Optical Photometry

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Abstract

Optical photometry involves characterising the magnitude, or the apparent flux, of a star. This report details the steps involved in performing aperture photometry for a set of 7 target stars using images of the Ring nebula. The images used in this project were obtained using an 8-inch Schmidt-Cassegrain telescope and an SBIG STC-7 camera with LRGB filters. The processes of reducing and stacking required to prepare the images for scientific analysis have been described here. Known BV magnitudes of standard stars present in the field of view of the images were used to obtain the transformation from LRGB to BV magnitudes and to subsequently find the standard BV magnitudes for the target stars. This report only refers to the reduction and analysis of the green (G) filter images.

1 Theoretical Background

Observations using optical telescopes are a function of both the optics and the detector used. The optics collect and direct light while the detector is sensitive to certain interactions with light and they convert such interactions into an electrical signal. Most detectors used in the optical regime are pixel detectors which work in the photon limit. They allow incoming photons to deposit energy and use the effects of the absorbed energy on the detector to characterise the incoming photons. These telescopes are also able to map photons with different incoming angles to different positions on the sensor, thereby creating a map of the intensity distribution in the sky. This allows us to image regions of the sky.

1.1 Cameras and Sensors

Camera sensors use 2D sensor arrays with individual detector units known as pixels. These are known as pixelated detectors. We can use a telescope in combination with a camera sensor in order to characterise intensity as a function of position (thereby producing an image). Here, we image a region of the sky and attempt to find the magnitude of the stars in that region. For optical astronomy, CCD (charge coupled device) cameras are used for imaging. These are composed of an array of detectors (called ‘pixels’) which are essentially potential wells. After a threshold number of photons strike the pixel, the potential well gets filled. Once these are filled, the image is read pixelwise by a detector. There could be a single detector at the end of the last row of pixels, or there could be an entire layer of detectors underlying the layer of pixels ('charge transfer CCD'). Each detector also has an associated amplifier. In either kind of camera, there is usually a 'bias' placed before the analog-to-digital converter (ADC) in the circuit. This prevents any negative values (due to thermal noise or instrumental errors) from going into the digitiser. Depending on the type of CCD, each row or each pixel might have its own bias. Since each row/pixel can have its own bias, and analog components cannot be perfectly identical to each other, the bias response of the camera as a whole needs to be determined for scientific applications.

1.2 Image Reduction

In addition to the bias, the readout of the camera is also affected by thermal noise in the various electronics. This noise is highly dependent on the operating temperature. The counts contributed by thermal noise are known as the 'dark current'. Finally, each pixel may not be exactly identical in its response to incident light. That is, the same number of incident photons might produce slightly different counts in two different pixels in the array. In order to isolate the counts due to our source, we need to characterise and account for the contributions from the bias, the dark current, and the pixel response. To do so, we obtain 'calibration frames' in addition to the source ('light') frames when collecting optical data. To account for the bias, we obtain an image with almost zero exposure such that the only counts measured are due to the bias. This is known as the 'bias' frame. To account for the dark current, we take an image with no illumination of the sensor of an equivalent exposure to the light frames (source images). Bias has an additive effect on every image taken with the camera. This is known as the 'dark' and it contains only the counts due to the dark current. Dark current also has an additive effect on all images with a significant exposure time. These counts in the dark frame naturally contain the bias as well. Finally, we take images with uniform illumination of the sensor in order to characterise the differential response of various pixels to the same number of pixels. These are known as 'flat' frames and their exposure time is chosen to prevent oversaturation of pixels. Flats have a multiplicative effect on the number of counts measured since they correspond to the ratio between incident flux and counts read out for each pixel. These contain contributions of both the dark current and the bias.

