   5.) Minimum separation between spectra
(maxsep =                1000.) Maximum separation between spectra
(order  =           increasing) Order of apertures

                               # RECENTERING PARAMETERS

(aprecen=                    ) Apertures for recentering calculation
(npeaks =                INDEF) Select brightest peaks
(shift  =                  yes) Use average shift instead of recentering?

                               # RESIZING PARAMETERS

(llimit =                INDEF) Lower aperture limit relative to center
```

```
(ulimit =                INDEF) Upper aperture limit relative to center
(ylevel =                  0.1) Fraction of peak or intensity for automatic widt
(peak   =                  yes) Is ylevel a fraction of the peak?
(bkg    =                  yes) Subtract background in automatic width?
(r_grow =                   0.) Grow limits by this factor
(avglimi=                   no) Average limits over all apertures?

                                # TRACING PARAMETERS

(t_nsum =                    4) Number of dispersion lines to sum
(t_step =                    4) Tracing step
(t_nlost=                    3) Number of consecutive times profile is lost befo
(t_funct=            legendre) Trace fitting function
(t_order=                    3) Trace fitting function order
(t_sampl=                    *) Trace sample regions
(t_naver=                    1) Trace average or median
(t_niter=                    0) Trace rejection iterations
(t_low_r=                   3.) Trace lower rejection sigma
(t_high_=                   3.) Trace upper rejection sigma
(t_grow =                   0.) Trace rejection growing radius

                                # EXTRACTION PARAMETERS

(backgro=                  fit) Background to subtract
(skybox =                    1) Box car smoothing length for sky
(weights=                 none) Extraction weights (none|variance)
(pfit   =                fit1d) Profile fitting type (fit1d|fit2d)
(clean  =                   no) Detect and replace bad pixels?
(saturat=                INDEF) Saturation level
(readnoi=                   0.) Read out noise sigma (photons)
(gain   =                   1.) Photon gain (photons/data number)
(lsigma =                   4.) Lower rejection threshold
(usigma =                   4.) Upper rejection threshold
(nsubaps=                    1) Number of subapertures per aperture
(mode   =                   ql)
```

`apall` has many parameters, but most of them are not critical. Bring your cursor to the field you want to change and type "`?`"; you will get options that can be selected. Set the following "critical" parameters, explained below, as follows: `line = 400, nsum = 20, t_nsum = 4, t_step = 4, t_order = 3, b_sample = -40:-30,30:40, backgro = fit, weights = none, clean = no`, and `extras = no`. Here, `extras = no` lets the program extract only signals in the specific case of the sample data.

Assuming that the spatial profile of the signal does not change with wavelength, we will check it at a certain wavelength (i.e., at a $y$ position where $y$ is the vertical coordinate). `line = 400` and `nsum = 20` specifies the location of the spatial profile from the pixel value $y = 400 \pm 10$. `t_nsum = 4` sums 4 pixels along the wavelength direction. `t_step = 4` sets the search for the peak position of the signal in the $x$ coordinate, by shifting 4 pixels along the wavelength axis (= the $y$ coordinate).

`t_order` is the order of the function that will be used to fit the peak position of the signal (at the $x$ coordinate). In general, fitting will be successful with `t_order = 3`. Notice that `t_order = 3` specifies a quadratic equation, i.e., $y = Ax^2 + Bx + C$. We selected the order set to 3 for the standard star because the S/N of the sample data is very high, allowing us to trace the peak $x$ value with high accuracy. On the other hand, fitting with a linear equation (`t_order = 2`; $y = Ax + B$) usually works well for scientific target as they are faint.

The counts of the `A-B` image, except for the signal counts, should ideally be scattered around the zero level within the noise. However, there often exist pixels whose values are non-zero (taking some positive or negative values), and whose absolute values vary with wavelength. These non-zero values indicate that the sky background level has changed during the exposure at the `A` and `B` positions [7]. If you specify `backgro = fit`, you can further subtract this residual pattern. `b_sample` is the distance in the $x$-coordinate from the peak position that defines a source-emission-free area where the sky-background level can be estimated. If you define the sky area on both sides of the peak position in the $x$-coordinate, then the linear sky gradient in the $x$-direction can be corrected for.

`weights = none` and `clean = no` extract a spectrum by summing the signal using the most straightforward method instead of using the optimal extraction. Here, optimal extraction is a method to add the signals at each pixel by giving a weight based on the noise at each pixel. If optimal extraction works well, you can expect to obtain an improved S/N ratio, compared to simple summation (see `http://archive.stsci.edu/imaps/expastro/node29.html`). Optimal extraction is known to work well on optical spectroscopic data. This is because the Earth's atmospheric

[7] At the wavelength where the Earth's atmospheric transmission is intrinsically small, the background emission is high (Recall 1 - transmission = absorption = emission), where a small difference of the relative sky level can result in high absolute value.

transmission is almost 100% over the band. Another factor, thanks to the above reason, is that most of the optical signals tend to show smooth profiles along the wavelength axis. On the contrary, the Earth's atmospheric transmission in the infrared strongly depends on wavelength. Hence the intensity of the signal varies considerably with wavelength. We have witnessed a couple of obvious examples where optimal extraction produces "strange" spectra accompanied by unusually large scatter of the data points especially at the wavelengths where the Earth's atmospheric transmission is intrinsically low. Therefore, we suggest simply summing signal over the aperture without weighting. If you plan to use optimal extraction, you should carefully read the original documents. Moreover, test with various combinations of the input parameters. Don't forget to compare the results using optimal extraction with those using the standard extraction (i.e., without weighting). Last, please note that optimal extraction executs automatically with `clean = yes` even if you specify `weight = none`.

It is highly likely that the results will be essentially the same even if you try to change the other parameters in `apall` that are mentioned above. Of course, there may be exceptions, e.g., in the case of a very faint source where `apall` may fail to trace a spectrum unless you have optimized the "minor" parameters. If this is the case, try to find the best parameters for your source by checking the help page (type `help apall` to get the help page). Shown below is `apall` usage:

