INTRODUCTION TO CCD IMAGING

SYNOPSIS: In this lab we will learn about some of the advantages of CCD cameras for use in astronomy and how to process an image.

EQUIPMENT: Computer with internet connection.

LENGTH: One lab period.

The first observations of the sky relied on the naked eye. It consists of photo-receptors called *rods* and *cones* that send signals to the brain when they are stimulated by photons. *Rods* are the more sensitive of the receptors but they only register in shades of gray and are concentrated along the periphery of the retina. *Cones* are less sensitive to light, they register across the visible color spectrum, and are concentrated in the center of the retina. The cumulative effect of these signals creates the images that make up the world around you.

Unfortunately our eyes are pretty inefficient for astronomical purposes. A dark-adapted eye usually requires between one and 10 photons to trigger a *rod* (the more sensitive receptor) and several *rods* must be triggered in order for a signal to be sent to the brain. This means the eye does not process all of the light it receives (in effect, only ~1% is registered). Our eyes are also limited in the wavelengths of light they can receive (only from ~400nm to 700nm).

Photographic film came into use around the end of the 19th century. While it is no more efficient at processing light then the naked eye (only ~1% is typically registered by the film) it does have several advantages. The biggest of these is the ability to expose the film for a long period of time. The amount of time between signals being sent to the brain from our eye is fixed (no matter how long you stare!) while the use of photographic film allows you to adjust the exposure time to suit your needs. Photographic film can also be manufactured to cover a wider range of wavelengths than our eye (from ~300 to 1100nm).

Charged-coupled devices (CCDs) were invented at AT&T's Bell Laboratories in the 1960s. They were originally intended to be computer memory components but it was soon realized that they had the side effect of being extremely sensitive to light. This discovery led to their eventual use as detectors in astronomy. They have several advantages over other imaging detectors.

•**Sensitivity** - CCDs have particularly high **quantum efficiency** (~60 to 90%). Quantum efficiency (QE) is a measure of number of incoming photons that are actually detected by the device being used:

$$QE = \text{\# photons detected} / \text{\# incoming photons}$$

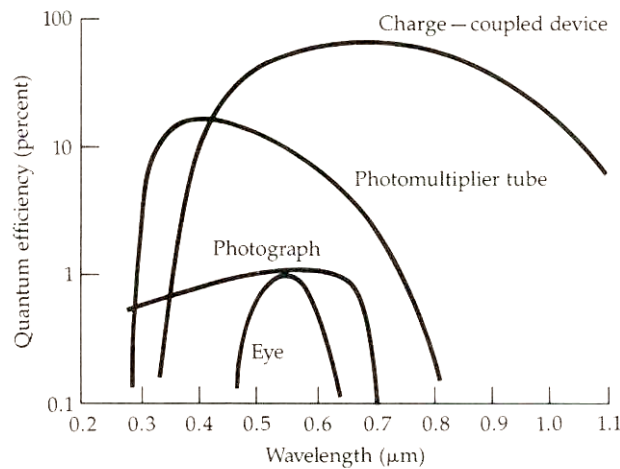Therefore the QE of the eye and photographic film is ~1%.

FIGURE 9–14 Response curves of the quantum efficiency (QE) of a charge-coupled device (CCD), photo-multiplier tube, photographic plate, and the human eye. *(J. Kristian)*

•**Linearity** - Twice the amount of light produces twice the signal value in a CCD, while the behavior of photographic film (as well as the eye) is much more complex; it is therefore much easier to analyze the results in a quantitative manner.

•**Dynamic range** - The CCD detector can accommodate a far larger range of intensity than film; useful information on both bright and dim objects can be obtained simultaneously in the same field and at the same time.

•**Threshold** - While photography and naked eye viewing requires a certain minimum of light before anything at all is recorded, CCDs respond to any level of light reaching the detector.

•**Digital processing** - Photography is a form of "analog" data, exhibiting a continuous range of gray-scale brightness that does not lend itself well to quantitative analysis. Further, development of film takes time and noxious chemicals, so you are unable to see your results (or worse, mistakes) until well after the fact. CCDs produce "digital" data: the image is acquired directly by a computer and the information is in the form of an array of digital values, ready for immediate analysis and processing.

