Name____________________ Class______

Charge-Coupled Devices - CCDs
(or: how my digital camera works)

How it Works:

1. A wafer of silicon crystal has “gates” grown onto it. The gate is one pixel. Our cup will be one pixel in this experiment.

2. A photon (packet of light) strikes the gate and causes an electron to form inside the gate. So we drop a bean into the cup when this happens in our simulation.

3. The gate stores the charge. Each pixel collects a supply of electrons (beans) that directly related to the number of photons that have hit the gate.

4. A CCD is composed of many rows of the these gates each of which can hold a maximum number of electrons.

5. Once the gates have been exposed to the photons, a control circuit causes each gate to transfer its contents (the beans) to its neighbor.

6. The last gate in the row dumps its electons or charge into an amplifier which converts it to a voltage.

7. These sequences of voltages are then stored digitally in some form of memory.

Procedure: Set up your 25 cups in a 5 by 5 grid representing the grid of pixels on a CCD. Make sure you have enough beans to fill at least 6 cups. Have a piece of paper, and a baseball close by for later. Each bean represents an electron generated by a photon hitting a pixel’s gate. Using your supplies, complete each scenario below and try to answer the questions!

Scenario 1:
A star emits 3 photons per second, and that light is spread between 3 adjacent pixels.

1. In this ideal scenario, how will the CCD look after 1 second?
2. After 2 seconds?
3. After 3 seconds?
4. In the real world how will the light be collected? What causes this difference? What role does the atmosphere play in determining how we detect the star?

5. Let's also think about what is going on around the star. Let's say we are observing the star against very dark background. How will this be reflected on the CCD?

Scenario 2:
Lets clear out our CCD and now suppose we are now observing a star that emits 3 photons per second, but there is a lot of atmospheric distortion, so this light is spread between four adjacent pixels, creating a square. Also suppose we are observing the star against a moderately bright background that emits 1 photon per second per pixel over the entire field of view.

6. How will the CCD look after 1 second?

7. After 2 seconds?

8. After 3 seconds?

9. After 10 seconds?

Scenario 3:
Finally, lets clear out our CCD and observe a very bright star which emits 20 photons per seconds over a 4 pixel square. Let's say the background is minimal (1 photon per second per pixel), but there is a dim star emitting 2 photons per second in a pixel adjacent to the bright star. Our exposure time will be 60 seconds. Fill up each cup with the appropriate number of beans.

10. What happens to the pixels that pick up photons from the bright star?

11. What about the pixel for the moderately bright star?

12. How might this cause difficulty for observers?

13. Lets say you've finished a 10 second observation of a star with a moderately bright background. How will the CCD record the information contained in each pixel in order to quantify and save it?

14. Imagine you are moving the beans from cup to cup while wearing mittens. What might happen?

<u>Read Noise</u> – is the natural error introduced to the values read-out by the CCD itself. This noise comes from both the CCD and the process of converting electric charge into the digital signal that is recorded.

Scenario 4:
Next, we cover the CCD with a lens cap (or in this case, some paper). Even if photons hit the cap, they won't penetrate to the gate and create an electron. Bounce some bean off the paper to test it out.

15. What is the electric current we should measure in this situation?

16. Examine the image at right. It is taken after a 0 second exposure. What do you notice?

<u>Bias</u> – caused by the spontaneous creation of charges within the silicon, which are then swept into pixels and read.

<u>Dark Current</u> – is a direct result of the temperature of the CCD. If we cooled the CCD down, the dark current would also go down. This is why most astronomical dectectors are cooled! To correct for this effect, we take images such as the one at right during observations and subtract them from our data and observations.

Scenario 5:

Our CCD will now come in contact with a slow moving cosmic ray. Place the baseball on top of one of the cups and repeat procedure Scenario 2. Using the cup with the baseball on it as one of the adjacent 3 cups. Once finished, use this same baseball to simulate another cosmic ray coming in much faster and hitting a random pixel in your grid.

17. What happens to a pixel if it comes in contact with a slow-moving cosmic ray?

18. What happens if the cosmic ray is moving really fast?

19. On Earth, energetic cosmic rays are usually stopped high in the atmosphere. The ray interacts with atmospheric molecules and decays into so-called secondary cosmic rays. These can still affect CCDs, and are partly to blame for the degrading of CCDs over time. If one cosmic ray destroys a pixel every 3 months, how long until you would find our CCD Is no longer usable?

20. In this exercise, we have assumed that one photon striking the silicon will create one electron in the pixel. This means our **gain** is 1. If we were very starved for photons, we might set a higher gain. If we had a gain of 10, this would mean one photon creates 10 electrons in a pixel. This increases the signal which is read out. When might it be useful to have a high gain? Why?

21. When would high gain be bad?

Cleanup: Make sure all your cups are stacked neatly and your beans are put back in the plastic bag to return. Baseball and piece of paper will also be returned.