

Observing with a CCD Camera Properties and Measuring Brightness & Position

Take Data: September 28 – October 3 (weather permitting)

Report Due: Thursday, October 11 (weather permitting)

Text Reference: Chapters 8 & 9

Purpose: This lab introduces the direct-imaging CCD system on the 0.5 m telescope in the context of a typical astronomical observation – measuring the brightness and location of an object. It also introduces the basic steps in obtaining and analyzing an astronomical observation.

Background: Charge Coupled Devices (CCDs) are solid-state imaging detectors that are the detector of choice for almost all astronomical applications. They have several desirable qualities. 1) High sensitivity – recording up to 85% to 90% of the photons that illuminate them. 2) Photometric stability – measurements of the intensity of the light that falls on them are accurate and reproducible. 3) Stable geometry – measurements of the positions of features in the images are accurate and reproducible. 4) Digital data – measured signals are easily digitized and recorded in computers for later analysis. The only significant limitations to CCDs are the need to cool them to low temperatures to reduce signals from thermal excitation, “dark current”, compared to photonic excitation and their limited sizes, although mosaics of multiple CCDs are now becoming common to produce larger effective sizes.

As with any instrument, the signal measured by the combination of telescope and CCD depends both on the incident light and on the properties of the optics and detector. Thus, it is necessary to obtain *calibration data* to measure the properties of the instrument as well as *science data* to measure the object in the sky. For our CCD system we will take images of a uniformly illuminated field to measure changes in the relative sensitivity across the detector and images with exposure times equal in length to those of the science images but with a closed shutter to measure both the bias level (the output when no signal is present) and the dark current. The former are called *flat field* images and the latter *dark images* (or *dark frames*).

Carrying out astronomical observations and their analysis typically involve the following steps.

1. Planning before going to the telescope in order to optimally use the scarce resource of time at the telescope. Determine when your targets are visible, how to find them, and what science and calibration data to take.
2. Taking both science data and calibration data at the telescope. Includes assessing data quality in real time – are you pointed in the right place, are the images focused, are your exposure times too short (not enough signal) or too long (target saturated)?
3. Calibrating the science data. The first step(s) of data analysis.
4. Scientific analysis of the calibrated images.

I. Preparation and Planning:

We will observe two objects for this lab: M39 and the asteroid 230 Athamantis. The locations of these objects are shown in *The Sky*.

1. Use *The Sky* running on a computer in the classroom or dome to find where these objects will be in the sky during your observing session. Are they visible? Will any be close to the horizon? Decide on the order in which you should observe them to have them as high in the sky as possible.
2. Zoom in with *The Sky* at the location of M39 until you can see the red rectangle that is the “footprint” of the CCD camera field of view on the sky. Compare the view with the finding chart from Lab 2 and ensure that you can get all of the labeled stars from that lab in a single image. Identify a 7th – 8th magnitude star within a few degrees of the cluster that could be used to focus with.
3. Similarly zoom in on the location of Athamantis *for the date and time of your lab period* (the asteroid moves on the sky). Identify a 7th – 8th magnitude star within a few degrees of the asteroid that could be used to focus with. Are there any 10th magnitude or brighter stars near the footprint of the guide CCD (the smaller of the two red boxes) that could be used with the autoguider when the field of view is nearly centered on Athamantis?

II. Observations of M39 and Athamantis:

If the weather is cloudy, do the first six steps and then skip to part III and take calibration data. If it is clear, continue with obtaining science data. You can take the calibration before the science data if you decide that observing them later will result in M39 and Athamantis being higher in the sky.