•**Coverage** – CCD detectors can observe in a much wider range of wavelengths than photographic film or the eye. While the eye can only see in visible wavelengths and photographic film can see visible and some infrared, CCDs can see from the x-ray range to the infrared (with some loss in the ultraviolet).

Getting Started

You will be looking at a series of CCD images on the computer. A widget has been designed to help you view and manipulate the images. Here's how to get your computer up and running:

(1)   Bring up a terminal window (You can do this by right clicking anywhere on the screen, and then select *Tools*, then *Terminal* from the dialog box)

(2)   In the terminal window type: **cd /scratch/ASTR1030**

(3)   Type: **idl**

(4)   You are now in the IDL environment. At the prompt (which looks like this: IDL>), type: **.compile ccdlab**

(5)   To run the program type: **ccdlab**

You should now see a box with a series of buttons. Each button corresponds to an exercise in this lab. When you are finished with the lab, you can exit the widget by clicking the *Exit* button. To exit IDL, you will need to type **exit** at the IDL prompt.

Most of the work you will be doing will be directly on the pop-up widgets. However, some data will be displayed in the IDL window. Be sure to adjust your display so that you can see both the widget window and the IDL window.

Part I. Linearity

In the introduction we described linearity as an advantage to using CCDs over other image detectors. However, a CCD only has a linear response over a certain range of counts. Imagine the CCD as a collection of buckets. If you then began filling the buckets with water, you would be able to keep an accurate account of the total amount of water they have received until they are completely filled. Once they are full, any additional water would flow over the sides and you would no longer be able to keep accurate track of the total amount of water that has been received. This is also true when you try to gather light with the pixels of a CCD. Each pixel can only hold a specific number of photons. In order to make sure nonlinear pixels do not show up in your science images, it is important to know what this range is. We will now test the linearity of the CCD on the 24in Telescope. We will do this by graphing the counts from a series of dome exposures taken for different lengths of time.

I.1   Select the button called *Testing CCD Linearity*.

I.2   You should now see a display screen with several buttons below. Use the droplist at the bottom left corner to select which exposure is being displayed.

I.3   Using the *Read Pixel Values* button, find a uniform area in the image and record the counts in the text box labeled *Counts*. If you are satisfied with the value you entered into the *Counts* box, click on the *Save Counts* button. Once the value has been saved it will disappear from the text box.

NOTE: The read pixel command displays the x and y coordinates as well as the number of counts for the current cursor position. This information will be displayed in the IDL window NOT on the widget window. You can record values by clicking the left mouse button and exit the read pixel mode by clicking the right mouse button.

Repeat this for each image in the time sequence, making sure you record the counts from the same pixel location from image to image.

I.4   Use the plot command to display your points. Describe the plot and print a copy for your lab report. At what count value does the CCD become nonlinear? What does this tell you about the exposure times you should use when taking your science images? Explain.

I.5   The *Exit* button will return you to the *Introduction to CCDs* display window.

Part II.   Plate Scale

In order to do a quantitative analysis of the angular size of images captured by the CCD, we need to determine the vertical and horizontal field of view of the chip (they can be different). You will use the plate scale to determine this. Plate scale is often given in arcseconds/pixel or arcseconds/mm. You will use two images to determine this. In one the telescope drives were turned off briefly, allowing a bright star to drift and leave a trail (horizontal). In the other the telescope was driven a particular distance north to create the same effect (vertical).

II.1   Select the button called *Finding Plate Scale*.

II.2   Display the north-south star trail. Use the *Read Pixel Values* button to determine the center location for the star at each end of the trail. Record the x and y coordinates in the appropriate text boxes.

II.3   Click the *Calculate* button to find the plate scale in arcseconds per pixel. Record this in your lab report. What equations were used in this calculation?

II.4   Repeat for the east-west image.

II.5   Do your plate scale values agree? If not, explain.

II.6   If each image is 1530 by 1020 pixels across, what is the field of view of the CCD in arcseconds?

II.7   Given the field of view of the CCD, could you fit the Orion Nebula (M42) in a single exposure? How about the Whirlpool galaxy (M51)? The Andromeda galaxy (M31)? If not, how many images would be necessary to create a mosaic that would cover the extent of the object. You can find the angular size of these objects in the SBO catalog.