```
ap> apall ana/fHR72_1 out=ana/fHR72_1pos

Find apertures for ana/fHR72_1?  (yes):
Number of apertures to be found automatically (1):
Resize apertures for ana/fHR72_1?  (yes):
Edit apertures for ana/fHR72_1?  (yes):
```

You will see that a Tektro window shown in Figure 7 pops up.

On the Tektro window, you can optimize graphically the range used for the spectral extraction. Move your cursor onto the window, and type e.g., "`:low -8`", "`:upper 8`", and "`:center 215`". Once you have provided a range to the program, type "`t`" to execute fitting. In Figure 7, the two horizontal (short) lines (around $x = 180$ and 250 in this example) with very short vertical bars are the ranges over which the sky-level will be calculated for its subtraction. Make sure the ranges are OK, then, press "`Yes`". The left-hand panel of Figure 8 shows how the fitting works, and the right-hand shows the extracted (i.e., one-dimensionalized) spectrum. If you are happy with the

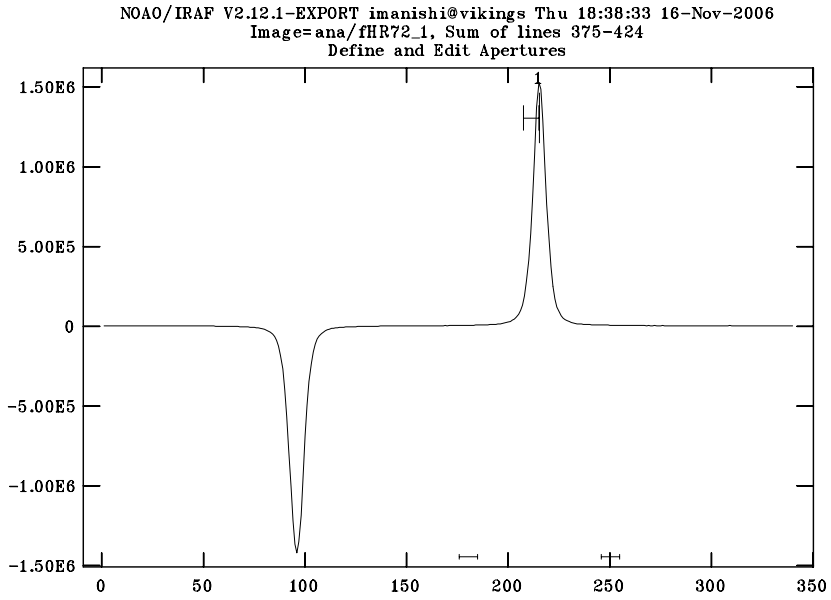



Figure 7: The output window for `apall`. This window is referred to as the Tektro window.

spectrum, return to IRAF command line (`cl>`) by typing "`q`". Use caution when you repeating `apall` on the same input file, as `apall` overwrites the results to the same output file. You may have seen a query from `Clobber ***` at a later stage of `apall` execution where the default setting of "`No`" prohibits overwriting of the results. If you want to save the second (or refined) fitting results after changing the parameters, don't forget to set the parameter to "`Yes`".

Recall that we have to extract the signal observed at slit position `B` in order to combine them to improve the S/N. Repeat the above procedures for the slit position `B` as follows:

```
ap> imarith ana/fHR72_1 * -1 ana/fHR72_1n

ap> apall ana/fHR72_1n out=ana/fHR72_1neg

ap> imarith ana/fHR72_1pos + ana/fHR72_1neg ana/fHR72_1ana
```

After combining both the `A` and `B` spectra of the standard star, the next step is reducing the target galaxy. It is certainly prudent to set `line=550` and `nsum=40,t_order=2` because the source is faint. Trace the signal as shown in Figure 9, and make the resultant file `fIR00188_1ana.fits`.

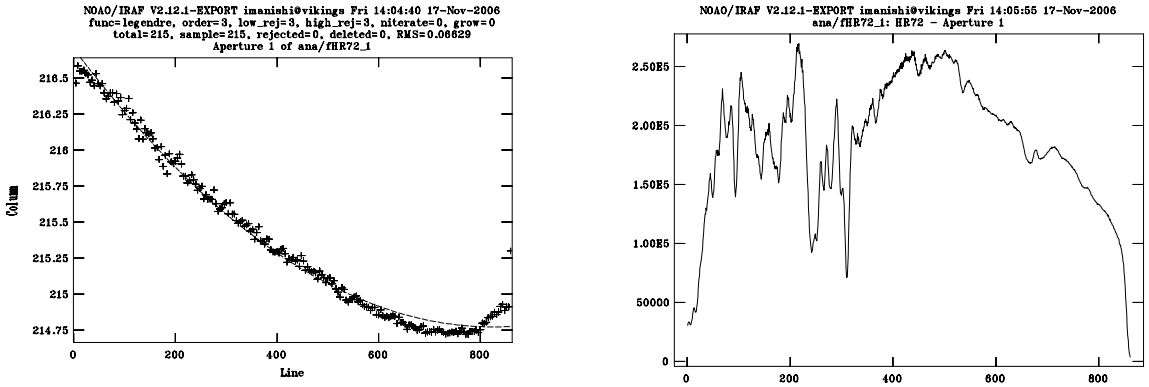



Figure 8: An example of the working windows that will pop up when running `apall`. The left panel shows how `apall` traces a spectrum. In this example, notice that the fitting curve (the dashed line) has obviously failed to trace the data at "Line" (the $x$ coordinate) $\gtrsim 600$ (the fitting curve is shifted by up to $\sim$0.25 pixel). You may have a better result by increasing the order of the fitting function. The right panel indicate the one-dimensionalized, i.e., the extracted spectrum.

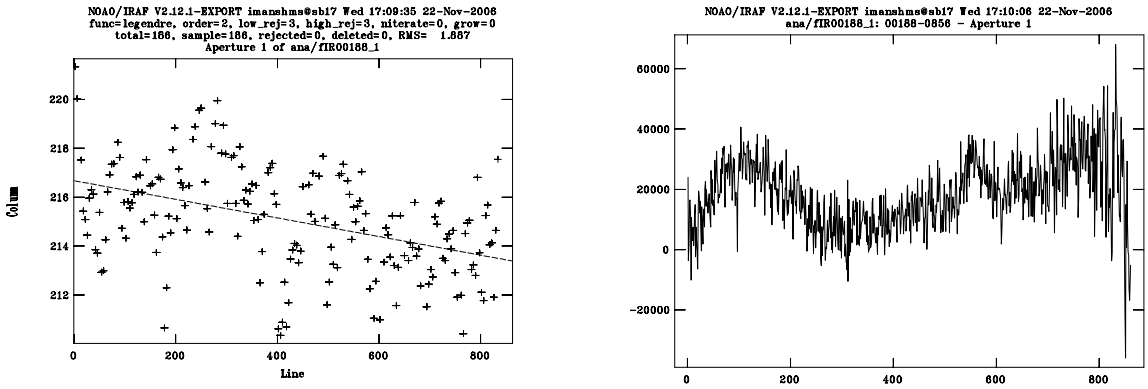



Figure 9: Results from `apall` of the target galaxy IRAS 00188. The left- and right-handed panels, respectively, show the spectral fitting and the spectrum obtained from the target galaxy.

Now, we have obtained a one-dimensional spectrum of the target galaxy. You may elect to continue to work with IRAF for further analysis such as binning and calculating errors. However, we must admit that IRAF is not necessarily the best tool for such detailed analysis. Because of this, many users seem to prefer transferring the extracted one-dimensional spectra into their own programs or/and other software packages.

To write the extracted spectrum into an ASCII text file, use IRAF task `wspectext` as follows:

```
ap> noao
```

```
no> onedspec

on> epar wspectext

                                  I R A F
                     Image Reduction and Analysis Facility
PACKAGE = onedspec
   TASK = wspectext

input   =           fHR72_1ana  Input list of image spectra
output  =                       Output list of text spectra
(header =                   no) Include header?
(wformat=                     ) Wavelength format
(mode   =                   ql)
```

Don't forget to select "`no`" for the header field, otherwise you may get long, unnecessary, header information.

