Project 2 – Imaging planetary nebulae

Due November 6, 2012

ASTR310 Fall 2012

1 Introduction

The aim of this project is to gain experience using the CCD camera by obtaining images of planetary nebulae or H II regions. Planetary nebulae are ionized clouds of gas surrounding very hot stars. The nebula is formed when a star of moderate mass reaches the end of its life as a red giant star, and makes the transition to its final state as a white dwarf. In this process the outer layers of the star are ejected to form the nebula, while the newly exposed core appears as a very hot central star, which emits most of its radiation in the far ultraviolet, thus ionizing and heating the nebula. Most of the radiation emitted by the nebular gas, which has a temperature of $\sim$10,000 K, is concentrated in the emission lines of a few elements such as oxygen and nitrogen, as well as the most abundant element, hydrogen. An H II region is an interstellar gas cloud with newly formed stars in or near it which are hot enough to ionize some of the gas. While the physical conditions in the gas and the emitted spectrum are similar to planetary nebulae, H II regions are much less regular in appearance and contain much more gas and dust.

We will take the images of the nebulae through two narrow-band filters (interference filters) which transmit the light of the strongest emission lines in the nebular spectrum. These are the Hα line of hydrogen at 656.3 nm and the line of doubly ionized oxygen (O^{++} or [O III]) at 500.7 nm. The great advantage of such narrow filters is that they only transmit light with wavelengths near that of the nebular emission line you are interested in observing. Thus you get all the photons of the nebular line, but greatly reduce the photons from the bright College Park sky, with its reflected city lights, since these are either due to incandescent lights (which emit continuum emission) or mercury lamps (which emit line emission at wavelengths not transmitted by the filters). Once you have the images, you can then compare them with published pictures, observe the differences in the distribution of H^+ compared to O^{++}, and perhaps measure the flux in the nebula compared to that in the star.

An alternative project would be to image a bright H II region. In this case, we would observe the nebula through the Hα filter and also through a filter centered on the Hβ line at 486.1 nm. These lines are always emitted with a *c*onstant intensity ratio, Hα/Hβ = 2.8. However, the ratio we observe may be different because the Hβ line suffers more absorption by interstellar dust than the Hα line. By studying the variations in this line ratio, we can map out the distribution of dust in the nebula. *T*he problem with this project is that the Orion Nebula, which is by far the best H II region, can only be observed in the early morning hours at this time of year!.

2 Project Overview

The basic idea behind this project is simple: make images of two planetary nebulae, but there are a number of steps. This overview list for the observations is an overview of what you'll be doing:

1. You will have two target nebulae, the Ring Nebula (M 57) and another you will pick. See Sec. 3.
2. Use the camera to focus the telescope. See Sec. 5.2.
3. Drive the telescope north and east to establish which directions on your image are north and east. See Sec. 5.3.

4. Image a double star to work out the "plate scale" in arseconds per pixel. See Sec. 5.4.

5. Get a raw image of the nebula in one filter! See Sec. 5.5.

6. Change filters, refocus, and get the raw image in the next filter band. See secs. 5.2 and 5.5.

7. Change to the other nebula and repeat the filter changing and refocusing.

8. Measure the dark current contribution to the raw images. See Sec. 5.6.

9. Measure the flat field (quantum efficiency) correction. See Sec. 5.7.

Section 4 is a review of the CCD fundamental equation to remind you why you are measuring each contribution to the image and to help guide you through the reduction and analysis. Section 5 describes the observations. Data reduction is covered in secs. 6. Analysis, Sec. 7, includes rotating the image of the Ring Nebula to make plots of its intensity versus radius and then comparing these to theoretical models given in Appendix 2. Finally, Sec. 8 will guide you in writing the report.

This is a large amount of work, so please don't underestimate the time it will take. These projects are 40% of your grade for a reason!

3 Selection of the Nebulae

We want to image planetary nebulae of sufficient size to be able to study their shapes. Since nebulae of this size are faint, all groups should start with the Ring Nebula (NGC 6720, M 57), which is probably the easiest object to find. It is in the constellation of Lyra, and the nebula is located almost exactly between two naked-eye stars. The nebula itself looks like a faint "smoke ring" in the main telescope. Look up the RA and Dec and find the object on a star chart before you go out to observe.

