

# Astronomy 480 - IRAF Tutorial and Exercise II

## Quick-look Photometry with Imexamine

### Images Used

/net/projects/Astro\_480/exercises/exercise2/  
m92.tar.gz

### Introduction

One of the most basic astronomical measurements involves determining the flux from an object, over a particular range in wavelength (“passband”), that is intercepted by the detector. The process of extracting flux measurements from images is called photometry. As you will see below, photometry is by no means trivial. Two of the major challenges are 1) compensating for the absorption of light by the atmosphere (extinction) and 2) eliminating unwanted light from sources other than the object of interest.

### Magnitudes

By convention, astronomical fluxes are measured in magnitudes. We need to first distinguish between “absolute” and “apparent” magnitudes. Apparent magnitudes are simply a measure of how much light gets to the Earth from a celestial object, and are represented with a lower-case letter, such as  $m = 12$ . This is determined both by the object’s intrinsic luminosity, by how far away it is, and how much stuff may be in between us and it that could block some of the light. The “absolute” magnitude of an object, on the other hand, refers only to its intrinsic luminosity, and is usually represented with an upper-case letter,  $M = 8$ , for example. This is usually tough to determine since you need a reliable way to establish the object’s distance. The measurement of line-of-sight distance is the one of the biggest challenges that astronomers face.

Magnitudes are a logarithmic scale. Two objects that differ in measured flux by a factor of 100 are defined as having 5 magnitudes difference. The fainter of the two objects is assigned the larger magnitude value, i.e. an object of 18<sup>th</sup> magnitude is 100 times fainter than an object of 13<sup>th</sup> magnitude. The apparent magnitude difference between 2 objects is then given by

$$m_1 - m_2 = -2.5 \log_{10} \left( \frac{f_1}{f_2} \right),$$

where  $m_1$  and  $m_2$  the magnitudes, and  $f_1$  and  $f_2$  are the observed photon fluxes. With the determination of the slope of the magnitude scale given by the definition above, there is an arbitrary constant that determines the “zeropoint” of any given photometric system. Traditionally, this has been defined by using the star Vega as the definition of 0<sup>th</sup> magnitude. This traces its roots to early attempts by the Greeks to classify stars according to their apparent brightness. First magnitude stars were supposed to be twice as bright as second magnitude stars, etc. The human eye is close to a logarithmic detector, and the contemporary magnitude scale still retains much of its historical heritage. Given the wide range in brightness spanned by astronomical objects, a logarithmic scale makes a lot of sense. The apparent magnitude of the Sun is about  $-27$ , the full moon is  $-12.5$ , and you can barely pick out stars as faint as 6<sup>th</sup> magnitude with the naked eye. The faintest objects observed with HST or ground-based telescopes are at around 30<sup>th</sup> magnitude.

For any given telescope, filter and detector system, the apparent brightness of an object, expressed in apparent magnitudes, is given by

$$m = -2.5 \log_{10}(f) + m_0$$

where the constant  $m_0$  (the “zeropoint”) is determined by measuring the flux for “standard” stars that serve as calibrators. This zeropoint in magnitude is the single scaling factor for an astronomical imaging system. You can

measure the flux in A/D converter units (“ADUs”) **per second**, plug those values into the formula above, and sweep all the calibration factors into the system’s zeropoint. If done this way, the zeropoint represents the magnitude of an object that would produce a detected signal accumulation of 1 ADU per second.

Astronomers often refer to “instrumental magnitudes,” where the value of  $m_0$  is not tied to a well-defined set of standards. This is perfectly fine as long as one is only interested in relative fluxes between measured objects. It’s important to make clear, however, whether one is referring to instrumental or calibrated magnitudes.

● **Thought Questions:** Under what conditions or when observing what kinds of objects would relative flux measurements be acceptable?

What advantages do relative flux measurements have over calibrated?

### Atmospheric Extinction

The magnitude scale is defined as flux that is incident at the top of the atmosphere, as if the measurements were being carried out by an ideal telescope in orbit above the Earth. This will require that we correct for the (wavelength-dependent) absorption of light by the atmosphere. The determination of these extinction corrections requires taking a set of observations that are specifically used to establish the values of the extinction correction parameters. One way to do this is to measure the apparent flux from a stable star at a variety of zenith angles, and make a plot of the flux vs. the amount of atmosphere along the line of sight. You then determine the flux extrapolated to zero atmospheres, i.e. an airmass of zero.