With our source images and these three calibration images, we can finally have data which correspond to the source intensity distribution. We perform pixelwise arithmetic operations in order to remove the instrumental contributions to the counts in the lights frames. Calibrated lights are the lights frames with the dark, bias and flat contributions removed. For exposure times T_L, T_F, T_D for the lights, flats and darks, respectively, we can write the following equation for these calibrated or 'reduced' images.

$$\text{Calibrated Light} = \frac{(\text{Light} - \text{Bias}) - T_L/T_D(\text{Dark} - \text{Bias})}{(\text{Flat} - \text{Bias}) - T_F/T_D(\text{Dark} - \text{Bias})} \tag{1}$$

The data used in this report was collected using a CMOS (complementary metal-oxide-semiconductor) camera. In such a camera, each pixel in the array has its own associated amplifier and detector. However, since these components lie on the same layer as the pixels, such detectors have lesser active area per pixel. In order to prevent missing out on some of the incident flux, they usually have an array of microlenses which focuses all the incoming flux onto the active pixels. Usually, scientific data is collected within a narrow wavelength band using a filter which only allows light within that band to be incident on the sensor. The data used here was collected in 4 filters- luminance (L), red (R), green (G), and blue (B). The analysis here refers only to the green filter, but the very same procedures can be used for each of the other filters.

When collecting data with a telescope, many factors such as errors in tracking objects in the sky, atmospheric variations, etc, contribute to the choice duration of a single exposure. In general, each individual exposure is short. However, this means that we get limited amount of light from faint sources. In order to improve the signal to noise ratio, we take many short exposures and then add ('stack') them together. This means that we add together the counts obtained pixel-wise. However, if we naively add the pixels together, the values are going to be very high, and any slight variation or error in an exposure can lead to large deviations in the results. Ideally, we want to add all the individual exposures together in a way that preserves their statistics. The best way to do this is to add them so that the median is preserved, since that is the statistic which is most impervious to outliers and stable for various distributions. Now, we scale the images so that they have the same median and then add them. However, for biases, we preserve the average when stacking since these frames in general have small fluctuations about a mean value. In general, both reduction and stacking are crucial prerequisites to using image data for scientific purposes.

1.3 Photometry

Photometry involves characterising the flux we receive from an astronomical source. This process relies on using telescope data to determine the intensity of the light received from the source. Such analysis is carried out on reduced images.

In general, a point source viewed through a telescope shows a characterstic intensity distribution known as the 'point-spread function' of the telescope. All points in an extended source would be subject to the same telescope response, and thus the telescope image obtained would be a convolution of the true image and the PSF of the telescope. This means that the flux due to a single star is spread over a finite region of some radius. However, this means that there are pixels around the star which have counts due to both the star and the background. Aperture photometry is a technique which helps us compute the background counts and thus find the flux due to a star. In this technique, we draw concentric circles around the star. We measure the total pixel values within the smaller circle, as well as the pixel values in the annulus between the two circles. The inner circle gives us the flux due to the star, while the annulus helps us characterise the background contribution to each pixel. We can then use both these values to find the counts that are truly due to the star. In general, we start with a small aperture and repeat this process for successively larger radii. The flux measured should initially increase with the aperture, and then plateau at a steady value once all the flux due to the star has been accounted for. However, this technique would face serious challenges if there was a nearby star also contributing to the background counts.

The flux due to a star is characterised by its 'magnitude' which is a dimensionless quantity defined on a reverse logarithmic scale. The apparent magnitude m of a star with flux F is given by,

$$m = -2.5 \log_{10} \left(\frac{F}{F_{\mathrm{ref}}} \right) + m_{\mathrm{ref}}, \qquad (2)$$

where m_{ref} and F_{ref} are the magnitude and flux, respectively, for a reference star. Usually, the star Vega ($m = 0$) is used as reference. The lower the magnitude of a star, the brighter it is.

The definition of magnitude relies on the wavelength band for which the value was calculated. In this report, we use data collected with LRGB filters in order to find the magnitude of 8 target stars. However, we know that standard magnitudes are calculated using BV filters (B here corresonds to a different band than the 'blue' filter in LRGB). We can obtain relative magnitudes for our targets from the data we have collected, but in order to find their standard (BV) magnitudes, we require some reference stars ('standards') for which the standard magnitude is already known. We find the LRGB magnitudes for the standard stars, while the known magnitudes of the standard stars are in BV. To convert from our system for magnitudes to the standard BV system, we assume that there is a linear transformation between the two systems. Let us indicate magnitudes corresonding to each band in the standard system by B_s, V_s and those in our LRGB system by L_a, R_a, G_a, B_a. B_a is the closest to B_s and G_a is the closest to V_s. We assume that the standard magnitudes are given by the closest LRGB magnitude plus some correction trems. Then, we assume transformations of the form,

$$B_s = Z_B + B_a + \alpha_1(B_a - R_a) + \alpha_2(B_a - G_a) + \alpha_3(B_a - L_a), \quad (3)$$