You will observe a second planetary nebula in addition to the Ring Nebula. You will want to pick a bright planetary nebula which has as large a size as possible without exceeding the field of view covered by the CCD camera. You will find the field of view of the CCD in the hand-out on the 14" telescope. You also want to pick an object that is high in the sky sometime during the evening (or early morning) hours. Look at the illustrations in the catalog to see what sort of structure the nebula has and if the central star is visible. It would be nice if you could observe the central star. (In principle, such observations would allow you to calculate the temperature of the star.)

To save time, look at a list of nebulae suitable for observation by amateur astronomers; that way you will not waste time on objects which are too faint. But at some point you should turn to the Strasbourg-ESO Catalogue (find it with whatever search engine you like) to obtain basic information such as the size, the flux in Hβ (Hα is always about 3 times brighter) and in [O III] λ5007. You will want nebulae that have [O III] as bright or brighter than Hα. The larger the value of Hβ the better – note that the number listed is the $n$egative logarithm of the flux, so a smaller number is a brighter nebula. Traditionally, observers would prepare a $f$inding chart to locate the object, but our telescopes should point accurately enough to get it into the field of view by just entering the coordinates or its name. If you want to locate it on a chart, we have found that the atlas "URANOMETRIA 2000.0" by Tirion, Rappaport, and Lovi (in the Astronomy Library and at the Observatory) has a convenient scale. You should also have at least one extra back-up object.

With regard to the H II regions, it is unfortunate that the only really good target is the Orion Nebula, which does not rise until the early morning hours (i.e. after 3:00 AM!) at this time of year.

4 The basic CCD equation

A CCD camera collects electrons from three sources.

1. Electrons produced by photons. This is generally what we want, the image of objects in the sky. Assuming that every photon produces an electrons, we will denote these electrons with the matrix N.

2. Electrons produced by the electronics to ensure that the ADC has signals within its input range. "Bias" electrons are represented by B .

3. Electrons produced by thermal excitation within the detector, called "dark current" electrons to distinguish them in origin from those produced by photons. Like the electrons from photons, those from dark current accumulate during the exposure, so the magnitude of the dark contribution depends on exposure time. Dark currents may be very small for short exposures or from high-performance detectors cooled to very low temperatures. Small or large in contribution, we denote the image from accumulated dark current as T.

Gathering these terms to make a sky image, S:

$$S = GN + B + T \ , \tag{1}$$

where G is a constant of proportionality that gives the relationship between the number of electrons in each pixel and the number of ADUs produced by the signal acquisition electronics. Equation (1) is still missing an important element, though: each pixel will have a different efficiency of converting photons to electrons, given by the system's *quantum efficiency*

$$\text{Quantum Efficiency} = \frac{\text{Number of electrons produced}}{\text{Number of photons incident}} \ . \tag{2}$$

This is often denoted QE, but we will stick with the slightly simpler Q here. The number of electrons is therefore related to the number of photons P as

$$N = QP \ . \tag{3}$$

This gets us to the basic CCD equation:

$$\boxed{S = GQP + B + T} \ . \tag{4}$$

We measure S in any exposure we make with the camera. Most of the time we want to find the image of the astronomical object given by P. All the other terms are necessary evils that we have to eliminate to get the image. Doing so is an important point in this lab.

5 Observations

5.1 Essential Preparations for Observing

You should dress very warmly. You are likely to get much colder than you might expect, since you'll be motionless outside at night for several hours. Dress in layers. Be sure to have a wind-proof shell. Especially later in the fall, gloves and a warm hat are a necessity. The concrete floor gets very cold, so it's best to have warm, thick socks and thick rubber-soled shoes. A thermos of a warm drink is also a good idea. You may wish to bring a flashlight. You should bring a notebook and pen for your notes.

We will use either the 20” telescope in the West Bay, or the Celestron 14” telescope in the East Bay. Before coming to the observatory, you should read through the instructions for operating both telescopes.

Please bring a USB drive with you to transfer your images from the control computer. We will try to have one on hand, just in case, but it will be better if you bring your own.

You should bring the relevant pages to the observatory with you when you observe.