Since the determination of atmospheric extinction requires a succession of measurements over time, the properties of the atmosphere must remain stable over that period. When the atmosphere is stable and flux depends only on airmass (and not on time) the conditions are considered to be “photometric,” i.e. adequate for making photometric measurements. In contrast, when it’s partially cloudy astronomers call the conditions “spectroscopic.” In practice, establishing whether the conditions are photometric is not trivial, since it’s pretty hard to see clouds at night, especially high cirrus (the bane of observational astronomers)! There are 4 ways (that we know of) that are used to determine whether conditions are photometric:

1. Check for any clouds at sunset and sunrise. If none are seen then assume it was clear all night.
2. Check to see if the photometry results have scatter that is consistent with Poisson noise, with no excess scatter.
3. Check on-line weather satellite IR images
4. Use an infrared camera to monitor the sky. Clouds are nicely visible at a wavelength of 10 microns.

This last technique is very effective. For example, if you were to get time on the Apache Point Observatory located in New Mexico, there is a 10 micron all-sky cloud camera in use. You could look at the results by going to the APO web site, <http://www.apo.nmsu.edu>, and moving to the link labeled “weather conditions.”

## Sky Subtraction

One complication in doing photometry is that the object of interest is superimposed on flux from the sky. This light comes from a variety of sources, including unresolved stars and galaxies, sunlight scattered into the beam (particularly from the Moon!), stray light bouncing around in the telescope, and light from man-made sources. A simple model for the sky is to assume it's uniform, at least in the immediate vicinity of the object of interest. The sky brightness is then given in magnitudes per square arc second. The sky brightness depends on the wavelength under consideration, as well as the phase of the Moon. (The Moon is bright in the ultraviolet but faint in the infrared. Infrared observers don't mind "bright time" observing.) Typical values at a dark site are  $\sim 20^{\text{th}}$  mag per square arc second. The flux from the sky is then equal to what you would see if a  $20^{\text{th}}$  magnitude star were placed in each square arcsecond of the sky, except of course the sky flux is uniform.

If you think of the flux from the object of interest as sitting on top of flux from the sky, then clearly we'd like to move away from the star, measure the sky background, and then subtract the sky level from the pixels that contain the object's flux. This process is called "sky subtraction." In very crowded fields it is often hard to get a good measure of the sky brightness, and this is a major source of systematic error.

● **Thought Question:** Why would this be a systematic error and not a random error?

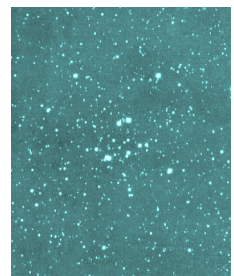
A common technique for determining the sky level is to specify an annulus around the star, and compute the mode or median (debates rage!) of the intensity in the annulus. This value is then subtracted from the pixels that contain the object of interest. A slightly more sophisticated mechanism uses a tilted plane model for the sky, fitting to the  $(x, y)$  intensity values in the sky annulus, and uses this model to subtract the sky. This allows for first order gradients in the sky brightness.

It is usually best to determine the sky value locally for each object of interest, rather than applying a single value to an entire frame.

## PSF-Fitting vs. Aperture Photometry

When the light from an astronomical point source is brought to a focus at the focal plane of a telescope, ideally we would see a diffraction-limited image, with Airy rings. In reality both the atmosphere and the telescope optics (especially poor focus) degrade the image, to something that is more like a 2-dimensional Gaussian profile. The 2-d function that describes the light distribution in the focal plane that comes from a point source is called the Point Spread Function, or PSF. Clearly, the integral of the flux "under" the PSF is proportional to the flux received from the source.

There are two common techniques to measure the flux of an object of interest: aperture photometry and PSF-fitting photometry. Aperture photometry is the simplest to understand: just place a circular aperture around the star of interest and add up the flux from the object that is within the aperture. This works well if the stars are well separated so that only the flux from a single object appears in the aperture.