$$V_s = Z_V + G_a + \beta_1(G_a - B_a) + \beta_2(G_a - R_a) + \alpha_3(G_a - L_a), \quad (4)$$

where Z_B, Z_V are constant offsets between the two systems and α, β are coefficients which determine the conversion. In order to obtain magnitudes in the standard system, we need to obtain all of these constants. Since we have access to both the standard and the LRGB magnitudes for the standard stars, we can use these to find the values of the coefficients. We can perform a least squares fit in order to obtain the values of the unknown constants. Since the transformation between the systems is independent of the stars being observed, we can then use the transformation we find to obtain the unknown standard magnitudes of the target stars.

2 Data and Software Used

The data used here was collected using an 8-inch (Schmidt-Cassegrain) telescope and a CMOS camera. It was processed using NOAO's Image Reduction and Analysis Facility (IRAF) along with the image viewer SAO DS9. IRAF is composed of a variety of tasks with diverse usage. These tasks are grouped under various packages and subpackages. For the purpose of this experiment, we use subpackages and tasks contained within the `noao` package.

3 Analysis

The data are available to us in the form of FITS files. These are the files obtained from the camera, and haven't undergone any calibration yet. Before we can perform any photometric study, we need to reduce in order to remove instrumental effects, and stack them in order to improve the signal to noise ratio. We perform all of these functions using IRAF. IRAF is ideally used within an `xgterm` terminal wherein it can be called by running the command `irafcl`. IRAF should be launched from the directory which contains the `login.cl` file. For image reduction and stacking, we use tasks within the `ccdred` package. It is a good idea to organise the raw data into a single directory. Here, all the green (G) filter images have been analysed. These are sorted into subdirectories for the various kinds of frames- *lights, darks, biases, and flats.* After running any task in IRAF, we can refer to the logfile created for that directory in order to find the history of operations. This is a good tool to verify that the right tasks were run.

The exposure times for all the frames have been tabulated below.

lights	30 s
darks	30 s
flats	0.1 s
biases	3.3×10^{-5} s

Table 1: Exposure time for all frames.

3.1 Stacking Calibration Frames

3.1.1 Biases

In the IRAF terminal, we navigate to `noao > imred > ccdred`. We must also `cd` into the directory which contains the biases. Now, we can use the task `zerocombine` to stack all the bias frames together. We use the command `epar zerocombine` to edit the task parameters. The parameters used have been tabulated below.

input	ring*Bias.fit
output	MasterZero.fits
combine	average
scale	none

Table 2: Parameters for `zerocombine`.

The task `imstat` can be used to find the statistics (minimum, maximum, mean and standard deviation of pixel values). It is extremely useful to compare the statistics before and after stacking to see the effects of the stacking operations on the image. We find that averaging N bias images reduces the standard deviation of the images by a factor of $\sqrt{N}$.

3.1.2 Darks and Flats

We first navigate to the directory which contains the darks/flats, and then use the task `combine` within the `ccdred` package. We use `epar combine` to change the task parameters. This must be repeated for both darks and flats within the relevant directories, and with the relevant input and output filenames. The parameters for each have been tabulated below.

input	boxlight_flats*G.fit/ring*D.fit
output	MasterFlatG.fits/MasterDark.fits
combine	median
scale	mode

Table 3: Parameters for `daofind`.

3.2 Reducing Light Frames

Once the calibration frames have been stacked, we can reduce the light frames according to Equation (1). To do so, we use the task `ccdproc` in the `ccdred` package. Before starting, we need to navigate to the directory containing the light frames, and copy all three calibration frames into this directory. Here, we used platesolved light frames which contain coordinate information for all pixels in the image. This allows us to identify specific stars later in the process. Since we have a large number of images for which to run this command, it is helpful to create a text file listing all the files to be reduced. To simply create this text file, we can run the command `ls ring*.fit > input.txt`. We can then create a copy of this input file called 'output.txt' (`cp input.txt output.txt`) in which to list the desired names of the output files. We can modify the list of names by using a replace command in a VI editor. For instance, if we want to rename 'ring-0001G.fit' to be 'ring-reduced-0001G.fit', we can run the following commands: `vi output.txt`; `:1,$s/ring/ring-reduced/g`, then write to file and exit VI. This will modify all listed files. Using these text files will allow us to save each reduced light frame with a corresponding name. To modify the task parameters, we run `epar ccdproc`. The parameters used have been tabulated below.