5.2 Telescope Focus: Observing a Bright Star

The optimum telescope focus position varies from night to night due to thermal expansion of the telescope tube. It can also vary with the elevation of the telescope. You need to find a relatively bright star (say magnitude 5 or 6), preferably not too far from your target. You want a star which is bright enough so that the exposure time is 2 to 4 seconds so that guiding is not needed, yet does not saturate. Take a series of exposures that range from a clearly out-of-focus setting, through good focus and on to out-of-focus on the other side of the focal point. Write down the focus setting from the micrometer and include it in your write-up. **Do this for each of the filters you will use, since the optimum focus can vary between filters.** Make sure the star is well exposed (more than 1000 counts), but it is essential to avoid saturation of the central pixel(s). While the CCD can record numbers up to $2^{16} = 65536$, the response becomes non-linear much before this, at around 16000 counts (it’s hard to give an exact number since the bias has been subtracted, and thus you don’t see the total counts).

The best focus setting is the one which gives the sharpest stellar images. Normally, astronomers find the stellar image which has the smallest full width at half maximum intensity (FWHM). To do this, zoom in on the star to a very high zoom. Then using the cursor, find the brightest pixel (again, make SURE it is not saturated!), and subtract the background brightness. Next, moving along a row, find the pixel with the brightness (after subtracting background) closest to half of the brightest pixel; and write down its column number (x number); then go to the other side and again find the pixel at half intensity; the difference in column number is the FWHM. Check to see that you get a similar number (to within a pixel) in the opposite direction. Keep in mind that as the focus improves, more and more light will be concentrated in fewer and fewer pixels, which may consequently saturate; keep checking, and adjust exposure time accordingly.

Keep in mind that you must adjust the stretch of the image displayed in order to see the essential brighter part of the stellar image. In other words, the maximum in the display stretch should be set maybe 10% above the value of the brightest pixel; the minimum should be around zero.

You do not need to save the focus images.

5.3 Determining North and East in the Image

Although if you know the optical layout of the telescope you can determine how the optics inverts the image, it is generally unclear how the CCD is oriented and read out. Relative to north, the observed image may be rotated by an unknown angle; in addition, it is possible for the image to be inverted (ie top to bottom or left to right). The simplest way to determine the image orientation is to

1. Set the guide speed to ”5 = B:1” (this may be different for the 20”, consult with your TA)

2. Begin an exposure of a bright star centered in the CCD frame.

3. Wait about $2 - 5$ seconds.

4. Guide the telescope to the North (by pushing the North guide button for about 5 seconds).

5. Drive the telescope to the east for about 10 seconds and stop the exposure.

The resulting image should show an L-shaped pattern, with a knob at one end of the L. The knob is where the star was when you started the exposure; the side of the L starting FROM the knob heads due South (lower declination) (since the telescope moved north); then, heading from the 90 degree bend in the L to the non-knob end points due West (lower right ascension). Save this image as a .fits file. If you do not obtain this image, get it from the common area (but so note in your report). Think about this: *i*f you drive the telescope north, the trail on the image goes south!

5.4 Focus and Plate Scale: Observing a Double Star

As a preliminary observation, you are to take an image of a well known double star. You will use the separation of the stars to determine the plate scale of the CCD. Choose either ϵ Lyr (separation 208 $''$), or β Cyg (Albireo; separation 34.4 $''$). Albireo is a beautiful double star, with a striking color contrast between the components. You can use the double star as the focus star discussed in section 5.2. But note that the *c*omponents of ϵ Lyr are themselves doubles with $\sim$2.5 $''$ separations, so don't mistake this for lack of focus! Save one of the best in-focus exposures to disk (as a .fits file) for measurement of the stars' separation (and also to get the exact orientation of your images).

5.5 Observing the Nebulae

Locate the Ring Nebula and center it in the main telescope. Take an image with the Hα filter first (we expect more counts with Hα than with [O III], but that is a function of the actual transmission of the filters). Try 60 sec to start. Look at the stars in the field to see if they are sharp. You could get some drift in even this short exposure if the telescope is not properly set up. You will need an exposure of at least 5 min (300 sec) to get a reasonable number of counts in the [O III] filter. (This filter is very narrow in wavelength, and its peak transmission is only 30%.) You should also take a 5 min (or longer) Hα exposure. Don't bother with the Hβ filter; the image will look similar to the Hα image, but it may be fainter.

