Lab 2: Characterizing the CCD detector

Overview

The CCD (Charge-Coupled Device) camera is a very important tool in astronomy because its efficiency at recording low light levels in a linear fashon. As with any measuring tool in science, it must first be calibrated and quantified. In order to better understand your astronomical images recorded with this device, you need to understand the CCD's intrinsic properties first. This lab is designed to give you experience in characterizing a CCD detector in terms of readnoise, dark current, system gain, and bad pixels. (see last week's handout for supplemental readings on these topcis)

Introduction

1.1 Signal & Noise

Your ability to detect a signal depends on the relative strengths of the signal and overall noise present on your detector. There are several types of noise you will will encounter with the CCD. For our purposes, noise will be quoted as the standard deviation of a signal level (x) over a sample range (i=1 to N) in time. $s=_{i=1}^{N}(x_i-<x>)^{2}N$ Shot noise is noise that is associated with events that occur with constant arrival rates. (i.e. photons collected by the telescope and electrons detected by the CCD). Shot noise follows Poisson statistics, and it can be estimated by the signal level with the relation: $s(e^-)^{a}signal(e^-)$ This relationship only holds true in the units of the events recorded at the detector. (electrons in our case, not ADU!) The readout electronics convert electrons detected at the CCD to digital numbers (ADU) stored in the image by way of the gain.

1.2 Dark Current

In addition to electrons collected on the CCD due to photons of light incident on the telescope, thermal motions of the CCD material itself adds "signal" to the CCD. This so called "Dark Current" is present whether there is light shining on the detector or not, and it is strongly affected by the temperature of the chip. (doubles every 6 degrees C) The small elevation of signal introduced by dark current can be removed by simply subtracting from the signal frame a dark frame of the same exposure time. However, the noise introduced by the slightly larger signal (noise signal) does not get removed by this subtraction. The noise can only be minimized by minimizing the dark current signal. Therefore, CCD detectors are cooled so as to lower the dark current signal, thereby reducing the noise contributed by the dark current to the overall image.

1.3 Read Noise

Noise is introduced into the system each time the chip is read out by the electronics. For a constant signal level on the detector, the value that the readout electronics assigns to each pixel is not exactly the same. Some of this noise is strictly due to readout of the electronics. The read noise is always present and in the same capacity, independent of exposure time.

1.4 System Gain

The value assigned to each pixel on the detector array relates to the number of electrons that were detected on the chip. The relation is linear, and the scale factor is the conversion from electrons (e^-) detected to data numbers (ADU) assigned in the readout image. Gain = e^-ADU A larger system gain allows for a high dynamic range of linear detectability on the chip, but at the expense of higher digitization noise. This quantity is then set to acheive a suitable balance between the two.

1.5 Bad Pixels

In every detector array, a small percentage of pixels are bad in some way. These are pixels that do not respond to light at all, or respond in a nonlinear way. Such pixels may have extreme dark current as well. It is important to identify these bad pixels on the chip and mask their aberrant values so they do not contribute the image you may be trying to quantify. Therefore, constructing a bad pixel image is useful in order to identify where the problem parts of the array lie, and to set those values on the array to zero.

Procedure

Of course, the data you need to take in this lab will involve using the CCD detector. But you do not need to look at any astronomical objects in order to characterize it. All that is needed are darks and flats. A dark frame is one where the CCD is exposed for a given amount of time, but with the shutter closed, so that no light reaches the detector. A flat frame is one where the telescope is pointed at a uniformly illuminated field, so that each of these photons reaching the detector are equally distributed across the chip.

Data needed

1.6 darks

Take 20 dark frames for each exposure time listed below:
t = 0.05sec, 0.1sec, 0.5sec, 1sec, 5sec, 10sec, 30sec

1.7 dome flats

There are two flat field sources you will use to get this data. The first is a white cardboard square that is taped to the inside of the telescope dome. There is an incandescent lamp for you to use to illuminate the “dome flat”. Point the telescope at the illuminated cardboard and take 20 frames for each exposure time listed below:

t = 0.05sec, 0.1sec, 0.5sec, 1sec, 3sec, 5sec, 7sec, 10sec, 15sec

If the 15sec exposure is not obviously saturating (i.e. most counts are below 15,000 ADU), then do another set at a longer exposure time. The goal here is to get a group of frames spanning the dynamic range of the detector.

1.8 sky flats

The second way you will use to get flats will be by taking images of the sky immediately after sunset, before the stars begin to come out, but without the sun present. Point the telescope overhead at the sky and following the same procedure above. These "sky flats" will probably be truer flats than the “dome flats”, since the illumination by the lamp at some angles could cause non-uniform lighting on the cardboard. You may want to experiment with different ways of illuminating the cardboard flat.

You now have all the data needed for this lab!

Analysis

Note: There will be a separate handout describing the IRAF commands needed for the following analysis.

1.9 Making bad pixel mask

Use IRAF to average all the dark frames together of a given short exposure time from your data set. Look at a histogram of the pixel values from this averaged dark frame. You will see an obvious grouping in the distribution. Pixels that deviate from this grouping are bad. You can assign a cutoff value (ADU level), above which the pixels you see are not part of the bulk distribution. Copy this averaged frame of darks to another frame that you will modify. With IRAF, you can modify pixel values which lie inside some range of values, and set them to another value. In this way you can manipute pixel values so that all your “good” pixels have values equal to 1 (ADU), and all your “bad” pixels have values equal to 0 (ADU). No you have constructed a mask for pixels that have abnormally high dark current (“hot” pixels).

Next, average together your flats of each given exposure time. Examine the histograms in each case. As before, you will see an obvious grouping in the distribution of pixel values. Pixels that have values below this grouping are ones that are minimally responsive (if at all) to light. Construct a mask of these bad pixels using the same technique above. This is your mask of “dead” pixels. (ones that do not respond to light normally)

By multiplying these two bad pixel masks together, you can make a mask that identifies both hot and dead pixels on the array. How many bad pixels have you flagged? What percentage of the whole array is it? Print out your pixel mask image. Are there any obvious clumps on the array where you will want to avoid? Since good pixels have values of 1 and bad pixels have values of 0, you can mask these bad pixels from any image you take while preserving the values of good pixels using image multiplication.

1.10 Measuring Dark Current

Average each group of darks at a given exposure time. Examine the histogram of pixel values for each averaged frame and note the range in pixel values for the bulk distribution. Find the mean of the pixels that lie inside this bulk distribution. Plot the mean vs. exposure time. Fit a line to this plot, and calcalute the slope. This slope (ADUsec) is the dark current. How does is compare to the factory value? (see handout)

1.11 Estimating Read Noise

For your shortest exposure data set of darks, find the average and standard deviation of each pixel in the 20 frames you took. IRAF will create an average frame and a sigma frame here. Look at the histogram of the sigma frame. This is the noise of each pixel across the array from 20 frames you took. Again, you'll see a bulk distribution, from which you can set limits to find the mean of the pixels in the distribution. This mean is one estimate of the readnoise, since it corresponds to images taken at very short exposure times where dark current should be negligable. Compare your value to factory value.

1.12 Measuring the System Gain

Take each group of flats for a given exposure time and make and average frame and a sigma frame (see above). Find the mean of each of these two resultant frames (for each exposure time). As before, you will want to find the mean of values that lie inside the bulk distribution you see from the histograms. You will end up with a mean signal and sigma value for each different exposure time. Plot the signal vs. sigma^2 for each exposure time and fit a line to these data points. The gain is the inverse slope of this line (e^-ADU).

Do this for your dome flats and sky flats. Which flats have less scatter and/or agree better with the factory value for the gain?