How Charged Coupled Detectors (CCDs) work and their use in Astronomy – Scott Mayle

Purpose

Imaging is essential to the field of astronomy. Therefore it is important for students in astronomy to understand modern imaging techniques. Most modern imaging is done with charged coupled detectors or ccd's. This lessons is designed to show, at a basic level, the fundamental science and engineering necessary for a ccd to operate and how this technology has influenced the field of astronomy. Furthermore this lesson also attempts to go beyond the explanation of how the device work and show some of the complexity involved in applying a science to a working technology which is often hidden in commercial applications (ie. digital cameras and cell phone cameras).

Overview

The first part of the lesson is a lecture that develops the science and engineering behind how a ccd works and operates. The lesson starts by reviewing basic properties of light (wave and particle natures) and then proceeds with a brief review of the Bohr atomic model with energy levels and photon induced electron level transitions. From here an explanation of how the energy levels shift as Bohr atoms are brought near each other is given, leading into an explanation of basic band theory (the different band structures between conductors, semiconductors, and insulators). From here a basic understanding of how photons can induce free charge in semiconductors should be developed. The lesson continues with a discussion of how the materials are engineered (again at a basic level) to be transformed from raw materials into a useful detector. This explanation should include how to isolate the charge produced from an incident photon, how to get spacial resolution, and how to get color.
Once an explanation is given of how a ccd works, the focus is shifted to the importance of imaging in astronomy and the advantages and disadvantages of different methods used to convey information about astronomical objects including written word, illustrations, film photography, and digital (ccd) photography. This second part of the lecture involves utilizing a simulation of a ccd and a guided activity work sheet. The simulator allows students to see the affect of different parameters that must be tuned to properly work a ccd and demonstrates the added complexity needed to implement science into a usable device.

Student Outcomes

Students should be able to demonstrate the importance of imaging in Astronomy.
(IL SS 13A 4C)
Students should be able to distinguish the advantages and disadvantages of the different imaging techniques.
(IL SS 13A 4C)
Students should also be able to describe the basic mechanisms and science behind of how ccd's works.
(IL SS 12C 5 and 12D 5)
Students should be able to utilize a simulation to see how important parameters, e.g. pixel density, exposure time, bias voltage, affect the overall image quality
(IL SS 11A 4a-c)

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Time
Three class periods of approximately 45 minutes.

Level
Senior or Junior level high school students in astronomy who have completed an introductory chemistry class.

Materials and Tools
- A computer with projector to be used along with the lecture to help demonstrate the operation of a ccd with: http://astro.unl.edu/classaction/animations/telescopes/buckets.html
- Computers uploaded with Netlogo and the ccd simulation (as created by S. Mayle)
- Guided simulation activity work sheet

Preparation
Ensure that Netlogo is working on the computers and that the students have access to the simulation file. If not comfortable with the simulator or Netlogo it would be useful to go through the guided activity on one's own before attempting with students.

Prerequisites
N/A

Background
Students should have knowledge of basic high school chemistry and physics. In particular students must have a understanding of the electromagnetic spectrum and the particle nature of light and a thorough understanding of the Bohr model of the atom.

Teaching Notes

I like to think that this lesson plan is divided into three distinct parts.

The first part describes how the ccd works and has two subsections. The science behind the device and then the engineering necessary for the device to be useful to astronomers. The science of the device starts by reviewing what basic physics/chemistry is necessary leading up to and including the Bohr model, then proceeding to a more applied scenario of the Bohr model with multiple interacting atoms and focusing on how this affects the simple Bohr energy levels. This then very easily leads to the development of simple band theory. The Bohr energy levels become slightly shifted and with a large (macroscopic) number of atoms the energy levels start to overlap and form bands. The structure of the bands gives the three types of materials conductors, semiconductors, and insulators. Conductors do not allow for discrete charge separation when hit by a photon and insulators have too large of an energy gap for an incident photon to create a free charge. This means that semiconductors are ideal for ccd detectors. This leads to the necessary engineering to make the device. A simple piece of semiconductor can not be used as a light detector and modifications need to be made for a useful device. First the charge produced by an incident photon must be collected to be a useful signal. This is done be applying an electric field or voltage to the semiconductor and collecting the charge in a separate region of the device. This device is now simply a light detector and does not give any spacial information, or what light came from where. To include this into the device, discrete sections, pixels, are created. Finally to include color imaging one must add red, blue, and green filters over the pixels. A quick discussion about Bayer masks could follow.

The second part of the lesson is more of a discussion about imaging in astronomy in general. This part of the lesson is started by asking students to either write a quick description from a picture of some stars or vice versa and have students compare their results either as a class or with other students. This is to demonstrate both the difficulty of this technique and the inherent problems with reproducibility. The next part of the discussion involves film photography (note a brief explanation as to how film photography works might be necessary) and its benefits and detriments. Students should be asked to identify these advantages and disadvantages to film photography and leading questions should be used to continue the discussion where necessary. Hopefully the discussion the disadvantages to film photography should lead into advantages to digital photography. Main advantages that should be highlighted are the reproducibility of the images, speed of image processing and the mobility associated with digital imaging (notably no satellite imaging would be possible without digital images) and most importantly the much greater efficiency of detecting single photons.

The final part of the lesson involves the ccd simulator in Netlogo. It might be useful to explain the part of the simulator in front of the class and explain the purpose of using the simulator to show some of the added work and forethought necessary to implement ccd technology to get a usable image. Students should then be able to work through the work sheet on their own or in small groups depending on the availability of computer and the Netlogo software.

Assessment

During the presentation portion of the activity, students should be informally assessed to make sure that they are following and understanding the information. Specifically students could be asked to give input with the following questions and further pushed for involvement with leading questions following these if no one answers:

What are the draw backs to using a Bohr atom as device that can turn light into a usable electric signal?
What does can a ccd/digital camera do that a Bohr atom cannot do?
What might happen if we consider more than one Bohr atom near each other?
What band structure (of the three conductor, semiconductor, and insulator) would be best suited to a ccd detector?
How might we isolate the charge produced by an incident photon on a semiconductor to be used for an electrical signal?
How might we modify a piece of semiconductor to get some information about where the photons come from?
How can we read the charge signal from each pixel?

How can we get color images from a ccd?

Following this last question if no one answers ask if anyone knows how colors are produced in TVs.

After illustration/written description activity poll class as to problems with techniques.
After explanation about film photography ask about advantages or disadvantages.
Ask about advantages and disadvantages of ccd or images produced by ccds.

Formally students can be given an exist slip or short quiz at the end of class involving the lecture to make sure they have comprehended the explanation of how a ccd works and its advantages used in astronomy.

For the simulation part of the activity the students will be given a packet with lab like instructions and questions designed to help the students understand how to use the simulation. At the end of the instructions further questions will be given regarding different set ups and asking students to try and get the best image possible by playing with the given parameters or suggesting something to be added to the simulation.

Additional Information
These are links to:
Netlogo simulation worksheet

https://docs.google.com/document/d/1M_Dgi5IltRh1xS3Bjwe7WzkTnOEb2qEYzJ3ToQNtpaM/edit?pli=1

Sample Exit slip
https://docs.google.com/a/d219.org/document/d/1nYeakCTO2K-oG8zXkdJy5n_hi20vQjzVrtR1C9cPCI0/edit?hl=en_US