Now locate your second target. Take at least one long Hα and one long [O III] exposure of it.

Save all your "good" images as .fits files.

5.6 Dark Frames

Thermal electrons (ie electrons which get excited due to the non-zero temperature of the CCD chip) get collected by the CCD just like electrons liberated by photons striking the CCD, and dark and light electrons obviously cannot be distinguished (the T term in eq. (4)). The number of thermal electrons collected increases with the exposure time, usually more or less linearly. Consequently, one needs a dark frame with an exposure identical to the exposure on the object (the "light frame"), although in a pinch one can be daring and scale a dark frame with one exposure time to another time. Just as is the case for bias, the accumulated dark current must be subtracted from the exposure of your object (see eq. (4) again). Note that since any exposure has a bias offset, subtraction of the dark frame from the light frame also automatically does the bias subtraction. Dark is easy to make: just make a normal exposure but keep the camera shutter closed.

Note that you must keep a record of all the exposure times for useful exposures, and then be sure that you have obtained and saved dark frames of identical exposure time. Since no light enters the telescope for a dark frame, the filter does not matter for a dark frame — all that matters is the exposure time. So a dark frame can be subtracted from any frame of identical exposure time, regardless of which filter was used.

Some settings of the CCD observing software will take both light and dark frames and automatically subtract the dark frame from the light frame. **If** this is done, you do **not** subtract a dark frame during the later reduction stages, since it has already been done.

Since telescope time in good weather is hard to get, however, it may be prudent to plan on obtaining the dark frames after astronomical observations in order to complete the astronomical observations as quickly as possible, in case the weather turns bad or the nebula sets. If this method is chosen, this means that you must be sure to record the exposure times for all useful exposures and then be sure to obtain dark frames for each of those exposure times. The risk with this method is that the rate at which dark electron accumulate with time may vary, for example if the temperature of the CCD varies; if this happens, then you will not get a good subtraction of the dark current.

To recapitulate, if object (i.e., light) frames are taken with automatic dark-frame subtraction, then do not subtract dark frames during later data reduction. If dark frames are not acquired and subtracted automatically, you must be sure to obtain manually dark frames of identical exposure time to your object frames, and subtract the dark frames from the object frames during your data reduction.

5.7 Taking Your Flat Field Images

An important part of observing with a CCD is what is called "flat-fielding". This will correct for the system quantum efficiency term (Q) in eq. (4). There may be variations in the sensitivity of the CCD from pixel to pixel, the filter transmission may vary from center to edge, or some other optical effect may change the efficiency of converting photons to electrons. We can discover and remove such quantum efficiency effects by taking an image that we know has uniform illumination across the array: then all pixels *s*hould have the same number of electrons. Not all will have the same number of electrons, but dividing an object image by this uniformly illuminated image corrects for the system quantum efficiency, pixel by pixel.

The best way to obtain an image of a uniformly illuminated source is to take an image of the twilight sky. This would involve being at the observatory early, or returning the next evening. Another method is to take an image of the white screen in each observatory bay. This is done with the roof closed. Lights are used to illuminate the white screen. Flats should be taken with each filter that you have used. You want to take an exposure that is long enough to get over 10,000 counts, so the *P*oisson noise fluctuations are small, but less than 14,000 counts to avoid non-linear effects. With the narrow nebular filters, the exposures may need to be several minutes to get the desired number of counts; exposures with broad-band (e.g., V or R) filters will be much shorter.

6 Data Reduction

This is set up to be done on the computers located in the computer lab room, CSS 1220. For this exercise the reduction consists of using the MATLAB language to do a number of tasks:

1. Read your images into MATLAB using **rfits**. Display the one where you trailed the star north, then east. See if they are in the standard orientation of north at the top, east to the left. If not, rotate them all with the MATLAB functions **transpose** (equivalent to **'**), **flipud**, or **fliplr**. Remember than North is up and East is to the *l*eft in an astronomical image!

2. Display your images using **imagesc**. Experiment with setting the display range (using **caxis**), the color table (using **colormap**), etc. to see all the detail that is in your data. If you would like to average some of the noise, try the **medfilt2** two-dimensional median filtering function to average out some of the noise. For example, **mf=medfilt2(im.data,[3,3])** will replace each pixel in the image with the corresponding median calculated over 3×3 pixel boxes.