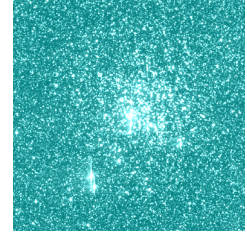


## Uncrowded Star Field

The choice of aperture size depends on the objective of the program. If you are interested in just the relative fluxes of objects in the image, then (as long as the stellar images are the same everywhere) the result is independent of aperture size. On the other hand, if you're interested in doing an absolute measurement (i.e. count every photon!) then the typical approach is to do aperture photometry for a sequence of apertures, and fit

the (increasing) measured flux as a function of aperture size. The asymptotic value at  $R_{\text{aperture}} = \infty$  is the best estimate of the total flux from the object. This is called a “curve of growth” analysis.

For crowded fields aperture photometry does not work very well. The stellar images blend together, and any given pixel might contain flux from multiple objects. In this case we try to first establish the *shape* of the stellar image, or Point Spread Function (PSF) from a bright, isolated star. The flux in an object of interest is then determined by fitting the image data to a model of the PSF.



Even in PSF-fitting photometry, there are choices to be made. Should the stars be fitted individually, or simultaneously? Is it better to use a mathematical model of the PSF, or to retain the details of the empirical PSF? There are two programs that are in common usage to perform PSF-fitting photometry: DAOPhot (which is bundled within IRAF) and DoPhot (a standalone program).

### Imexamine photometry, and sky subtraction

It is often useful to do quick-look photometry while taking data. The IRAF task `imexamine` is a very powerful way to do this. You can do sky-subtracted radial fits to stars, using parameters that you can set as desired, and IRAF will make initial estimates of the flux using radial integrals. We strongly suggest you use `phelp imexamine` to learn how the sky subtraction and quick-look photometry functions work. Concentrate on the sections that deal with the “a” and “r” commands.

Notice that the “r” task does aperture photometry, and also plots PSF fits using either Gaussian or Moffat models. We’ll get to the details of these fitting functions in Ch. 5 of Howell.

You should make a subdirectory within your IRAF images directory titled **exercise2**. Go ahead and copy **m92.tar.gz** over into this subdirectory. Gunzip this file and extract the individual files from the tarball.

**Absolute path to your exercise2 directory: /net/projects/Astro\_480/spring-??/yourusername/images/exercise2/**

The IRAF task `imexamine` can be also used to illustrate the issue of background (or sky) subtraction. Bring up one of the images of M92 in IRAF, using DS9. Choose two stars that are well separated from any others, and use `imexamine` to investigate them. First use “s” to make a surface plot of the light distribution:

```
ecl> display m920004 1 ; note typing “fits” optional
ecl> imexamine
ecl> s ; This shows a picture of the PSF of the star.
```

Now use the “r” function to make a radial plot of the object. This task will also compute the FWHM, the radial integral of the flux, and a sky value. The “r” task produces a number of interesting quantities that pertain to the object of interest. Notice that the pixel values of the centroid of the object appear in the title section of the graphics window, with a resolution much better than an integer pixel value. Also, along the bottom of the graphics window, in the yellow band, appears a line of numbers. These are all described in the on-line help documentation for the `imexamine` task. If you look at the section around line 630 in the `imexamine` documentation (do `phelp imexamine`) you can see the quantities that are produced.

**Thought Questions:** The “r” task in `imexamine` does nearly the same thing as the “a” task. Try them both. What is different? Work with “r” and “s.” Do you need to move the cursor off of the star?

On a scratch piece of paper, draw a gaussian curve. Would a gaussian fit necessarily accurately describe the profile of a star? How about a very bright star versus a very dim star? What is meant by the FWHM of the stellar profile?

Along the top of the graphics window are the centroid x and y (in pixels). Across the bottom of the graphics window it gives:

- The object radius used for aperture photometry
- The object's magnitude
- The total flux, in A/D units
- The mean sky background, in A/D units
- The peak value of the PSF fit
- The ellipticity of the object (round has  $e=0$ )
- The "position angle" of the ellipse, i.e. its orientation, in degrees (aligned with x axis =0)
- If a Moffatt function is used to describe the PSF, a parameter Beta of that function is given next
- Then come 3 different estimates of the FWHM (Full Width at Half Maximum) of the PSF. The last one of these is probably the best one to use, as it uses the data alone and does not depend on model fitting.

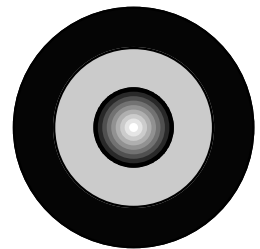
Do "r" for a few stars, in the m920004 frame. Compare the task's output with the listing given above. Compare very bright stars with very dim stars.