```
on> wspectext ana/fHR72_1ana spec/fHR72_1.qdp
```

Here the extracted files are stored under "`spec`" directory. The same procedure should be repeated for the target galaxy as well. Here, the extension of the file, `.qdp`, is arbitrary[8]. We prefer to use it as it is convenient for the later steps.

If your source is too faint to be traced by `apall`, you can use data of a bright source (i.e., standard stars) as a reference to tell `apall` how to trace the data. Such a reference image can be supplied to `apall` with the "`referen`" parameter. In the above example, you may use it as, e.g., `apall ana/fIR00188_1 out=ana/fIR00188_1pos refe=ana/fHR72_1`. Keep in mind that, in order to apply the results from the bright source (standard star), both the bright and the dim (target) sources must have been observed at the same slit position. If not, you have to shift either of the images slightly along the $x$-direction, using the IRAF command "`imshift`".

[8]To use `qdp`, add the following path in your login shell. If the case of bash, add the following to `.bashrc`: `PATH=$PATH:/usr/local/headas-6.5/x86_64-unknown-linux-gnu-libc2.5/bin`, and execute: `source /usr/local/headas-6.5/heagen/x86_64-unknown-linux-gnu-libc2.5/headas-init.sh`.

### 5.2.7 Correction for Non-Linearity

The ideal detector should generate a signal whose intensity is perfectly proportional to the numbers of the incident photons. However, infrared detectors (CCDs at the optical regime as well) in practice do not show such a behavior. Below, we attempt to explain how the infrared detectors work by returning to the principals, with the understanding that its mechanism cannot be so idealized. If you are interested in the details, please refer to "Electronic Imaging in Astronomy Detectors and Instrumentation" by Ian S. McLean in the WILEY series.

Detectors produce a depletion layer by setting an inverse-bias voltage on the pn-junction which consists of p- and n-type semiconductors. A photon incident to the depletion layer will generate an electron[9] that causes an electron and a hole to apparently move in opposite directions from each other. This reduces the inverse-bias voltage. If there are a large number of the incident photons and if the inverse voltage drops to near zero, the depletion layer disappears, causing a loss of sensitivity to incident photons. Such a saturated situation corresponds to the so-called "full-well" level of the detector.

In other words, the above mechanism may be compared to how a capacitor with a capacity, $C$, works. If charge $Q$ is stored at both the sides of the polar plates, a voltage of $V = Q/C$ will be generated. The $Q$ value will vary with the amount of the incident photons, i.e., the number of the electrons generated by the photo-electric effect. If the capacity, $C$, remains constant, the variation of the voltage should be proportional to the number of the generated electrons, unless the detector is saturated. In summary, the detector counts the number of the incident photons by counting those generated electrons, namely, the variation of the voltage. Variation of the voltage is an analog quantity which is digitized by the AD converter. In other words, we are dealing with digitized count numbers in ADU, as seen in the image viewer.

Figure 10 shows that the generated (output) voltage tends to decrease once the detector has stored a large number of electrons. In other words, the output voltage does not increase proportionally to the numbers of the incident photons. In the above explanation, this would correspond to a situation where the capacity of the capacitor has increased as the number of the stored electrons has increased. The difference between the actual and the expected output voltage increases abruptly once the incident photon numbers exceeds a certain threshold (see Figure 10). Below this threshold, the difference stays at a negligible level. For this reason, one must select a proper exposure time for the detector used in observations so as not reach the threshold value. In the specific case of

[9]If the detector outputs an electron for an input photon, its quantum efficiency (QE) is referred to as 100%. The infrared detectors currently being used are considered to have an efficiency of 70 – 90%, which is high enough to be comparable to the CCDs used in the optical regime.

IRCS, the offset values with respect to the ideal linear-response is known to be at most 1–2 %, if the ADU count is configured to be less than 4000. If your data are low-resolution spectroscopy data with a modest S/N (e.g., $\sim 10 - 30$), the linear deviation is certainly smaller than the noise level. Therefore, correction for the non-linearity should not be so critical.

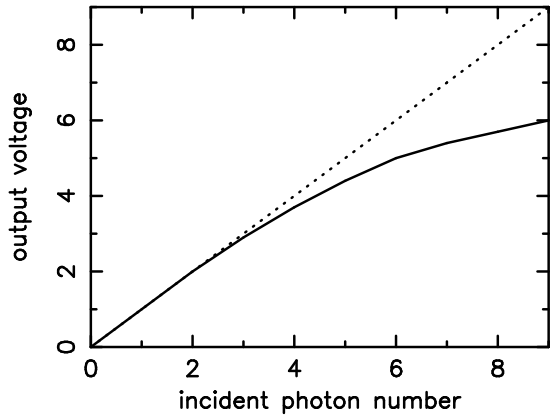



Figure 10: A plot of the ideal (the dashed line) and the actual (the thick curve) detectors' responses as a function of the incident photon numbers.

With the following explanation, it is possible to understand the mechanism of why the capacity, $C$, increases with the numbers of the stored charges. It is known that the capacity, $C$, is represented by $\propto S/d$ where $S$ and $d$ are the surface area and separation of the two polar plates, respectively. The decrease of the depletion layer by the incident photons can be thought of as a decrease in the separation of the dual polar plates, i.e., the decrease of $d$ causes an increase of $C$, explaining the actual behavior of detectors.

Although **you must verify the signal level before starting the data reduction**, let us check the signal levels of the IRCS data. Notice that the count value of the IRCS data have been multiplied by the product of the NDR and COADD values, so we have to divide the data by this product before checking the count values (in ADU unit). Let's take `IRCA00070351.fits` as an example. The fits header tells us that the data were taken with NDR = 2 and COADD = 10; therefore, we should divide the image by a factor of 20 ($= 2 \times 10$), as follows:

```
cl> imarith fits/IRCA00070351 / 20.0 fits/IRCA00070351d

cl> display fits/IRCS00070351d 1 z1=0 z2=4000
```

If you move your cursor onto the `ds9` window, you get the count value in ADU unit for each pixel. If you want to have more detailed information, try this:

```
cl> imexamine
```

```
cl> z
```

Have you obtained the count values for the region of interests? Type "q" to go back to the `cl>` prompt. Carefully check whether or not all the pixels have counts below 4,000, except for those in the uppermost (long wavelength) region of the image and some hot pixels[10]. We also need to check this for IRAS 00188. Keep in mind that the object frames have NDR = 6 and COADD = 15.

