Project 2
CCD Imaging of Planetary Nebulae or H II Regions

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 interference filters which transmit the light of the strongest emission lines in the nebular spectrum. These are the H$\alpha$ line of hydrogen at 656.3 $\mu$m and the line of doubly ionized oxygen (O$^{++}$ or [O III]) at 500.7 $\mu$m. 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 H$\alpha$ filter and also through a filter centered on the H$\beta$ line at 486.1 $\mu$m. These lines are always emitted with a constant intensity ratio, H$\alpha$/H$\beta = 2.8$. However, the ratio we observe may be different because the H$\beta$ line suffers more absorption by interstellar dust than the H$\alpha$ line. By studying the variations in this line ratio, we can map out the distribution of dust in the nebula. The 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. Selection of the Nebula

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 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 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 negative logarithm of the flux, so a smaller number is a brighter nebula. Traditionally, observers would prepare a finding 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. If you wish to do the H II region, we can arrange to try it, but we will have to make arrangements for a mutually acceptable date(s).
3. Observations

3.1. 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.

Because of problems with the 20” telescope in the West Bay, we will have to use the Celestron 14” telescope in the East Bay. (The 20” telescope uses the (relatively) new Apogee CCD camera. Unfortunately, we don’t have operating instructions for the Apogee written up yet.) This handout is written, for the most part, as if you were using the 14” telescope.

Before coming to the observatory, you should read through the instructions for operating the telescope.

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

3.2. Dark Frames

Thermal electrons (i.e., 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 number of thermal electrons collected increases linearly with the exposure time. Consequently, one needs a dark frame with an exposure identical to the exposure on the object (called the light frame). This must be subtracted from the exposure of your object. Note that since any exposure has a bias offset, subtraction of the dark frame from the light frame also automatically does the bias subtraction.

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. By the way, since no light enters the telescope for a dark frame, obviously 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.

Actually, the 14” CCD observing software will usually 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.

However, since telescope time in good weather is hard to get, we might prefer to obtain 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 recap, 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.

3.3. 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.

3.4. 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” (2) begin an exposure of a bright star centered in the CCD frame. (3) Wait about 30 seconds. (4) Then guide the telescope to the North (by pushing the North guide button for about 10 seconds). (5) Next, drive the telescope to the east for about 30 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 .fit file. If you do not obtain this image, get it from the common area (but so note in your report).

3.5. 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 $\epsilon$ Lyr (separation 208 $^\prime$) or $\beta$ Cyg (Albireo; separation 34.4 $^\prime$). 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 3.3. But note that the components of $\epsilon$ Lyr are themselves doubles with $\sim$2.5 $^\prime$ separations, so don’t mistake this for lack of focus! Save one of the best in-focus exposures to disk (as a .fit file) for measurement of the stars’ separation (and also to get the exact orientation of your images).

3.6. Observing the Nebulae

Locate the Ring Nebula and center it in the main telescope. Take an image with the Hα filter first, since you will get more counts with this filter than with [O III]. Try 60 sec to start. Look at the stars in the field to see if they are sharp. You may get some drift in even this short exposure. 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 just like the Hα image, but it will be much 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 .fit files.

3.7. Taking Your Flat Field Images

An important part of observing with a CCD is what is called “flat-fielding”. There may be variations in the sensitivity of the CCD from point to point. Or, the filter transmission may vary from center to edge. We can discover and remove such effects by using an image that is uniformly illuminated. The best way to do this 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 wall of the observatory bay. This is done with the telescope in its parked position, with the roof closed. Lights are used to illuminate the white target, which is on a black background so that light does not enter off-axis. 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 Poisson noise (remember that?) fluctuations are small (but keep to less than 14,000 counts to avoid the 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.

3.8. Copy Your Images to the Zip Disk

When you are done, copy your frames to a ZIP disk. You have to leave SkyPro to do this. It can be done in the Windows File Manager, or using the DOS copy command. Make sure that the copy really worked (list the files in F:) and then delete your frames from the disk to leave room for the next group.