Now quit imexamine (for the moment) and list the parameters you've been using, with

```
cl> lpar rimexam
```

"But, wait," you say! "Where did 'rimexam' come from? If I do 'help rimexam' it says no such task"! Perhaps you did not review **all** of the details of the task imexamine. Do so now, or at least find the section where it deals with parameter sets. IRAF tasks can and do invoke many other tasks—separate tasks that each have their own parameter sets.

The sky background is determined from 3 parameters, "radius," "buffer" and "width." You should think of 3 concentric circles, centered on the star. The parameter "object radius" is the radius of the first circle, which is used to compute the object flux, with aperture photometry. Then comes an annular buffer with a radius given by "Background buffer width," followed by an annular region in which the sky value will be computed. The radial size of the background region is given by "Background width." These parameters can all be modified, with `epar rimexam`. We'll do this in a moment. Compare the sketch at the right to Fig. 5.2 of Howell (2006).



Imexamine is a little too clever for us, though. It will automatically modify the radii it uses, based on the FWHM of the stellar image, unless we insist that it not do so. This is controlled by the "iterations" parameter. Modify the values for rimexam so they match the following list:

```
ecl> epar rimexam ;list continues on the next page
```

```
(banner =          yes) Standard banner
(title   =          ) Title
(xlabel  =          Radius) X-axis label
(ylabel  =          Pixel Value) Y-axis label
(fitplot =          yes) Overplot profile fit?
```

```

(fittype=      moffat) Profile type to fit
(center =      yes) Center object in aperture?
(backgro=      yes) Fit and subtract background?
(radius =      2.) Object radius
(buffer =      0.) Background buffer width
(width =       1.) Background width
(iterati=      1) Number radius adjustment iterations
(xorder =      0) Background x order
(yorder =      0) Background y order
(magzero=     25.) Magnitude zero point
(beta =       INDEF) Moffat beta parameter
(rplot =      8.) Plotting radius
(x1 =         INDEF) X-axis window limit

```

<ctrl> d ;gets you out of the epar mode, saving changes

Change the values of the radius and sky subtraction parameters and see how they affect the photometry of two stars that you choose. The radius is also the aperture used for this implementation of aperture photometry. In particular, try setting the radius equal to one half of the FWHM, with buffer=0. This will then compute sky from a “contaminated” region, and using “r” will show a sky baseline that is clearly wrong. Play around with this some, enough to get the sense for the process of sky subtraction. Again, try bright stars and dim stars using the same parameters and then the same star using different parameters.

**⚠ Important Note:** You can store the results of imexmaine in a logfile. Do “epar imexamine” to turn on the logging feature. It may be a good thing to use different files for each part of the exercise.

Take a look at some other image frames and get a feel for the imexamine tool.

## References

Howell, Handbook of CCD Astronomy, Chapter 5.

A User’s Guide to Stellar CCD Photometry with IRAF, by Philip Massey and Lindsey E. Davis, April 1992.

A User’s Guide to the IRAF Aphot Package, by Lindsey Elspeth Davis, May 1989.

Specifications for the Aperture Photometry Package, Lindsey Davis, October 1987.

### An aside- Distance Modulus

Although the notion of the magnitude scale takes some getting used to, it is in fact a very useful and practical scheme for expressing fluxes. Magnitude differences are a logarithmic expression of flux ratios. The difference of magnitudes in different optical passbands is then a measure of the spectral energy distribution of objects. Magnitudes are also used as a way to express distances. The absolute magnitude of an object is defined as the apparent magnitude you’d see if it were a distance of 10 parsecs away. The distances to more remote objects can then be given as a “distance modulus,” which is simply an expression of how much a stable star’s apparent magnitude would change if it were translated from a distance of 10 pc to the location of the object in question.. For example, the Large Magellanic Cloud, one of our near neighbor galaxies, lies at a distance modulus of  $D = 18.5$  mag. If an object with an absolute magnitude of 3 were moved from a distance of 10 pc away to the LMC, it would have an apparent magnitude of  $3 + 18.5 = 21.5$ . In general, since flux scales like  $1/r^2$ , the distance modulus is given by