```
cl> imarith fits/IRCA00070368 / 90.0 fits/IRCA00070368d
```

```
cl> display fits/IRCS00070368d 1 z1=0 z2=4000
```

Last but not least, we strongly recommend checking the count values for all the files.

### 5.2.8 Wavelength Calibration

In order to precisely associate the pixel coordinate with the absolute wavelength, it is ideal to observe the light from a lamp that emits many lines whose wavelengths are well-known and line widths are small. Unfortunately, there is no such an ideal lamp for wavelength calibrations in the infrared $L$ band ($\lambda = 2.8 - 4.2$ $\mu$m) spectroscopy with IRCS, unlike the optical regime and short-wavelength ($\lambda \lesssim 2.5$ $\mu$m) infrared. We therefore utilize the transmission spectrum of the Earth's atmosphere for wavelength calibration. This situation is similar at the longer wavelength $M$ band ($\lambda = 4.5$–$5.0$ $\mu$m) as well.

Figure 11 enlarges the wavelength dependency of the Earth's atmospheric transmission (Figure 2) in the $L$ band ($\lambda = 2.8 - 4.2$ $\mu$m); one can utilize the strong (intrinsic) wavelength dependent transmission for this purpose. Of course, this concept can be applied to the data taken at the short wavelength, i.e., some observers use the very peaky OH airglow (vibration-rotation lines) emanated from Earth's atmosphere.

[10]The pixel values showing counts higher than 4000 ADU are the data for $\lambda \sim 4.2\,\mu$m in the case of the sample data. The data around this wavelength range are not our interest. We (M. Imanishi), therefore, have intentionally set the signals at $\lambda \sim 4.2\,\mu$m above the 4000 ADU level (i.e., long exposure), to maximize the observing efficiency.

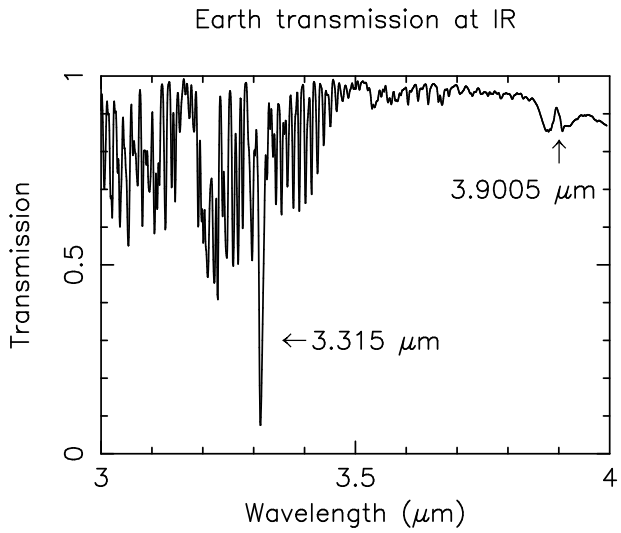



Figure 11: The Earth's atmospheric transmission curve for the $L$ band ($\lambda$ = 2.8–4.2 $\mu$m). This plot is a enlarged version of Figure 2. Image courtesy of the UKIRT (`http://www.jach.hawaii.edu/UKIRT/astronomy/utils/atmos-index.html`).

If you want to know the exact wavelengths of the peaks in Figure 11, you can get ASCII formated data from `http://www.jach.hawaii.edu/UKIRT/astronomy/utils/atmos-index.html` and click on "Text version".

For a simplicity, we are going to make a linear fit to the data using the methane absorption line at 3.315 $\mu$m and the emission at 3.9005 $\mu$m for many cases. You can try to fit the data with a high order functions using least-square fitting. However, the resultant accuracy would not improve so much.

Subsequently, we will compare the spectrum of the bright standard star with the intrinsic transmission spectrum in the ASCII text format. In the following steps, we will abandon IRAF, and use software written by one of the authors (Imanishi) in `gawk`. Of course, you can use any existing software you like, but we recommend to writing your own for a better understanding.

Since the first column of the extracted ASCII data (`fHR72_1.qdp`) does not have line numbers staring from 1, we have to correct it by:

```
gawk -f tools/pix fHR72_1.qdp > fHR72_1c.qdp
```

Here `pix` contains a simple sentence of

```
{printf("%5.6f %5.6f\n",NR,$2)}
```

where NR is the system variable implemented in `gawk`.

The next step is to verify the spectra by displaying with `qdp` (or your favorite, e.g., SuperMongo, gnuplot, IDL, etc). Here, you can obtain `qdp` from
`http://wwwastro.msfc.nasa.gov/qdp/`. In this CookBook, we present basic concepts of further analysis on the extracted spectrum using `qdp`, as we are familiar with `qdp`.

```
qdp fHR72_1c.qdp
```

```
/xs (or /xw)
```

which provides the plot shown in the left-hand panel of Figure 12. Comparing the two panels in Figure 12, the very narrow dip at $x = 310$ corresponds to $3.315\,\mu$m, and the peak around $x = 680$ with $3.9005\,\mu$m. Such a correspondence can be obtained by e.g., checking the ASCII text file by opening it with an editor, or by magnifying the data around $x = 300$ to 400 with `qdp` command "`r x 300 400`". If we fit the data with a linear equation, the best-fit is represented by $\lambda = 1.5975\times10^{-3}x + 2.8174$. Using the results, let us associate the first column from the row number with the absolute wavelength. Here we will use a program written by us,

```
gawk -f tools/wavecal spec/fHR72_1c.qdp > spec/fHR72_1cw.qdp
```

where `wavecal` contains

```
{printf("%5.6f %5.6f\n",$1*0.0015975+2.8174,$2)}
```

It is known that the Earth's atmospheric transmission at wavelengths shorter than 2.8 $\mu$m degrades significantly. Moreover, the background emission level around $\lambda \sim 4.2$ $\mu$m is too high for the linear response range (Recall §5.2.7) [11]. In fact, there are some data points exceeding 4000 ADU at $\lambda = 4.10 - 4.15\,\mu$m in the object frame. We therefore delete the wavelength ranges where the Earth's atmospheric transmission is intrinsically small, and the counts exceeds 4000 ADU ($\lambda \sim 4.2$ $\mu$m), as follows.

[11] The lines of our interests exist in $\lambda \lesssim 4.1\,\mu$m, hence the excess over the linearity range does not harm our scientific discussion. If we want to obtain the galaxy's spectrum up to $\sim 4.2\,\mu$m, we need to shorten the exposure time. However, this makes the observing efficiency low.

