Physics 629 **Lab 2** **Due: 18 Oct 2004**

CCD Characteristics

Purpose:

The first charge coupled devices (CCDs) were produced just 30 years ago — at Bell Labs in in New Jersey. They have become the detector of choice for most astronomical observations in the UV and optical spectral regions, and are becoming increasingly popular for X-ray observations. There are a number of reasons for this popularity. The best CCDs have high quantum efficiency ($\eta \sim 90\%$), low readnoise ($r \sim$ 2-3 e^-), relatively uniform response, large dynamic range ($D \lesssim 100$ dB) and excellent linearity. Virtually all large observatories maintain websites describing the characteristics of their CCDs, and it is important to know which detector is right for your observing program. It is also wise to *measure* and *test* these characteristics during the course of your observing run, rather than accept them as a matter of faith. In this lab, you will characterize the following properties of the Serin Observatory's direct CCD:

- the detector gain and readnoise
- the detector linearity
- the detector dark current, and its dependence on temperature

Note that this lab does not require nighttime observations.

Background and Procedure:

(1) Gain and Readnoise: Every CCD relies on an amplifier to measure the electrons contained within the various detector pixels; *readnoise* is defined as the mean error contributed to a pixel by the amplifier. The amplifier signal is in turn digitized by an Analog-to-Digital (A-to-D) converter, and the *gain* is number of electrons per data unit produced in the conversion (i.e., e^- per A-to-D conversion units, or ADUs). The lower the gain, the smaller the signal entering the A-to-D converter for a given number of electrons in the pixel (i.e., a low gain refers to a higher a value of e^-/ADU).

It is possible to calculate the gain and readnoise by measuring the mean and standard deviations of pixel values in two pairs of images which have much different signal levels: i.e., a pair of bias images and a pair of flat-field images. In the bias images, the measured variation in the pixel values must arise solely from the readnoise of the amplifier for the simple reason that the image exposure time is zero seconds (i.e., the shutter never opens). The standard deviation of this variation is the readnoise. Given a bias image, it is a simple matter to calculate the readnoise in ADUs, but we are interested in its value in electrons. To convert from a readnoise measured in ADUs to one in electrons, we must also measure the amplifier gain.

A clever method to solve simultaneously for the gain, g, and readnoise, r, of a CCD was devised by Jim Janesick of PixelVision. Although repeated measurements of one pixel would determine the readnoise, this is obviously a tedious approach. Instead, if we assume that the pixels are nearly the same, we may calculate the standard deviation about the mean value by using many different pixels. In practice, this approach is complicated by the fact that detectors often exhibit large-scale gradients in their bias levels. Such gradients serve to increase the measured standard deviation; they are, however, not caused by readnoise. The effect of these gradients can easily be eliminated by taking the difference in two exposures of identical exposure time. The standard deviation about the mean pixel value in the difference image of a pair of bias frames is then just $\sqrt{2}r$.

A similar strategy can be used to measure the gain. In this case, we use exposures with much higher signal levels than the bias images: frequently dome or sky flat-field exposures. Once again, a pair of exposures is used to form a difference image, and the standard deviation is measured. In this case, though, the measured standard deviation contains a component from the pixel readnoise, and a random (Poisson) component due to the arrival time of the photons from the dome or sky. The larger the gain, the larger the measured pixel-to-pixel deviation.

This can be expressed quantitatively in the following way. Let s be the average signal measured in ADUs, and n_e the average number of electrons detected, so that $n_e = gs$. If r is the readnoise measured in ADUS, then the measured standard deviation of s is

$$\sigma_s^2 = (\sigma_{n_e}/g)^2 + r^2 = (\sqrt{n_e}/g)^2 + r^2 \tag{1}$$

or

$$\sigma_s^2 = s/g + r^2. \tag{2}$$

Solving for the gain gives

$$g = s/(\sigma_s^2 - r^2) \tag{3}$$

Recall that we are using the difference of two images to determine the gain, so the measured standard deviation will be $\sqrt{2}\sigma_s$.

Procedure

Follow the procedure in the documents *"Operating the Serin 0.5m Telescope"* and *"Operating the Serin Observatory Direct CCD System"*. Both are available from the course website: http://www.physics.rutgers.edu/grad/629

Allow about 15 minutes for the CCD temperature to stabilize. It should cool down to $\sim$ 230 K. Without opening the dome, remove the mirror cover from the telescope and point it at a reasonably blank portion of the dome interior. Set the camera zoom to 210 and use the V filter. (The minimum zoom of 82 gives the largest field and, thus, the largest amount of light per pixel for a given illumination. However, this setting illuminates the CCD unevenly — vignetting — which is undesirable for this lab.)

- Use the "Browse" button on the CCD interface to create a subdirectory in the *ph629data* directory on Hipparchus to store your data. Use a name of the form *mmddyourinitials* where *mmdd* are the month and day. Set this subdirectory as the file path.

- Set the gain to low on the CCD interface.

- Turn off the lights and take two bias frames.