3. Do dark-subtraction (if necessary) and flat-fielding to get each image onto a uniform basis (i.e., dividing each image by the corresponding flat field image using the MATLAB **./** operator). Solving eq. (4) for the number of photons in each pixel, P (a matrix),

$$P = \frac{S - (B + T)}{GQ} \ . \tag{5}$$

If the dark frame has the same exposure time as the sky, then

$$S_{\text{sky}} - S_{\text{dark,s}} = (GQP_{\text{sky}} + B + T) - (B + T) = GQP_{\text{sky}} \ , \tag{6}$$

or

$$P_{\text{sky}} = \frac{S_{\text{sky}} - S_{\text{dark,s}}}{GQ} \ . \tag{7}$$

This is almost what we need, except for the corrections for the quantum efficiency that relates the number of photons to electrons, Q and gain factor G. These we can get from the flat field image. With a matching dark exposure, the flat field image gives

$$S_{\text{flat}} - S_{\text{dark,f}} = (GQP_{\text{flat}} + B + T) - (B + T) = GQP_{\text{flat}} \ , \tag{8}$$

or

$$GQ = \frac{S_{\text{flat}} - S_{\text{dark,f}}}{P_{\text{flat}}} \ . \tag{9}$$

Combining eqs. (7) and (9), we solve for the number of photons from the astronomical source

$$P_{\text{sky}} = \frac{S_{\text{sky}} - S_{\text{dark,s}}}{S_{\text{flat}} - S_{\text{dark,f}}} \, P_{\text{flat}} \ . \tag{10}$$

This is a relationship between the number of photons in each pixel from the source, P_{sky}, and the number of photons in each pixel from the flat, P_{flat}. If the flat is truly flat, uniform illumination, then all elements in the matrix P_{flat} would be the same and

$$\boxed{P_{\text{sky}} = K \, \frac{S_{\text{sky}} - S_{\text{dark,s}}}{S_{\text{flat}} - S_{\text{dark,f}}}} \tag{11}$$

where K is some constant we have to determine. Equation (10) shows that if we knew the absolute number of photons in P_{flat} we would know the absolute number of photons from the source: K would be equal to any element in P_{flat} (all elements would be the same for a true flat). We usually do not know this number (the twilight sky and a lamp shining on a screen are not well controlled sources), so we generally live with the proportionality expression eq. (11) and work out the true intensity by making a comparison with a star of known brightness to get K. That is another story for another time and another project, however.

The preceding development assumed that the light and dark exposures were the same so that $\mathcal{T}_{\rm light} = \mathcal{T}_{\rm dark}$. This is not always the case, since telescope time is valuable and we may not want to spend time taking darks of different lengths. One can be daring and assume that the dark current is constant in time so that $\mathcal{T}$ increases linearly in time. This is usually a good but not perfect assumption. In that case

$$\mathcal{T} \approx \mathcal{T}_0 \, \frac{t_{\rm exposure}}{t_0} \, , \tag{12}$$

where $t_{\rm exposure}$ is the exposure time for an image and $\mathcal{T}_0$ and is a comparison dark current measurement with exposure time t_0. The dark current terms in equations (6) and (8) can be scaled appropriately to derive a version of eq. (11) that accounts for different exposure times in the sky, dark, and flat images. Follow your TA's instructions on whether you should make dark exposures that match your sky and flat exposures, or whether you should scale. The decision will depend on the weather and time available for measurements.

No matter how you calibrate, you should display and examine the flat field image. You will see an overall pattern of variation, plus some "spots", which are probably due to dust on one of the optical elements. If pixels in the flat are close to zero, division in the denominator of eq. (11) will make the same pixels in the image very noisy.

4. Measure the x and y coordinates of the components of the double star in pixels. This will allow you to calculate the separation of the stars and the position angle of the line connecting them. (The *p*osition angle is the angle from the North direction to the direction of the vector formed by connecting the two stars measured through East.) To measure it, think of a vector located on the bright star and pointing North, and tell us what angle it forms with a vector located on the bright star and pointing to the faint star. Positive values are toward the East direction, which should be on the left side of your screen (North is up). That is, if you have oriented everything properly the position angle is measured counter-clockwise.