```
cp spec/fHR72_1cw.qdp fHR72_1ccw.qdp (Copying the file, just for the sake of saving)

emacs fHR72_1ccw.qdp & (delete unnecessary rows)
```

Later on it will be convenient, when spectral channel binning (§5.2.10), to have a pixel numbers be multiples of 8.

```
qdp fHR72_1ccw.qdp

/xs
```

We suppose that you obtained a spectrum whose $x$-axis has been converted into wavelength, similar to the right-hand panel of Figure 12.

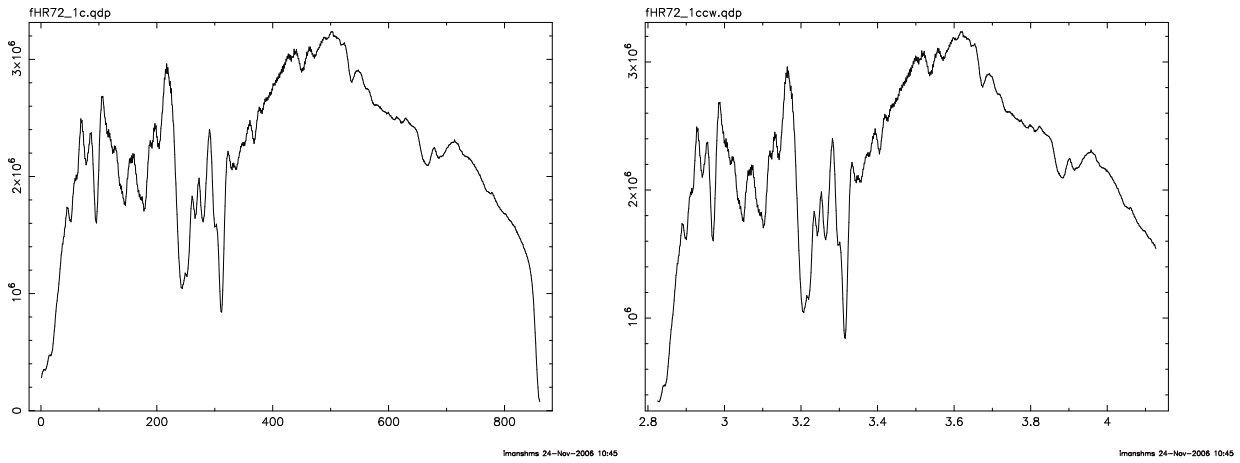



Figure 12: Spectra of the standard star HR 72 before (left) and after (right) the wavelength calibration.

If you are satisfied with the standard star's spectrum, apply the same procedure to the target galaxy to obtain the wavelength-calibrated spectrum shown in Figure 13.

For cases where you have performed spectroscopic observations at wavelengths shorter than 2.5 $\mu$m using a calibration lamp, you may use the IRAF tasks, e.g., `identify, refs` and/or `dispcor`, which are optimized for wavelength calibration. Please see the IRAF manual for more details.

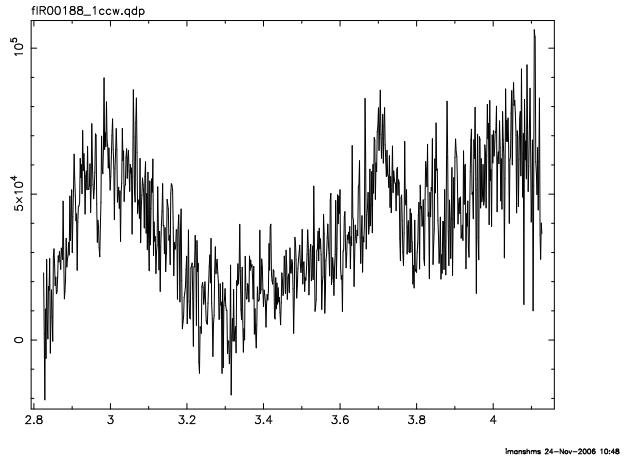



Figure 13: The wavelength calibrated spectrum of the object galaxy, IRAS 00188 ($z = 0.128$). The peak emission seen at 3.7 $\mu$m is considered to be the redshifted PAH emission whose wavelength in the rest-frame is 3.3 $\mu$m.

### 5.2.9 Airmass Correction

The path-length of where the astronomical signal has traveled through the Earth's atmosphere varies with airmass. However, as long as you have observed both the target(s) and standard stars within an airmass difference of less than $\approx 0.1$, you may not need to apply such corrections for low-dispersion grism spectroscopic data taken with IRCS with an S/N $\lesssim 10 - 30$.

However, if your data have substantially good S/N, e.g., exceeding $\sim 30$, you probably realize a need for applying airmass corrections. Please see IRAF documents and the other resources for details.

### 5.2.10 Binning Spectrum Channels

If you have observed with a slit width of 0.″9, this corresponds to 16 pixels on the IRCS detector. This defines an effective wavelength resolution, $R \sim$150. On the other hand, you will realize, e.g., by opening the extracted ASCII-text file, that the extracted spectrum consists of a numerical pair of wavelength and the signal intensity at EACH pixel of the detector. This spectral pixel (i.e., channel) increment is 16 times larger than the effective wavelength resolution, namely, oversampled. We, therefore, perform binning of the data along the wavelength axis at 16-pixel intervals. According to the Nyquist's sampling theorem, information that is two times $R$ is sensible (i.e., having independent information). Let us apply spectral channel binning of each 8-pixel group. Although you can do

this with your favorite software, we show an example using the software that is written by us (M. Imanishi).