1. Slide the fold mirror in the red instrument adapter box to the “CCD” position following the directions in the *0.5 m Telescope User’s Guide*. Check the other side of the box to ensure that the spectroscopic pick-off mirror is out (rivet in the “direct” location). Make sure that the plastic plug is in the eyepiece tube. Turn on the imaging CCD system with the power strip in the telescope mount base.
2. Start *The Sky*, *IDL*, and the imaging *CCDSOFT* program on Hipparchus. In *IDL* start *RUPhAst* to view the saved images.
3. In *CCDSOFT*, click on *Camera/Setup* to bring up the Camera Control tool. You will use this tool for running the CCD. On the *Setup* tab, click *Connect*, and observe that the Imager and Autoguider become “linked” with Status “ready”. Click on the *Temperature* button, and on the pop-up menu enter a setpoint temperature that is 35 to 40 °C cooler than the ambient, select the “On” radio button, and then click “Ok”. Observe that the cooler power goes to 100% and the CCD temperature begins dropping. It will take a few minutes for the CCD to stabilize at the selected temperature. Note the percent power used – it will be near 100% while cooling, but should drop to a lower value when the setpoint is reached. If it takes more than about 90% power to maintain the setpoint, raise the setpoint temperature a bit.
4. Select the *AutoSave* tab, and make sure that the *Image* radio button is selected. Click on “Choose Folder...” and navigate to *G:/Ph344/lab3/*. Create a new folder there, named with

the date and your initials (e.g., sep24tp), and then select this folder. Set the *starting number* to 1. Select a *prefix* image name – you may want to use different names for each group of files created in the steps below. Make sure that *Save As FITS* is selected, and *AutoSave* is on.

5. Select the *Take Image* tab. Set the *Exposure Time* to 1 second, the *Bin* to 2x2, *Series of* to 1, *Subframe* off (i.e., read out the whole CCD), *Filter* to V, *Frame* to Light (i.e., open the shutter during the exposure) and *Reduction* to None. This last setting means that no calibration data is obtained automatically. We will later use the Autodark setting, which automatically follows each science image by an equal-length dark image (or uses a previously-taken dark image if taking repeated images with the same exposure time) and subtracts it from the science image.
6. The telescope is focused by moving the secondary mirror using the stepper-motor controller on the observing desk. Turn on the encoder readout above these controls with the green button. Use the focus motion buttons on the panel below to set the encoder to a reasonable first guess at a good focus. This value is 2.40 mm if the air temperature is about 20 °C and increases by about 0.100 mm for every 5 °C *decrease* in temperature.
7. Open the dome, remove the telescope cover, and initialize the pointing of the telescope starting from the zenith position in the same way as for visual observing. The only difference is that you will take images instead of looking through the eyepiece and center the star in the field of view of the camera. Centering is performed using the *Telescope/Motion Controls* in *The Sky*.
 - a. After slewing to the first bright star, take a 1 second exposure.
 - b. The bright star should be in the image – shrink the displayed image in the *CCDSOFT* window so that you can see all of it (change the cursor to “zoom out” and click one or more times on the image; then go back to the “select” cursor; click once on the frame of the image to get it to resize).
 - c. Display the image in *RUPhast* and note that it is flipped top-to-bottom compared to the *CCDSOFT* display.
 - d. Center the bright star in the field using the telescope motion controls and taking an exposure after each move. The long axis of the CCD is north/south and about 32 arcminutes across.
 - e. Once the star is centered, sync the telescope coordinates.
8. Slew to a star near your first target that is magnitude 3 or brighter. Take another 1-second exposure to check and, if necessary, refine the pointing.
9. Slew to the focus star you selected for your target. Set *Reduction* to Autodark, *Filter* to V, and take a 5-second exposure. Confirm that you are pointed where you expect to be.
10. Focus the camera.
 - a. Set *Bin* to 1x1 and *Reduction* to None. Take a 1-second exposure.