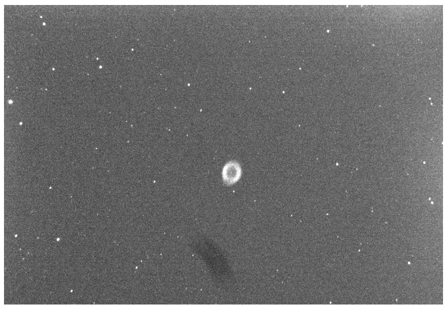

Figure 1: Raw G filter image of the Ring nebula.

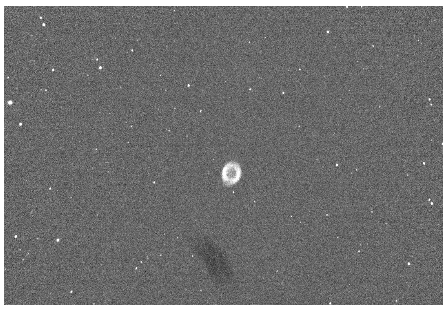

Figure 2: Reduced G filter image of the Ring nebula.

images	@input.txt
output	@output.txt
trim	yes
darkcorr	yes
zerocorr	yes
flatcorr	yes
zero	MasterZero.fits
dark	MasterDark.fits
flat	MasterFlatG.fits

Table 4: Parameters for `ccdproc`.

3.3 Aligning and stacking light frames

Once we have the reduced light frames, we want to make sure that all physical features in these images align with each other. Since stacking is a pixelwise operation, we need to make sure that the physical features of all the light frames correspond to each other pixelwise. In order to do so, we display all the reduced light frames on ds9. ds9 allows us to note the pixel coordinates corresponding to any astronomical coordinates in the image. We choose a reference image from the middle of the set such that it is representative of the entire set. For this analysis, the reference frame chosen was 'ring-reduced-0004G.fit'. We pick a set of stars that are well distributed in the frame and note down their image coordinates in each light frame. We then calculate the offset of the coordinates of each star in each frame with respect to its coordinates in the reference frame. We can store these shifts in a file 'shifts.txt'. This file should contain the x,y shifts (separated by a space) for each frame in order.

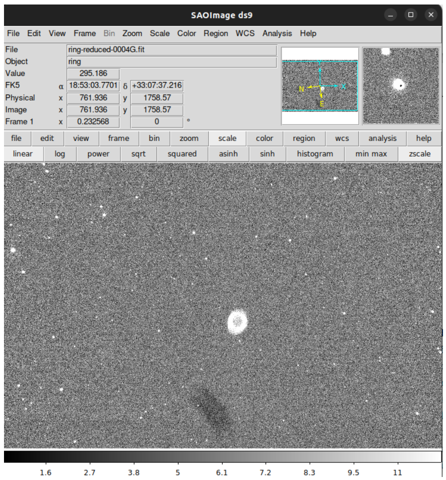

Figure 3: SAO ds9 showing the pixel coordinates as well as the RA, Dec coordinates for the star over which the cursor is placed.

Now, we navigate to `noao > digiphot > apphot`. We use the task `imexam` with the reference frame displayed on ds9 (`disp ring-reduced-0004G.fit`) and press 'r' in order to find the radial profile of a star in the frame. This gives us the HWHM of the image. We can also use `imstat ring-reduced-0004G.fit` to find the noise level in the image. We can now use the task `daofind` which looks for all the stars in an image that meet certain threshold criteria. We edit the parameters to fix the image name.

image	ring-reduced-0004G.fits

When executing `daofind`, we enter the following parameters, leaving the rest as default.

FWHM	7.5
sigma	7
detection threshold	15

Table 5: Parameters for `daofind`.

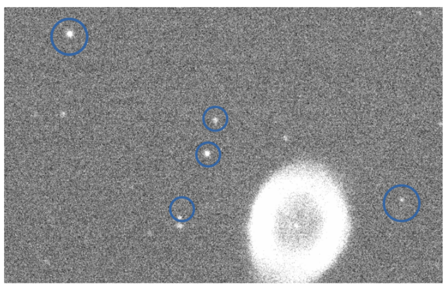

Figure 4: Stars used to find the shifts in the lights frame.