```
cd spec (going to the spec directory)

tools/bin2_2col fHR72_1ccw.qdp > fHR72_1ccwb2.qdp

tools/bin2_2col fHR72_1ccwb2.qdp > fHR72_1ccwb4.qdp

tools/bin2_2col fHR72_1ccwb4.qdp > fHR72_1ccwb8.qdp
```

Since the software, `bin2_2col`, performs binning at every two pixels (i.e., channels), we have to run it three times[12]. In addition, the program assumes that the user will supply data having an even number of pixels. So it would be the best to select your data with a multiple of 8 before running the program.

If your source is faint, you may consider applying further smoothing. Generally speaking, many $L$ band spectra do not have good S/N ratio. In addition, they show a bumpy shape because the Earth's atmospheric transmission is intrinsically low at that wavelength, especially at $\lambda \lesssim 3.4$ $\mu$m (recall Figure 11). Therefore, many observers prefer to perform channel binning particularly for the short-wavelength regime.

For the sources whose accumulated signal photons are deficient, you may need smoothing the spectrum as many times as possible to improve the S/N and/or reduce the bumpy features seen in the profile. However, if you smooth spectra too much, you lose the needed wavelength resolution required for your scientific goal. As we have seen, there is no way to improve such a situation (unless you integrate further using more telescope time) for the data whose amount of the signal photons is intrinsically small.

If you continue to work with IRAF, try the task `blkavg` to bin a spectrum extracted by `apall`, see the IRAF help page for the detail.

### 5.2.11 Dividing the Object Spectrum by Standard Star Spectrum

Now, we have wavelength-calibrated spectrum whose intensity represents (i.e., is convolved with) a product of not only the intrinsic spectrum of the object but also the other factors. These factors

[12]It is prudent to check line numbers of the output files using e.g., Unix/Linux command `wc`.

are the Earth's atmospheric transmission curve, and the various wavelength-dependent response functions of the instrument itself. Clearly, we have to eliminate contributions from these factors to extract the intrinsic spectrum of the source. This correction can be done as follows,

```
paste fIR00188_1ccwb8.qdp fHR72_1ccwb8.qdp > tmp1

gawk -f tools/div2 tmp1 > fIR00188_fHR72_1b8ccw.qdp
```

The above operation by the `gawk` commands (written in `div2` file) divides the target source data by that of the standard source. Here, `paste` is a Unix/Linux command (see its man page for usage). For your knowledge, the `div2` file consists of a very straightforward command of

```
{printf("%5.5f %5.6f\n",$1,$2/$4)}
```

### 5.2.12 Multiplying Standard Star's Blackbody Spectrum

Once you know the spectral type of the standard star, you have knowledge about its temperature. For instance, the intrinsic spectra of G-type stars can be approximated by a (single) blackbody spectrum given by a temperature. This will work in many cases for B-, A-, and F-type stars, except for the narrow lines emanating from atomic hydrogen in the stellar atmosphere. On the other hand, you cannot use late-type stars, such as K- and M-type stars, for spectroscopic calibrations because their spectra cannot be treated as blackbody radiation owing to the significant absorption by the stellar atmosphere.

Here, we know that our standard star of HR 72 is categorized as G0V star, yielding a $T$ of 5930 K (see Allen's Astrophysical Quantities, fourth edition, p. 151). We therefore simply multiply the blackbody spectrum at 5930 K.

It should be noticed that, when you use B- or/and A-type star(s) as a standard star, you will have spurious (i.e., not real) emission lines at the rest-frame wavelength of Pf$\gamma$ ($\lambda = 3.74\mu$m) and Br$\alpha$ (4.05$\mu$m) in the $L$ band due to their deep absorptions. In this case, you have to estimate flux density of the star by interpolating the stellar spectrum; you have to supply an appropriate value by interpolating from the adjacent (or neighbor) values.

```
gawk -f tools/bb5930 fIR00188_fHR72_1b8ccw.qdp > fIR00188_fHR72_1b8ccwbb5930.qdp
```

Now we have the desired spectrum. In the above example, we have multiplied a (constant) scale factor to the spectrum. The content of `bb5930` is as follows.

```
{printf("%1.6f %lf\n",$1,$2*1.1906*10^5/($1^5)/(exp(14388.3/$1/5930)-1))}
```

### 5.2.13 Flux Calibration

The very last step of data reduction is flux calibration. If there have been photometric observations taken with a small aperture at the same band, you can obtain the flux scale from those observations. If there are no such observations, you will have to derive the brightness of the target on the basis of an intensity (measured over the slit width) ratio between the target and the standard star. We can estimate the $L$ band magnitude of HR 72 to be 5.00 mag from the $V$ band magnitude of 6.46 mag and the color $V - L = 1.46$ for G0V (see Allen's Astrophysical Quantities, fourth edition, p. 151). Since the $L$ band magnitude was measured over a wavelength range of $\lambda = 3.547 \pm 0.285$ $\mu$m (Allen's Astrophysical Quantities, fourth edition, p150), we should compare the integrated intensity (along the wavelength axis; i.e., $S = \int_{3.547-0.285\mu\mathrm{m}}^{3.547+0.285\mu\mathrm{m}} B_\lambda d\lambda$ ) of the target source over the wavelength range with that of the standard star. In addition, we have to consider the total integration time when comparing them[13]. In practice, we have to consider the following points,

1. The signal from HR 72 is approximately 80 times brighter than that of IRAS 00188 when measured over the entire $L$ band range ($\lambda = 3.262 - 3.832$ $\mu$m). If you only extract the spectral data within the above wavelength range, a program named `normalize` written by us (Imanishi) will calculate the integrated intensity.

2. The target data have a larger product of EXPITIME×NDR×COADD as compared to the standard source by a factor of 18.75. See their FITS headers to confirm this; the standard star and the object, respectively, have EXPTIME = 1.0 and 2.5 sec, NDR = 2 and 6, and

[13]The total integration time for IRCS data can be calculated from EXPITIME (exposure time per frame) × NDR (number of NDRs) × COADD (numbers of the exposure at each slit position) × the frame numbers you combined (§5.2.3). If you had combined multiple frames with averaging (i.e., `comb = average` for task `imcombine`), instead of summation (i.e., `imsum` task or `comb = sum` for task `imcombine`), the last frame number term should be 1.0.

COADD = 10 and 15. Recall that we have combined 12 and 20 frames for the standard star and the target, respectively (see §5.2.3).

3. HR72 has $L = 5.00$ mag

Using the above information, we can calculate that IRAS 00188 should have integrated intensity over the slit of $L = 12.9$ magnitude [14]. Since $L$ =0 mag is defined by the flux density of $F_\lambda = 6.59 \times 10^{-11}$ (W m$^{-2}$ $\mu$m$^{-1}$) (see Allen's Astrophysical Quantities, fourth edition, p.150), the signal of $L = 12.9$ mag corresponds to $F_\lambda = 4.6 \times 10^{-16}$ (W m$^{-2}$ $\mu$m$^{-1}$) at $\lambda \sim 3.55$ $\mu$m. If you want to present the data in the flux density scale [$F_\lambda = 10^{-16}$ (W m$^{-2}$ $\mu$m$^{-1}$)], you can get it by scaling by a factor of about 2.0 because the spectrum before the flux calibration (`fIR00188_fHR72_1b8ccwbb5930.qdp`) has a mean signal of 2.3 over the wavelength range $\lambda = 3.547 \pm 0.285$ $\mu$m.