3.9. Problems

Here is an interesting web site that includes examples of various CCD mishaps.
http://www.astro.lsa.umich.edu/users/kaspar/obs_mishaps/mishaps.html.
Most of them are quite esoteric, but it may be instructive.
4. Data Reduction

This is set up to be done on the Gateways located in the computer lab room, CSS 1220. All the machines have both floppy and ZIP drives. Put your ZIP disk in the drive and use the “fast-FTP” tool you used earlier to copy your .fts image files to your directory on ursa.

For this exercise the reduction consists of using the IDL language to do a number of tasks:

0) Read in your images. Rotate them all with the IDL function

\texttt{im = rotate(im,7)}

which will bring them \emph{approximately} to the standard orientation of north at the top, east to the left. (Note: this is different from the 20-inch CCD, where you used “rotate(im,3)”.)

1) Display your images. Experiment with setting the display range, color table, etc. to see all the detail that is in your data. Try the \texttt{smooth} function to average out some of the noise.

2) Do flat-fielding to get each image onto a uniform basis (i.e., dividing each image by the corresponding flat field image). First, 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. Take the \texttt{mean} of the entire image and divide that into the image itself. This scaled image will have values near unity. Then divide this scaled flat field into the images taken through that filter. This will compensate for the variations (i.e., where the flat is dark, you will be dividing by a number less than unity and thus will boost the image values there, etc.).

3) 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 \textit{position angle} is the angle from the north direction to the direction of the vector formed by connecting the two stars, with the tip of the vector on the fainter of the two stars.)

4) Examine the images. Compare the H\alpha with the [O III] image. Consider that takes much more energy to remove two electrons from oxygen to produce O\textsuperscript{++} 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 H\alpha emission.

5. Data Analysis

1) Look up in a catalog the separation in arc seconds of the components of the double star, and the \textit{position angle} of the pair. Use this to determine the \texttt{plate scale} in arc seconds/pixel, of the CCD. 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 IDL `rot` function to rotate the image through different amounts till the major axis is vertical. 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) I have placed two simple IDL functions, `hstrip` and `vstrip`, 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 = hstrip(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. Make a vector like `x = scale*findgen(n)` where `n` is the width of the image in pixels, 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 `vstrip` 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. Here’s an example of some IDL code that can do this – the second bit of code is to make a color postscript file for printing.

```idl
ha=readfits('m57-ha.fit',ha)
o3=readfits('m57-o3.fit',ho)
window,xs=765,ys=510
ib=bytscl(o3<450>100) & ig=ib ; store the O III image in both green & blue
ir=bytscl(ha<400>120) ; store the Hα image in red
sr=shift(ir,-20,-14) ; shift red image 20 pix in x, 14 pix in y
loadct,0
```
tc=color_quan(sr,ig,ib,r,g,b) ; make a color composite image called "tc"
tvct,r,g,b ; load the r,g,b color tables from above
tvscl,tc ; display the image
curval,tc ; experiment with shift values

set_plot,'ps',/copy,/interpolate
device,yoffset=8.0,bits_per_pixel=8,/color
device,filename='ring.ps'
tc=color_quan(sr,ig,ib,r,g,b)
tvct,r,b,g
tvscl,tc,xsize=18.0,ysize=12.0,/centimeters
device,/close
set_plot,'x'

6. 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.

Data Reduction 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 [OIII], and ratios of [OIII] to Hα. These contour plots should be on an RA/DEC grid, and the contours should be selected to properly display the data. Can you estimate the angular resolution of the images which you have used in your this analysis?

Analysis 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.

Look at the IDL 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, with the dimensions in seconds of arc.

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

7. Appendix: 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 possible 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

Due: 26 October 2006
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.)

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

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

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

<table>
<thead>
<tr>
<th>T</th>
<th>$I(\text{center}) / I(\text{max})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.6547</td>
</tr>
<tr>
<td>0.4</td>
<td>0.5000</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3333</td>
</tr>
<tr>
<td>0.1</td>
<td>0.2294</td>
</tr>
<tr>
<td>0.05</td>
<td>0.1601</td>
</tr>
</tbody>
</table>

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.
Fig. 1.— Lines of sight through a spherical shell.
Fig. 2.— Intensity across spherical shells. T is fractional thickness.