- b. Shrink the *CCDSOFT* display to see the whole image, if necessary. Click and drag a selection box to include your focus star and several other stars in the *CCDSOFT* image display. Note that this automatically checks the *Subframe* box. Take another test image and verify that everything is ok in the subframe display box. Then select *Reduction: AutoDark* and take one more image.
 - c. Select the *AutoSave* tab and set a reasonable filename (*i.e.*, focus) and then go back to the *Image* tab. Set the telescope focus value to about 0.150 mm less than the estimated optimum value. (*E.g.*, if the best focus is guessed to be -0.450 , start the focus series at -0.600). Take a set of 7 exposures, all with a 5 second exposure time, increasing the focus value in steps of 0.050 mm between exposures. You should thus take the last exposure at 0.150 mm above the central value.
 - d. Examine these 7 images with *RUPhAst*, measuring the FWHM of the focus star in each using the radial profile routine (“p” key or left mouse button in Imexam mode). There should be a clear minimum in FWHM and the best value may be between two of the sampled positions. If the best focus is at either end of the sequence, repeat step 10-c using the best focus value so far as the center of the focus series.
 - e. Set the telescope focus to your optimum value. **Include the value of your best focus and the air temperature in your lab report.**
11. Take a science image.
- a. Slew to your first target. Set *Bin* to 2x2, *Subframe* off, and, in the *AutoSave* tab, change the filename to something more reasonable than focus. Take a 5-second exposure and examine the image in *RUPhAst*. Center your target, if necessary.
 - b. Set up the guider, if a reasonable star is available. I or the TA will guide you through the procedure.
 - c. For M39, take a 90-sec exposure if guiding is possible and a 30-sec exposure if it is not. Athamantis is of moderate brightness, so similar exposure times will probably work. Just be sure to avoid saturating its image. Determine the peak signal of the profile of the asteroid image (p key in *RUPhAst* again) and adjust the exposure time, if necessary, to keep the peak below 50,000 ADU (nearing saturation). Once you determine your exposure time, take two images of Athamantis separated by at least 10 minutes.
12. Repeat step 11 for your other target. If you are not sure that you are pointed in the right place, repeat step 8 using a nearby bright star. You will probably not need to refocus after moving to your other target but check the quality of the focus and refocus (steps 9 and 10) if it seems much worse.

III. Acquisition of CCD Calibration Data:

1. Start shutting down the telescope by sending it to the home position. Drop the link with the computer and turn off the black telescope interface box. Point the telescope horizontally by hand and close the dome shutter.
2. Turn on the dome white lights and point the telescope to a region of the inside of the dome that is unshadowed and as free of “structures” as possible.

3. Select the *AutoSave* tab. Turn *AutoSave* on and choose a filename of *flatV*, since we are observing with the V-band filter.
4. **Flat field images:** Select the *Take Image* tab. Set the *Exposure Time* to 7.5 seconds, *Series of* to 2, and *Reduction* to None. Click the *Take Series* button to take two sequential images. During these exposures, no one should move in the dome, since this can change the illumination pattern on the dome. Use the cursor on the displayed image to verify that the exposure has produced an intensity of roughly 30,000 ADU per pixel.
5. **Gain and read noise measurement:** Change *Reduction* to None and *Frame* to Bias. Take a series of two bias (zero exposure time) images.
6. Cover the telescope and point it to the zenith. End the *CCDSOFT* program and turn off the power to the CCD at the plug strip in the telescope base (if this is the last data that you are taking in your lab period).

IV. Data Analysis Part 1: Visual Observing vs. CCD imaging

This and subsequent parts of the lab can be done at any time using the server computer, astrolab. Use VNC to connect to astrolab from anywhere and analyze your data. If you were not able to take images of M39 and Athamantis, you will be assigned images taken by others.

CCDs detect a larger fraction of the incident light than the human eye. More importantly, a CCD can also integrate longer than the roughly 0.1 second of the human eye. Here you will examine an image of the star cluster M39 that you observed visually in Lab 2.