```
gawk -f tools/multi20E0 fIR00188_fHR72_1b8ccwbb5930.qdp >
 fIR00188_fHR72_final.qdp
```

The above gives you the fully calibrated and desired FINAL! spectrum. The `multi20E0` file contains argument for `gawk` as follows,

```
{printf("%5.6f %5.6f\n",$1,$2*2.0)}
```

Finally, the following command shows you the final spectrum (shown in Figure 14):

```
qdp fIR00188_fHR72_final.qdp

/xs
```

[14] ¿From the definition, if the signal is a factor of A times dimmer, its magnitude increases by a factor of $2.5\log_{10}(A)$ mag.

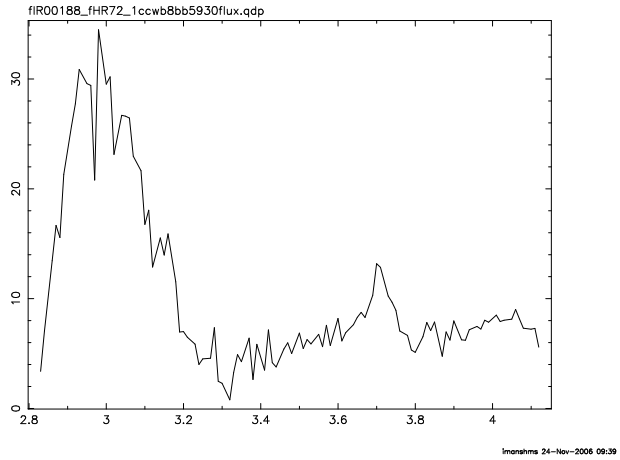



Figure 14: The fully calibrated final spectrum.

```
qdp> hardcopy

qdp> q

lpr pgplot.ps
```

The above command prints the spectrum. If you want to have a more elegant plot, e.g., writing labels, changing scales etc, you can play with the `qdp` parameters by consulting the manual.

```
qdp fIR00188_fHR72_final.qdp

/xs

qdp> la x Wavelength (\gmm)

qdp> la y F\d\gl\u (10\u-16\d W m\u-2\d \gmm\u-1\d)
```

Notice that the above brightness is that measured in the slit of IRCS. If you observe a compact object with IRCS, the image size at the $L$-band ($\lesssim 0\farcs5$) is usually smaller than the slit width ($0\farcs9$).

The good tracking accuracy of Subaru Telescope produces very small slit loss. Even if the slit loss stays around the 10–20% level, the effect cancels out each other by dividing the object with the standard star. In this case, the resultant flux calibration uncertainty would be smaller than that in each spectrum (10–20%).

In the case of the short wavelength observations at $\lambda \lesssim 2.5$ $\mu$m, the background emission is less intense, hence, one can use a fainter standard star. In addition, we can utilize 2MASS data, allowing us to compare directly the magnitudes of the standard star at the $J$, $H$, and $K$ bands. Unfortunately, there is no such widely used catalog for the $L$ band. We therefore have to extrapolate the desired flux of a standard star to the $L$ band from short wavelengths flux using the stellar colors. In general, bright standard stars, which are suitable as standard stars for $L$-band spectroscopy, are saturated in the 2MASS measurements and accompanied by large uncertainties. We usually estimate the $L$ band flux of a bright standard star from the optical $V$ band flux. In conclusion, the users should pay special attention to the fact that the photometric error of standard stars at $L$ band is significantly larger than those for optical and short-wavelength infrared measurements.

Regardless of these drawbacks, we believe that the above approach will give reasonable results in the sense that the uncertainty level is at most 20–30 %. This is because the resultant fluxes for compact sources (e.g., AGNs) estimated in this way have a fairly good consistency with the published photometry results taken with small apertures.

# Appendix

## A Error Estimates

The readers should bear in mind that the method to evaluate errors described below is one of the many possible approaches.

By dividing the spectrum of the target by that of the standard star, we obtained the final spectrum, but the spectrum does not have error bars. Even without error bars, the readers of your paper can guess the uncertainty from the scatter of the data points at the line-free wavelengths. However, there is no doubt about the usefulness of providing uncertainties of the flux levels for the individual spectral elements. We realize that the method to evaluate uncertainties certainly is not unique and depends on researchers. For instance, one may adopt Poisson noise of the total signal, including both the target and background emission, as an uncertainty.

One of the approaches, we describe here, is to give uncertainties from the standard deviation of several (independent) measurements toward an object. Here, all the measurements must be done with exactly the identical observing parameters. For this purpose, we will split the whole data sets of the target and standard star into a few sub-sets, and obtain one-dimensional spectra for the individual sub-datasets. Subsequently we normalize each spectrum to equalize the flux levels, and then estimate uncertainties based on the scatter of each spectral element among the sub-sets. Finally, we should obtain a final spectrum with errors through dividing target spectrum by that of standard star (here, we suppose that the both have error bars), multiplying the blackbody spectrum of the standard star, and flux-calibrating.

In §5.2.2, we reduced only the first-half of the entire dataset for both the standard star HR 72 and the target IRAS 00188. By analyzing the remaining data in the same fashion, we can estimate the uncertainties. Specifically, we perform the following operations using the software prepared by ourselves. We create the text files, `fHR72_1.qdp` and `fHR72_2.qdp`, from the former and the latter half of the HR 72 data. We also make the text files, `fIR00188_1.qdp` and `fIR00188_2.qdp`, from the IRAS00188 sub-datasets. We simply repeat the previous procedures accordingly up to wavelength calibration (§5.2.8), and then bin 8 spectral elements. After completing all the steps on the second half of the data, do the following:

```
cd spec

tools/normalize fHR72_1ccwb8.qdp > fHR72_1normccwb8.qdp

tools/normalize fHR72_2ccwb8.qdp > fHR72_2normccwb8.qdp

paste fHR72_1normccw.qdp fHR72_2normccwb8.qdp > fHR72_12normccwb8.tmp
```

Above, we normalized the spectra of the former and the latter halves of the standard star's data, based on the signal levels, then combined them. In general, the slit losses do not stay at a constant value between sub-datasets, and varies slightly. We believe that we do not need to consider such variation of the absolute value of the signal as it causes unnecessarily large (i.e., physically no-sense) error bars. Since our primary interest lies in the spectral shape, above procedures would be justified. However, we encourage the readers to address this issue from various aspects.

```
emacs fHR72_12normccwb8.tmp
```

We should delete the first three rows because the program appends unnecessary information, such as pixel numbers, sum of signals, and the normalization constant, all of which are not required for the latter stages.

Next is:

```
gawk -f tools/sigma fHR72_12normccwb8.tmp > fHR72_12normccwb8.qdp
```

We combine the former and latter half datasets after the normalization step. At the same time, the uncertainties (standard deviation) are also derived.

The content of the file `sigma` is as follows:

```
{printf("%1.5f %lf %lf\n",$1,1/2*($2+$4),sqrt((($2-($2+$4)/2)^2+($4-($2+$4)/2)^2)/2))}
```

When combining three sub-datasets, the following calculation is required.