5. Examine the images. Compare the Hα with the [O III] image. Consider that it takes much more energy to remove two electrons from oxygen to produce O^{++} than to remove one electron from hydrogen. Thus you should understand why the intensity in the [O III] image should be concentrated nearer the star than Hα emission. Comment on this on your report.

7 Data Analysis

1) Look up in a catalog the separation in arc seconds of the components of the double star, and the *p*osition angle of the pair. Use this to determine the the **plate scale** in arc seconds/pixel, of the CCD (remember homework 1!). We will use this to convert the dimensions of the nebulae from pixels to seconds of arc.

2) Note that the Ring Nebula has a major (long) and minor (short) axis. Use the MATLAB **imrotate** function to rotate the image through different amounts till the major axis is vertical (remember to enforce that the pixels be square by issuing a **axis equal** or **axis image** after using **imagesc** for display. What angle is this? From the known position angle of the double star, calculate the position angle of the major axis of the nebula. Use the rotated image in the next step.

3) Write two simple MATLAB functions, **h_strip** and **v_strip**, in your directory. They will help you plot how the intensity varies across the nebula along the major and minor axes. If **pn** is the name of your image then **ix = h_strip(pn,y1,y2)** will take the values of all the pixels between y=y1 and y=y2 and sum them down each column. The result **ix** is a vector with the

same length as the width of the image whose values are the intensities along the strip. You can then plot **ix** to see a trace of the intensity across the nebula. My suggestion is to use the fact that you can tell MATLAB to compute the mean along a particular direction. Thus, for example, **mean(u(:,190:210),2)** will compute the mean of the columns 190, 191,..., 210 for every row of the matrix **u**. Similarly, **mean(u(490:510,:),1)** will compute the mean of the 21 rows centered on row 500 for each column of the matrix **u**. Afterward, make a vector like

x = scale*[1:n];

where **n** is the width of the image in pixels (you can find it using **size**), and **scale** is the plate scale you found in step (1). Then **plot(x,ix)** will plot the intensity along the minor axis with the scale in arc seconds.

Use **v_strip** in the same way to make a plot of the intensity along the major axis. You should choose the values of y1 and y2 to define a strip that is smaller than the nebula, but wide enough to average over a number of pixels and thus reduce the noise. What are the dimensions of the nebula in arcsec? Compare the full width at half maximum of the Hα image that of the [O III] image. Which is larger? Why?

Measure the ratio of the intensity at the center of the image to the peak intensity for both filters and along both axes. (This can tell you if the nebula is a spherical shell, or really has a hole like a doughnut.)

4) You should shift one of the images so that it is aligned with the other: you want the stars in the images to line up. Once you have done this, you will be able to combine the two to make a two-color composite image, where one image is, say red, and the other blue or green. This will show very clearly how the two emission lines differ. Below is an example of some MATLAB code that can do this.

The easiest way to make a composite image is to create an RGB image. RGB stands for the primary colors, red, green, and blue. These images have 3 planes, one for each of the primary colors. In the example below, we use the [O III] image to make both the green and blue planes, and Hα to make the red plane. Each plane has a normalized intensity between 0 and 1 (1 is for the brightest points, 0 for the darkest). The trick to make nice RGB images is to: a) properly align the planes, and b) scale their colors as to produce the best effect. In order to get the best alignment, use the graphical cursor button (or the **ginput** function) in MATLAB to locate a point that you think it is the same in both images (e.g., the center of the nebula, or a star if you see any). You can also do this with your analysis of the size of the region with **h_strip** and **v_strip** above. In any case, once you have located the same point in both images, the difference in its coordinates will tell you how much one has to be shifted to match the other. I have written the function **imshift** to shift an image. Let's say that in your analysis you have arrived to the conclusion that the best match is attained by shifting the [O III] image by **10** rows and **-20** columns. You can use **ims=imshift(im,10,-20)** to do so.

```
ha=rfits('m57-ha.fits');       read in the H-alpha image
o3=rfits('m57-o3.fits');       read in the [O III] image
rgb=zeros([size(ha.data),3]);  create a matrix that has 3 planes of
                             ;  the correct size
has=imshift(ha.data,-35,22) ;  shift the images to align them
rgb(:,:,1)=imscale(has,200,100); rescale the Ha image and
                               ; insert it in the first plane (the red)
rgb(:,:,2)=imscale(o3.data,150,110); store the [O III] image in both green
rgb(:,:,3)=imscale(o3.data,150,110); and blue
imagesc(rgb); display it
```

```
print -djpeg m57_rgb.jpg ; print it as a JPEG
print -depsc2 m57_rgb.eps ; print it as an encapsulated postscript
```

8 Report

Your report should contain the following:

Abstract In a paragraph or two, summarize the scientific purpose of the observations, what was done, the results, and your conclusions.