Here, the threshold is chosen to be somewhat high since the green filter image is not typically very bright. This produces a file ('ring-reduced-0004G.fits.coo.1') containing the coordinates of all the stars that meet the threshold criteria specified above. Since this file contains some comments as well, we can move just the star coordinates into another file 'refcoords.txt'. We now know the coordinates of the brightest stars in the reference frame as well as an approximation to the amount by which each pixel in the other frames must be shifted in order to align them to the reference frame. With these inputs, the task `imalign` can interpolate the pixel coordinates in each image such that the coordinates of all the stars are the same. We run `epar imalign` and set the following parameters.

input	ring-reduced*.fit
reference	ring-reduced-0004G.fit
coords	refcoords.txt
output	@output-shifted.txt
shifts	shifts.txt
boxsize	10
bigboxsize	15
negative	no
interp	spline3
boundarytype	constant
constant	0
trimimages	no

Table 6: Parameters for `imalign`.

Here, 'output-shifted.txt' is a file which contains files named 'ring-reduced-shifted-000*G.fit'. We can now check, using ds9, that the pixel coordinates of corresponding stars in each light frame are exactly the same. We can now stack all the light frames while preserving the physical features of the image. We use the task `combine` just as we did before, with median combine and mode scaling, to stack the aligned light frames and produce 'ring-light-stacked.fits'. At this stage, we can optionally use `crutils` package to remove the effects of cosmic rays at this stage. For this image, there did not seem to be any cosmic rays that hit the sensor during the course of observations.

3.4 Photometry

To find the magnitudes of our target stars, we first need to identify their locations, as well as those of standard reference stars, in the reduced image. The astronomical coordinates of these stars are known (Table (7). We use these to identify the stars in the image and note down their approximate pixel coordinates. Then, we run the task `daofind` on this image in order to find the precise coordinates of all the stars in the frame. The parameters used are the same as those listed in Table (3). We identify our stars of interest (both standards and targets) from the list produced by `daofind` by comparing the listed coordinates with our list of approximate coordinates. In this case, two stars (targets 1 and 5) could not be found in the `daofind` result. We copy the precise coordinates of all the stars that we find into a new file 'ring_green_esha.coo'.

Star	RA	Dec
HD175267	18h53m08.69s	$+33^o12'36.08''$
TYC 2642-1578-1	18h53m37.22s	$+32^o56'10.89''$
TYC 2642-1568-1	18h53m17.28s	$+32^o58'21.96''$
TYC 2642-285-1	18h53m02.33s	$+33^o10'06.21''$
TYC 2642-84-1	18h53m03.71s	$+33^o07'38.12''$
Target 1	18h53m00.75s	$+33^o05'50.0''$
Target 2	18h53m04.00s	$+32^o55'32.4''$
Target 3	18h53m15.07s	$+33^o00'03.3''$
Target 5	18h53m34.22s	$+33^o05'49.0''$
Target 6	18h53m44.64s	$+33^o11'17.7''$
Target 7	18h53m48.12s	$+32^o58'58.3''$
Target 8	18h54m04.47s	$+32^o53'16.9''$

Table 7: Coordinates of standard and target stars.

Now that we know the precise position of the stars of interest in the image, we can find their magnitudes. Before we begin using any photometry tasks, we must set some global parameters. We type `centerpars` in the ecl command prompt and set the following parameters.

calgori	centroid
cbox	8.
cthresh	0

Table 8: `centerpars`.

We do the same with `datapars` and `fitskypars`.

scale	1
fwhmpsf	7.5
emisso	yes
exposur	EXPTIME
itime	30.0
epadu	5.5
readnoi	5
filter	FILTER

Table 9: `datapars`.

salgori	centroid
annulus	30.

Table 10: `fitskypars`.

Once these parameters are set, we can use the task `qphot` to find the magnitudes of the stars that we are interested in. We edit the parameters for this task as shown below.

image	ring-light-stacked.fits
cbox	8.
annulus	30.
dannulus	2.
apertures	3.0,5.0,8.0,10.0,15.0,20.0,30.0
coords	ring_green_esha.coo
epaadu	5.5

Table 11: Parameters for `qphot`.