1. Start IDL in your astrolab account and, if necessary, set it up. You should have already set the software path in IDL for Lab 1 – if you haven't done this, do it now. [In IDLDE, click on *window/preferences*, then select *IDL* and *Paths*; click on *Insert*, and then in the Places window navigate to *File System* and double click. Then navigate to */usr/local/src/idl* (make sure *idl* is highlighted) and click *OK*. This path will be added to the path window. Check the box preceding this item to include the subdirectories. Then click *Apply* and *OK*. You only need to do this once, and then the IDL astronomy libraries will be automatically added to your path every time you run IDL.]
2. Copy your image of M39 to a location in your home directory. Use the file manager tool to copy the image (or Linux commands if you are a Linux wizard).
3. Display your M39 image in *RUPhAst* and use the finding chart and list of magnitudes given in Lab 2 to determine the faintest star visible in the image. How does this compare to your limit from visual observing?

V. Data Analysis Part 2: Image Scale

The image scale is an important parameter for a camera on a telescope. Typically this is expressed as the number of arcseconds per pixel in the image. In this section you will use your M39 image to measure the image scale for our camera binned 2×2.

1. Pick three stars from the list below that are visible and not saturated in your M39 image and measure their (x,y) position in pixels using the p-key in *RUPhAst*.
2. Determine the three separations between three stars in pixels.
3. Use the right ascensions and declinations of the stars (from the Initial Gaia Source List catalog) to determine the separations in arcseconds.
4. Use the above results to calculate the average image scale and estimate the uncertainty in your measurement. Ignore the complication that your three separations are not completely independent measurements.

Star	V Magnitude	RA, Dec (2000)
GSC 3594:86	12.3	21h 31m 27.692s, +48° 31' 36.03"
GSC 3594:384	12.9	21h 32m 11.836s, +48° 30' 38.28"
GSC 3594:2331	11.0	21h 32m 32.170s, +48° 32' 07.04"
GSC 3594:2539	13.3	21h 32m 04.432s, +48° 27' 17.96"
TP C	12.7	21h 32m 43.794s, +48° 29' 21.30"

VI. Data Calibration Part 1: CCD Gain and Read Noise

A fundamental property of a CCD camera (i.e., the solid-state detector and its associated electronics) is the relation between the number of photons detected in a pixel and the output signal for that pixel. The units of this output signal are somewhat arbitrarily designated as digital units (du) or analog-to-digital units (ADU). The *gain* of a CCD camera is the number of Type equation here. detected electrons per ADU. Measuring the gain would be simple if there were a method that deposited a known number of electrons in a CCD pixel. Radioactive decays that produce x-ray photons of known energy (which produce a maximum number of electrons when absorbed by the CCD) are a possibility, but this is inconvenient in practice (it requires a fairly strongly radioactive source!). So the usual method to measure the gain exploits the Poisson statistics of photon arrival, specifically that for a collection of pixels with an average signal of N detected photons, the standard deviation of the detected signals around their mean will be \sqrt{N} .

Our camera has two possible gains (high and low) that are selected automatically depending on the selected binning – 2×2 binning has more electrons per ADU (low gain) than does 1×1 binning (high gain). The low versus high nomenclature makes sense if you think in terms of the amount of amplification of the original signal read out of the CCD. In professional CCD cameras, the gain and binning can be selected independently.

Another important property of the CCD camera is the noise added to the measured signal by the CCD electronics, called the *read noise*. This is generally measured by looking at the values from a collection of pixels in a zero-length exposure bias frame. The standard deviation of the values around the mean is the read noise in electrons times the gain.

We start the measurement of the gain and read noise with some practice manipulating images with IDL and measuring the statistical properties of an image.