Introduction Provide several paragraphs of background discussion regarding the purpose of the lab and its goals.

Observations Provide a table listing the important exposures that were actually taken the night you were at the telescopes, including object, date/time of exposure, filter, exposure time, and comments (e.g. hazy, guider problems, etc). Note that some of this information is available in the FITS header (e.g. look for things like " COMMENT FILTER = Ha 6561-19/ OPTICAL FILTER NAME". Briefly describe the observations, and in particular any special problems.

Results Describe the steps taken in reducing your data. Note any particular problems, and what might be done to improve things. Indicate where and why you used data which was not taken the night you were at the telescope. Present contour plots of Hα and [O III], and ratios of [O III] to Hα (taking ratios is tricky, you may want to blank some very low values in the denominator). These contour plots should be on an RA/DEC grid, and the contours should be selected to properly display the data (look at the documentation for the **contour** function in MATLAB). Can you estimate the angular resolution of the images which you have used in the analysis? (Suggestion: look at the apparent sizes of the stars.)

Discussion and conclusions This section covers your analysis and the conclusions you reach. Discuss the differences you found between the images taken with the two filters. Compare the dimensions of the nebula from your images with the dimensions given in the catalogs. Be sure to answer all the questions asked in this handout.

Look at the MATLAB handout to see how to produce printed images. Print out images through the two filters and include them in your report. The images should be displayed in whatever fashion you think shows the most detail. Also include the plots of intensity along the major and the minor axes, *w*ith the dimensions in seconds of arc.

Your write-up should be accompanied by the name of your ursa directory which has all of the .fits files.

9 Appendix 1: Planetary Nebulae

The fundamental reference is the **Strasbourg-ESO Catalogue of Galactic Planetary Nebulae**. Lists of planetary nebulae that are easily observed can be found in the **Observers Handbook** (pp 212-219).

Here is a list of *p*ossible **candidate nebulae**:
NGC 7009 (The Saturn Nebula)
NGC 7662
NGC 2392 (The Eskimo)
NGC 6543 (The Cat's Eye)
NGC 6853 (The Dumbbell Nebula)
NGC 7027

10 Appendix 2: The 3-Dimensional Structure of Planetary Nebulae

Planetary Nebulae often have a regular shape, and in many cases they are approximately circular. One question which arises is whether an object like the Ring Nebula might be a spherically symmetric shell, or whether it is more like a doughnut seen from above.

Look at Figure 1, which represents two lines of sight through a spherical shell. You see that the line through the center passes through less material than the other line. As a result, a nebula with this shape will be less bright in the center than out near its edge: it will look like a ring. On the other hand, the nebula will have *some* brightness in the center. Clearly, if the nebula were completely dark in the center, it would have to have a hole, like a doughnut.

We can make this more quantitative by computing the appearance on the sky of nebula whose 3-dimensional shape is that of a spherical shell. Figure 2 shows the scan of brightness across such projected shells. The top curve is the appearance of a filled sphere, while the other curves show the appearance of shells of different thickness. (The point of maximum intensity corresponds to the inner edge of the shell, like the off-center line in Figure 1.)

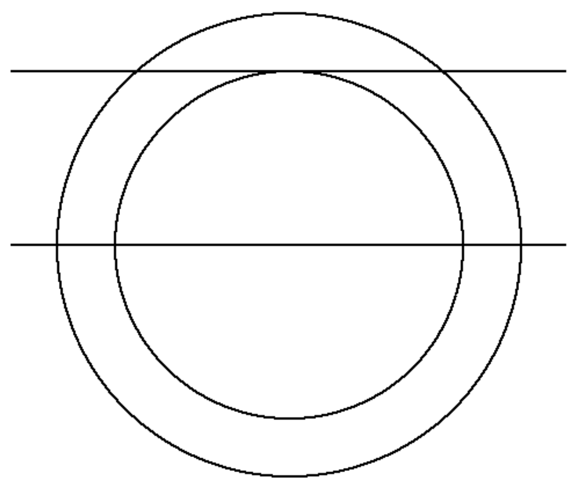

FIG. 1

Figure 1: Lines of sight through a spherical shell.