This task performs aperture photometry by successively considering apertures from the supplied list and measuring the number of counts in each annulus. We expect that the value will asymptotically approach the number of counts for the star. This task produces the file 'ring-light-stacked.fits.mag.1' which contains the magnitude for each of the listed apertures. We can check this file to ensure that the magnitude converges for the larger apertures. We create a new file which contains the names, image coordinates, and magnitudes for each of the stars of interest. The magnitudes for the green filter were obtained from the work described here, and the magnitudes in the other filters were similarly obtained by others in the class. These collated values have been tabulated below.

Star	B_s	V_s
HD175267	8.89	8.77
TYC 2642-1578-1	11.55	10.97
TYC 2642-1568-1	13.61	11.56
TYC 2642-285-1	12.83	11.66
TYC 2642-84-1	11.40	10.41

Table 12: Standard magnitudes of reference stars.

Star	L_a	R_a	G_a	B_a
HD175267	11.02	12.36	12.35	11.86
TYC 2642-1578-1	13.44	14.51	14.80	14.52
TYC 2642-1568-1	13.92	14.62	15.36	15.51
TYC 2642-285-1	13.94	14.67	15.44	15.39
TYC 2642-84-1	12.67	13.49	15.03	14.13
Target 1	14.39	15.02	15.88	16.26
Target 2	12.81	13.67	14.29	14.32
Target 3	14.67	15.80	16.01	15.61
Target 5	14.74	15.67	16.10	15.81
Target 6	12.71	13.21	14.29	14.61
Target 7	15.64	16.59	17.06	16.71
Target 8	13.55	13.67	15.00	15.03

Table 13: LRGB magnitudes obtained for standard and target stars.

3.5 Standardisation of magnitudes

From the results of qphot, we have the relative magnitudes for all the stars of interest. We would now like to obtain the absolute magnitudes for these stars. To find the transformation from the LRGB to the standard magnitudes, we can use Equation (4). We can perform a least-squares fit in order to find the best fitting parameters. We can find the best fitting parameters using the python module `curve_fit` from the `scipy.optimize` package. Alternatively, we can also find the parameters by solving Equation (4) as a matrix equation. We performed both kinds of analysis, and used the best values. For the conversion to B_s magnitudes, we use the coefficients obtained from the matrix inversion method while for the conversion to V_s magnitudes we use those obtained from least squares fitting. The final choice of parameters have been tabulated below.

Parameter	Best-fit Value
Z_B	-5.57
α_1	-0.76
α_2	0.74
α_3	2.48
Z_V	-3.22
β_1	-0.5202
β_2	-0.3489
β_3	-0.1881

Table 14: Best fit values of transformation parameters.

Now that we have fully determined the equations required to transform to the standard magnitudes, we can put into these equations the relative LRGB magnitudes we found earlier and thus find the standard magnitudes for our target stars.

Star	B_s	V_s
Target 1	13.69	12.13
Target 2	11.88	10.56
Target 3	11.93	12.21
Target 5	12.57	12.32
Target 6	12.71	10.53
Target 7	13.46	13.22
Target 8	11.95	11.03

Table 15: Standard magnitudes of target stars calculated using transformation equation.

4 Discussion

During image reduction, we are essentially modifying image statistics. It is very helpful to run the command `imstat` at each stage of image reduction. This allows us to understand the expected statistics of each frame, and to understand the changes made to these statistics by various operations. For instance, after stacking, we expect that the standard deviation in the lights should reduce by a factor $\sqrt{N}$ for N stacked frames. If we do not see this change after perfoming stacking, we immediately know that some operation has not been executed properly.

Another useful diagnostic when working with IRAF is the logfile. Each command creates a logfile in that directory which maintains a history of all the commands and tasks run on the files within that directory. It is advisable to check the logfile after running any task in order to confirm that the right task has been properly executed. Similarly, always checking the parameter file for a task before running it helps keep track of the parameter choices. IRAF stores the parameter values after each edit of the parameter file, and checking the file before each run allows us to ensure that there are no unintentionally changed parameters.

5 References

1. 'A user's guide to stellar CCD photometry with IRAF' by Philip Massey, 1992.

2. 'A beginner's guide to using IRAF' by Jeannette Barnes, 1993.

3. 'Photometry using IRAF' by Lisa A. Wells, 1994.

4. IRAF Tutorial I by Larson