Part III. Noise Reduction

You will soon find that images acquired from a CCD do not look quite like you would expect. There will be various forms of distortion in the image that are all considered "noise". It will be your task to eliminate this noise and bring out the true image.

III.1   Select the button called *Noise Reduction.*

You should now see a draw window with several buttons below. On the left you will see a list of the CCD frames that you can display in the window. The first four (Bias, Dark, Flat, Raw Image) are the CCD frames taken with the camera on the 24-inch telescope. The entries labeled *Processed Image #* are where you will store the CCD images you create by combining existing frames. Once you select a frame, you can then use the buttons labeled *Display CCD Frame, Read Pixel Values, and Print Image.* You will also notice that after you select a frame, the text in the label box below the list of frames will change to match your selection.

III.2   Display the raw image and describe it. Note: You can change the color table used for display by clicking the *Change Colors* button. This may help you to see other features in the image. Print a copy of the raw image for your lab report.

There are several sources of noise in the raw image. Some are shared with other detectors like photographic plates:

1. Cosmic Rays – energetic particles that **<u>randomly</u>** hit the CCD
2. Sky noise – noise associated with ambient light reflected in the atmosphere, haze, and/or pollution

while others are intrinsic to CCDs (electronics creates heat creates noise):

1. Read noise – Noise inherent in the transfer process from the chip to the computer. It consists of two parts: conversion of the analog signal to a digital number and addition of electrons from the electronics. Read noise is usually expressed as **electrons per pixel**.
2. Dark current – Thermal noise. We try to eliminate as much of this as possible by cooling the CCD. Dark current is usually expressed as **electrons per pixel per second**.
3. Hot pixels – Noise in the chip.

We can remove most sources of noise by combining the raw science image with one or more of the following CCD frames:

1. Bias – A short (**~0 second**) exposure with the shutter closed
2. Dark – An exposure taken over **some time period** with the shutter closed
3. Flat – An exposure of a uniformly illuminated surface, such as the "great white spot" on the dome housing the 24-inch telescope

III.3   Display a bias frame and using the *Read Pixel Values* button to record several values (at least 10) across the chip. Average these values to determine the average bias on the CCD chip.

III.4   Is the length (i.e., exposure time) of a bias frame dependent on the exposure time of your raw image? Why or why not?

III.5   Print and describe the dark frame.

III.6   Is the length of a dark frame dependent on the exposure time of your raw image? Why or why not?

III.7   Is it necessary to use both a dark frame and bias in your noise reduction? Explain.

III.8   Now with the bias, the dark, or both use one of the procedures (add, subtract, multiply, divide) to remove some of the noise from the raw image. Store your data by selecting one of the processed images from the droplist (You can store up to four processed images so be sure to note which image number you used). Report the procedure used and describe the resulting image.

III.9   Display the flat field and describe it. Compare it to the raw image. Do you see any similarities?

The numerous small circular features (called 'dust donuts') are out of focus dust specks. The overall circular appearance of the image is caused by vignetting (NOT by the shape of the white spot on the dome wall!). Vignetting refers to the fact that some of the light is being blocked within the telescope.

III.10   Use one of the procedures to take the flat field out of the image you created in step III.7. Report the procedure used and describe the image afterwards. Print a copy of this image for your lab report. (Note: Some processing has already been done to the flat field image. We have removed some of the noise using the dark frame and/or bias frame, and the flat field has been normalized so that the count values are between 0 and 1.)

III.11   Is the image now free of noise? Explain.

Part IV. Follow-up Questions

IV.1   Our biases, darks, and flats were actually the average of three. Why would this be an advantageous thing to do?

IV.2   If you are using different filters, do you need to take a dark frame for each one? Flat field for each one? Bias frame for each one? Explain (HINT – think about how the respective frames are obtained)

IV.3   How do you remove the effects of a cosmic ray hit in your science (raw) image?

IV.4   Professional observatories often take only bias frames. How can they do that and why would it be advantageous?

IV.5   Would you need to cool a CCD on an instrument in space?