The ratio of the brightness at the center to the maximum at the shell edge can be found from simple geometry to be

$$\frac{I(center)}{I(max)} = \left[\frac{2}{T} - 1\right]^{-1/2} ,$$

where $T = (Shell\ Thickness)/(Outer\ Radius)$. Here are some numerical values:

T	I(center)/I(max)
0.6	0.6547
0.4	0.5000
0.2	0.3333
0.1	0.2294
0.05	0.1601

You can see that if the center of the nebula is very dark compared to the peak brightness of the ring, then the shell must be thin compared to the radius of the nebula. Look at your plots of the intensity through the Ring Nebula, and discuss whether you think your data is more consistent with a "shell-like" nebula, or if a "doughnut-like" shape seems more likely.

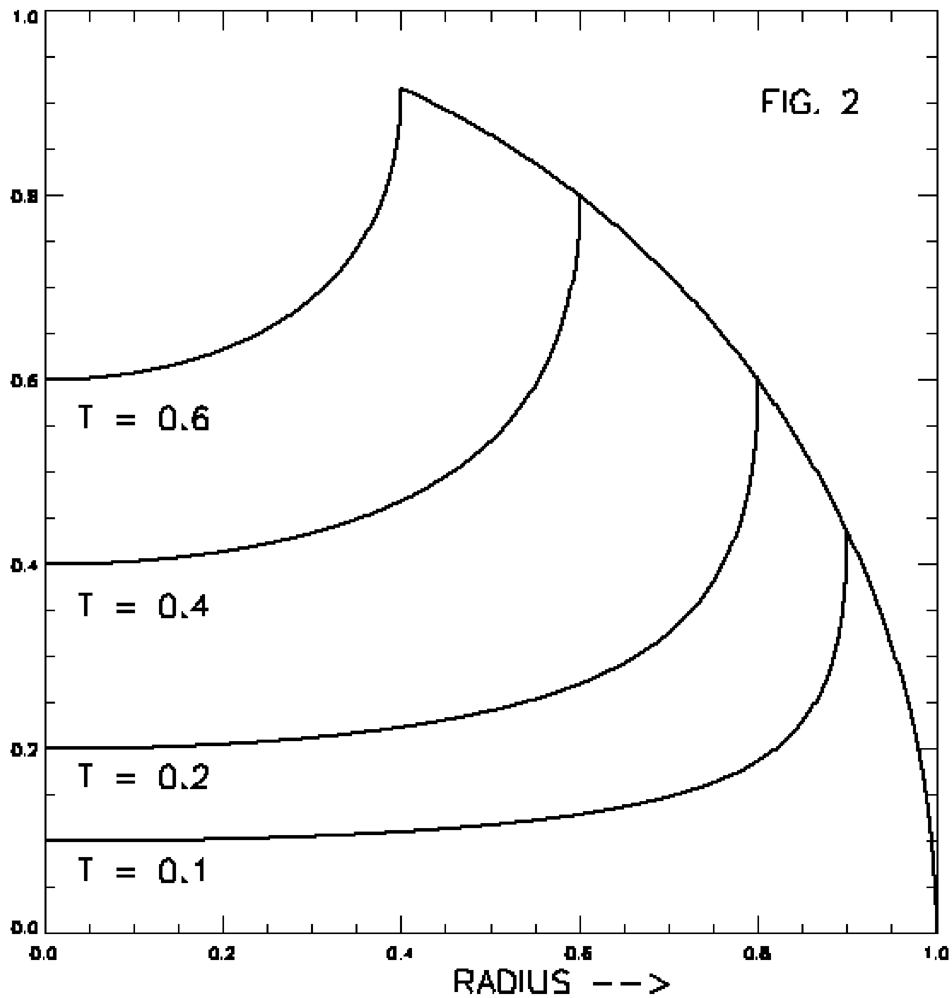

Figure 2: Intensity across spherical shells. T is fractional thickness.