1. In IDL, create a two-dimensional array of Gaussian random numbers with zero mean and a standard deviation of one by typing the following into the IDL> command line box at the bottom of the developer environment window:

```
a = randomu(seed,400,400,normal=1)
```

Display this array using *RUPhAst* by typing:

```
ruphast, a
```

2. Change the display contrast and brightness by holding down the left mouse button and dragging: left-right changes the brightness, and up-down changes the contrast. How does this image appear?
3. Get the image statistics for an 11 x 11 pixel box centered at X=200, Y=200. In your report, list the minimum and maximum pixel values in this region, the mean, the median, and the standard deviation of the pixel values about the mean. (Make sure that you understand the meaning of all these statistics.) Why is the mean not exactly zero, and the standard deviation not exactly one?
4. Repeat the exercise with a 151 x 151 pixel box centered about X=200, Y=200 and report the values. Comment on the differences between the small and large samples.

Now proceed to measure the actual gain and read noise for the low-gain mode of our CCD camera.

5. **IMPORTANT!** Copy all of your Lab 3 CCD images from the folder /home/ph344/lab3/... to a folder in your home area. Make sure that you always work on these copies, not the original images! Use the file manager tool to copy the images (or Linux commands if you are a Linux wizard). Also copy the file /home/ph344/lab3/phast.conf into your lab3 folder. This configuration file initializes certain quantities in *ruphast*, most notably the CCD gain and readnoise. Examine the contents of this file.
6. Depending on where you were in the filesystem when you started IDLDE, you will need to change the path so that you can find your image files. IDL does this with the *cd* command:

```
cd, "/home/yourusername/thedirectorywhereyouputthedata"
```

Note that the quotes are important, as is the comma. Obviously, replace "yourusername" with your user name on the system, and "thedirectorywhereyouputthedata" with the appropriate path to the place where you saved the copies of the original images.

7. Examine one of your Flat and Bias images with *RUPhAst*. Explore the headers of the images to see what information was recorded. Describe the structure that you see in the images.
8. Read in two of your Flat images and your two Bias images into arrays for processing:

```
f1=readfits('image.00000001.FIT',h) * 1.0  
f2=readfits('image.00000002.FIT',h) * 1.0
```

```
b1=readfits('image.00000003.BIAS.FIT',h) * 1.0
b2=readfits('image.00000004.BIAS.FIT',h) * 1.0
```

Note that you can use the up arrow key to recall a previous IDL command – saves a lot of typing. Multiplying each image by 1.0 forces them to be saved as floating point numbers rather than unsigned integers. Your images may have different names – obviously, use the actual filenames of your images.

- Form the difference of the two flats and biases:

```
db = b1 - b2
df = f1 - f2
```

- Use *RUPhAst* to load and examine these six images (two biases, two flats, and two differences), using the command:

```
phast, b1
```

(and replace b1 with the names of the other 5 arrays). Use the “i” command in RUPhAst to measure the image statistics in a 51 x 51 pixel box centered at x=1000, y=650 in each image, and record the mean and standard deviation for each frame. The ambitious may want to measure more than one region on the image.

- Calculate the gain (in e⁻/adu) and read noise (in e⁻) for the system using the statistical data from step 10:

$$gain = \frac{mean(f1) + mean(f2) - mean(b1) - mean(b2)}{[stdev(df)]^2 - [stdev(db)]^2}$$

$$read\ noise = gain \times \left(\frac{stdev(db)}{\sqrt{2}} \right) = gain \times \left(\frac{stdev(db)}{1.414} \right)$$

In these equations “mean(f1)” is the mean of the image f1 measured with the “i” command and “stdev(df)” is the standard deviation of image df measured with the “i” command, etc..

VII. Identify Athamantis and Measure its Motion

Compare your two images of Athamantis and identify the asteroid as the object that moves compared to the stars between the two exposures. Measure the shift of Athamantis in pixels between the two images. Unless you were guiding, the stars will also move in the image between the two exposures due to telescope tracking errors. So you will have to measure and remove the shift in the positions of the stars from your shift in the position of the asteroid. Then use your image scale and the time between your exposures (accurately recorded in the image headers) to calculate the motion of the asteroid in arcseconds per hour. Also estimate an uncertainty in your measured motion.