```
{printf("%1.5f %lf %lf\n",$1,1/3*($2+$4+$6),sqrt((($2-($2+$4+$6)/3)^2+
($3-($2+$4+$6)/3)^2+($4-($2+$4+$6)/3)^2)/3))}
```

The above procedures are for the standard star data. For the target data, the same procedures must be applied accordingly. The readers should perform the following:

```
tools/normalize fIR00188_1ccwb8.qdp > fIR00188_1normccwb8.qdp

tools/normalize fIR00188_2ccwb8.qdp > fIR00188_2normccwb8.qdp

paste fIR00188_1normccw.qdp fIR00188_2normccwb8.qdp > fIR00188_12normccwb8.tmp

emacs fIR00188_12normccwb8.tmp (delete the first three unnecessary rows)

gawk -f tools/sigma fIR00188_12normccwb8.tmp > fIR00188_12normccwb8.qdp
```

At this stage, we have obtained spectra with error bars for both the standard star and the target. Next, we should divide (1) the target spectrum by that of the standard star, (2) multiply the blackbody spectrum corresponding to the standard star's temperature, and (3) apply flux-calibration. After these operations, we hope that you have obtained a FINAL spectrum where the uncertainties are included. The following steps should guide you toward that goal:

```
paste fIR00188_12normccw.qdp fHR72_12normccwb8.qdp > fIR00188_fHR72_12normccwb8.tmp
```

Here, we have combined the text files of the standard star and the target using the Unix command "paste", then,

```
gawk -f tools/spectrum fIR00188_fHR72_12normccwb8.tmp >
fIR00188_fHR72_12normccwb8.qdp
```

The "gawk" scripts consists of the following,

```
{printf("%1.6f %lf %lf\n",$1,$2/$5,sqrt($3*$3/$5/$5+$6*$6*$2*$2/$5/$5/$5/$5))}
```

It should be noted that we calculated an error propagation for the divided spectrum because both the standard star and target spectra have their own uncertainties. If the target data are represented by $\mathrm{X} \pm \sigma_{\mathrm{X}}$ and those for the standard star as $\mathrm{Y} \pm \sigma_{\mathrm{Y}}$, then the propagated uncertainties associated with $X/Y$ can be written as $\sqrt{\left(\frac{\sigma_{\mathrm{X}}}{Y}\right)^2 + \left(\frac{\sigma_{\mathrm{Y}} \cdot X}{Y^2}\right)^2}$. Then, we multiply with the blackbody spectrum.

```
gawk -f tools/bb5930a fIR00188_fHR72_12normccwb8.qdp >
IR00188_fHR72_12normccwb8bb5930.qdp
```

The content of the file "bb5930a" is as follows:

```
{printf("%1.6f %lf %lf\n",$1,$2*1.1906*10^5/($1^5)/(exp(14388.3/$1/5930)-1),\\
$3*1.1906*10^5/($1^5)/(exp(14388.3/$1/5930)-1))}
```

Notice that we made a minor correction to the previously-used gawk file "bb5930" because the current data has error bars consisting of three columns, then

```
gawk -f tools/multi530E-2a fIR00188_fHR72_12normccwb8bb5930.qdp >
fIR00188_fHR72_12normccwb8bb5930flux.qdp
```

We subsequently make the flux-calibration to the target spectrum based on the calculation mentioned in §5.2.13; the gawk file "multi530E-2a" consists of

```
{printf("%5.6f %5.6f %5.6f\n",$1,$2*0.05300,$3*0.0530)}
```

Of course, the normalization factor is different for data with and data without error bars.

Insert `read serr 2` to the first line of the file opened by the editor,

```
emacs fIR00188_fHR72_12normccwb8bb5930flux.qdp &

qdp fIR00188_fHR72_12normccwb8bb5930flux.qdp

/xs
```

The last two commands display the spectrum with error bars (Figure 15).

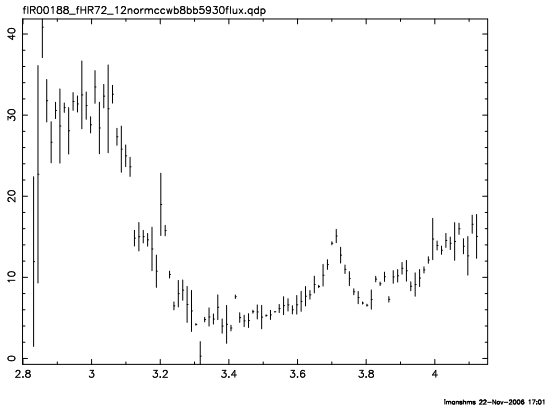



Figure 15: Obtained spectrum of IRAS00188 with error bars.

Inspecting the 8 pixel-bin'ed spectrum in Figure 15, one probably realize that the scatter of the spectrum is large at the short wavelength region, which is caused by the descent Earth's atmospheric transmission. We thus decided to increase the numbers of the binning pixels in the wavelength range.

As described before, the number of binning pixels should be optimized on the basis of the spectral quality of the target. Notice that we dealt with the target and the standard star data separately before dividing the former by the latter when binned the spectral elements. In other words, we are not in favor of performing spectral binning on the resultant spectrum obtained by dividing the (target) spectrum by the standard star spectrum. It is true that both methods will certainly produce very similar results with respect to each other at wavelengths where the Earth's atmospheric transmission curve is smooth. However, in the wavelength range where the Earth's atmospheric transmission is highly dependent upon the wavelength (e.g., the short wavelength range of the infrared $L$-band), the former method must be selected, as the latter procedure is inappropriate. We strongly encourage readers to address this issue.

Consequently, after searching for appropriate binning numbers, we obtained the desired spectrum as shown in Figure 16. Have you obtained a similar spectrum? If so, you should be ready to write the paper!

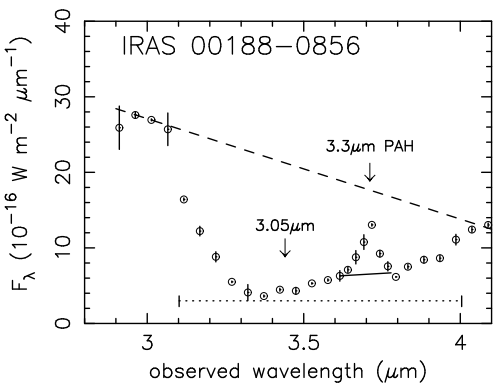



Figure 16: The final spectrum of IRAS 00188, adopted from Imanishi et al. (2006 ApJ 637 114).