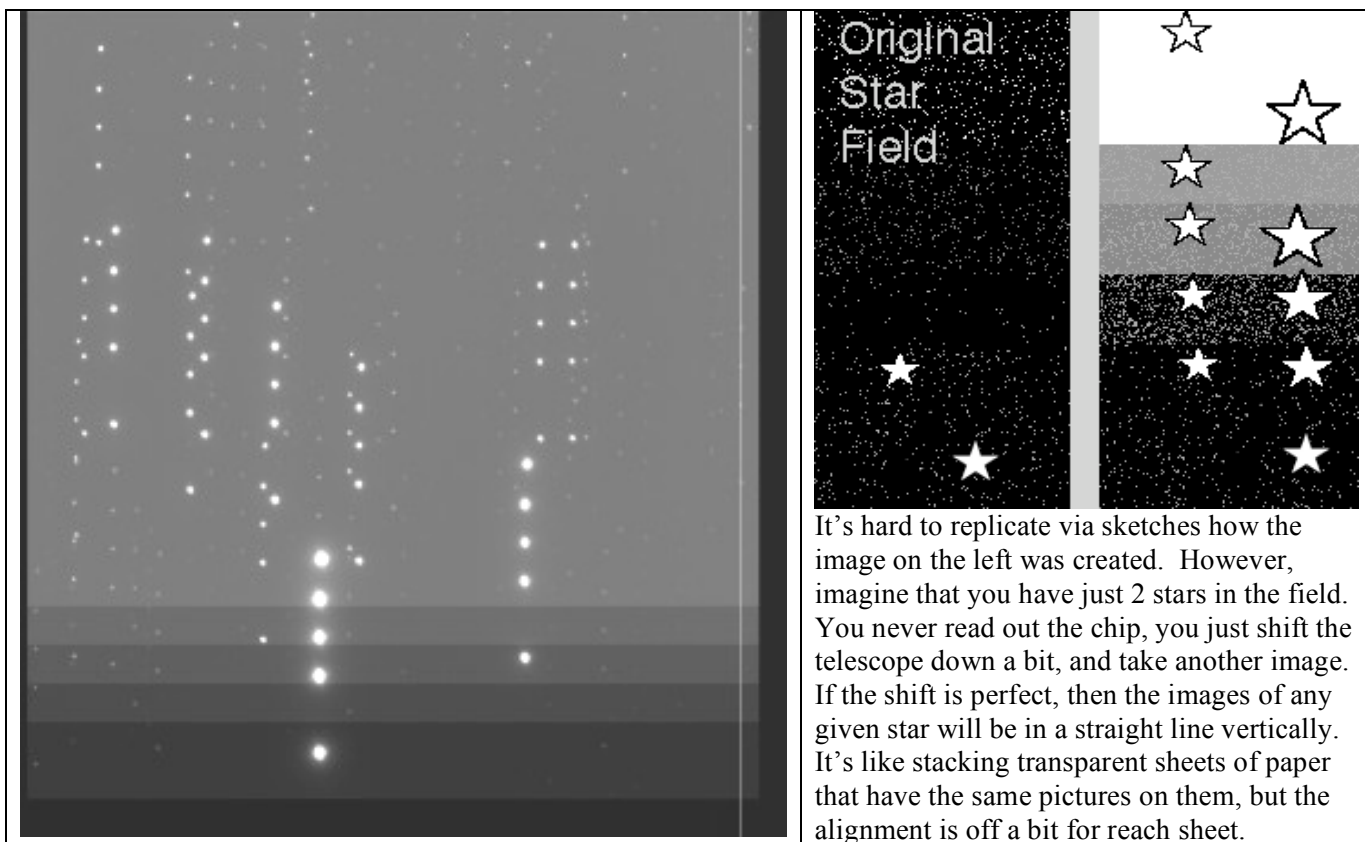
$$m - M = -2.5 \log_{10} \left[ \frac{f(r)}{f(10 \text{ pc})} \right] = -2.5 \log_{10} \left[ \frac{r}{10 \text{ pc}} \right]^{-2} = 5 \log_{10} \left[ \frac{r}{10 \text{ pc}} \right] .$$