- With the dome lights on, experiment with flat-field exposure times (with the "save box" on the CCD interface unchecked) until you find an exposure time that gives a maximum of 3500 ADUs per pixel. You may examine the images using the ATV display in IDL, which runs on Hipparchus. Note that lowercase "i" gives the average, minimum and maximum values for a block of pixels around the location of the cursor.

- When you have settled on a good exposure time, take (and save!) two of these flat field images.

- Repeat each of the above steps with the gain set to high.

- Continue with the procedure described in §2.

(2) Linearity: One the most appealing features of CCDs as astronomical detectors is their linearity: the degree to which the output signal is proportional to the incoming photons received by the detector. Examine the linearity of the CCD in the following manner:

<u>Procedure</u>

- Using the exposure times, t_{max}, that you found to give counts of about 3500 ADUs, take a series of exposures, *for both the high and low gain settings*, of duration $0.75t$, $0.5t$, $0.25t$, $0.125t$, $0.0625t$, $0.03125t$, $0.015625t$ and $0.0078125t$.

- Continue with the procedure described in §3.

(3) Dark Current: All CCDs contain a dark current caused by electrons which are boosted into the conduction band by thermal excitation. At room temperatures, this dark current will usually exceed most astrophysically interesting signals, but it can be suppressed by cooling the detector. The dark current should vary according to the relation

$$DC = AT^{3/2} \exp\left[-E_g/2kT\right], \tag{4}$$

where A is a constant (in, say, ADUs per pixel per second), E_g, is the the difference in energy between the Fermi level and the bottom of the conduction band for the semiconductor (see Chapter 2 of Reike 2003), and T is the detector temperature. Temperature control for the CCD on the 0.5m is provided by a thermoelectric cooling system which produces a maximum reduction of 50–60 K below ambient. By measuring the dark current at different detector temperatures, it is possible to determine the values of A and E_g in equation (4).

<u>Procedure</u>

- With the CCD at its lowest temperature, take one dark frame of 20s. (A dark frame is an exposure in which the shutter does not open and the detector is not illuminated.) Record the CCD temperature.

- The grey box next to the telescope contains two rocker switches which control the power to the CCD and the thermoelectric cooler. Turn off the power to the latter with the switch which is nearest to the telescope. Note that the power for the LCD display which records the CCD temperature is controlled by the CCD power. As the temperature rises (and it will do so very rapidly during the first few minutes!), take a series of 20s dark frames, carefully recording the CCD temperature at the midpoint of each exposure. You should be able to take 15-20 dark frames in the time it takes for CCD temperature to stabilize.

- Once the CCD has reached the ambient temperature, turn off the power and shut down the telescope and computer controls, following the procedures in the telescope user's manual.

Analysis:

First, transfer the images from the data directory on Hipparchus to your home directory. It is simplest to use the same "SSH Secure File Transfer" program that you used for Lab 1.

To proceed with the analysis, you will need to know how to run IRAF (or some other image analysis package such as IDL or MIDAS) to measure the mean and standard deviations of the pixel values in images you have collected. Recall that a copy of the IRAF Beginner's Guide is available from the course website. If you have not already done so, read it and carry out the IRAF tutorials which are also available from the course website. (For the purposes of this lab, you need only have completed the first IRAF tutorial: i.e., the "introductory" tutorial.) Since you will also need to display the images, you will need to familiarize yourself with an image display utility such as *ximtool* or, preferably, *ds9*.

Part 1: Gain and Readnoise: Following the procedure described above, *calculate the gain and readnoise of the CCD in both low-gain and high-gain modes.* Give the readnoise in both ADUs and electrons. In calculating the means and standard deviations, be sure to use the same region of the image (say, a subraster of 100×100 pixels) for both the biases and flat-fields. Try to avoid cosmetic defects such as bad columns, and regions which contain "hot" pixels or cosmic rays. Although the CCD measures 612×512 pixels, be sure to avoid the first and last 50 columns in your calculations as these are "prescan" and "overscan" regions. The pixels in these regions do not really exist; they are generated by the readout electronics so that the zero level of the amplifier can be monitored.

Part 2: Linearity: Using the series of exposures taken in part 2, calculate the mean number of ADUs per pixel, for both the high and low gain settings. Once again, try to avoid cosmetic defects, bad columns, cosmic rays, etc. *Plot your mean counts in ADUs as a function of exposure time for both gain settings.* (Note that the actual exposure time may differ slightly from what you requested at the telescope; the actual time that the shutter was open is given in the image header under the keyword EXPTIME.) What are the best fit linear relations? What is the significance of the intercepts of these relations? Do they agree with expectations? What are the best-fit *quadratic* relations for the two datasets? What do you conclude about the linearity of the detector? Justify your conclusions with the appropriate statistical test.

Part 3: Dark Current Using the dark frames that you collected as the CCD warmed up, measure the mean pixel value. Remember that the dark current you are measuring is superimposed on a bias level which is non-zero. Use the overscan region of each CCD frame (i.e., the area covered by columns 562 to 612) to *calculate the net dark current in each exposure in ADUs per pixel per second. Plot the dark current as a function of temperature, and determine the values of* A *and* E_g *which best fit your data. How does your derived value of* E_g *compare with the energy gap of silicon?*