Name: \_\_\_\_\_ Due Date: \_\_\_\_\_

## IRAF Exercise 2

Score: \_\_\_\_\_ / 25

There is an image called “spicamfocus.fits.gz” in the directory: `/net/projects/Astro_480/exercises/exercise2/` that you should copy to your directory. It is a typical focus frame, taken with an instrument called SPICam on the Apache Point 3.5 meter telescope. Each pixel in the image spans 0.28 arcseconds on the sky. The picture contains multiple images of each star, each at a different focus setting. This is accomplished by doing 5 iterations of 1) open the shutter for 10 sec, 2) close the shutter, 3) shift the charge on the detector down by a few rows, 4) change the telescope focus, 5) repeat. The CCD is then read out. To keep track of things there is a double-skip in the charge transfer on the last iteration. For this frame, assume the focus was set to (1100, 1200, 1300, 1400, 1500) microns with the 1500 micron setting corresponding to the images that are “double-spaced.”



It's hard to replicate via sketches how the image on the left was created. However, imagine that you have just 2 stars in the field. You never read out the chip, you just shift the telescope down a bit, and take another image. If the shift is perfect, then the images of any given star will be in a straight line vertically. It's like stacking transparent sheets of paper that have the same pictures on them, but the alignment is off a bit for each sheet.

●\* **Caution:** Be sure to keep the focus settings straight between the image and the tables below. Also, the stars you choose cannot be saturated in **any** of the focus frames, so check all 5 images of the star before actually choosing it.

1. <1pt> By how many rows is the image shifted between focus settings? (The single-space shift) \_\_\_\_\_

2. <4 pts> When the telescope has its best focus, the images should be axisymmetric (ellipticity = 0), smallest (min FWHM), and highest peak intensity (peak at a max). Ideally these would all occur at the same focus setting, but that is not always the case. Check out the faint star whose 3<sup>rd</sup> image is at  $\sim (693, 470)$ . Notice that the 3<sup>rd</sup> image seems better than the rest. This is a clue that the best focus setting will likely be around 1300 microns, but let's do it quantitatively. Edit the “rimexam” parameter file so that the object radius=4, background buffer width=2 and background width=1. Now choose two well-behaved (**unsaturated and isolated**) stars and fill in the tables below.

Star 1		Double-skip centroid: x=                      y=                      (pixels)		
Focus Setting	Peak Flux	Ellipticity	FWHM (pixels)	FWHM (arcsec)
1100				
1200				
1300				
1400				
1500				

Star 2		Double-skip centroid: x=                      y=                      (pixels)		
Focus Setting	Peak Flux	Ellipticity	FWHM (pixels)	FWHM (arcsec)
1100				
1200				
1300				
1400				
1500				

3. <2 pts> What would you choose as the best focus setting for the telescope? On what basis? Which FWHM value did you use?

4. <1 pt> Just using the ds9 pixel readout (accessed from the Analysis menu at the top), what would you estimate as the background sky value for this image, in A/D units? \_\_\_\_\_

5. <5 pts> Let's investigate how the rimexam parameters affect the results you obtain for aperture photometry. The settings of the object radius, buffer width, and background width will affect the determination of the sky values and object flux. Edit the rimexam parameter file and set **rplot=15** (note – this is **not** the aperture radius), **buffer=1**, **width=1**. For the values of Object radius given, fill in the table below. As you fill in the Table, notice how the sky value in the radial plot varies. **Use the isolated star at (523,497) that is in focus.** [Don't forget to set up a log file to save your work. **Also, make sure that the iterations parameter in rimexam is set to 1!**]

(radius =	1.) Object radius	#change this value
-----------	-------------------	--------------------

For Object at x= 523            y= 497

Object radius	Magnitude	Flux	Sky	Peak	FWHM
1					
2					
3					
4					
8					
12					
16					

6. <2 pts> From your data in the table above, explain how the sky, peak and FWHM values depend on the object radius.



7. <4 pts> Roughly graph the magnitude and FWHM vs radius values in the table below (use different colors or symbols). Do they tend to asymptotic values as the object radius gets larger? Explain.

FWHM																					Magnitude	
		1	2	3	4		8		12		16											

7) <2 pts> If the “right” answer is obtained with a very large object radius, what disadvantages might dissuade you from using an object radius of, say, 25 pixels?

8) <4 pts> Summarize briefly what the task imexamine does to determine the astronomical flux from a star. We are **not** looking for the steps you took (such as, epar’ing, typing ‘r,’ making a log file, etc.), but the actual process going on. What is IRAF doing to get the peaks, FWHM, sky values, and magnitudes?