Detectors in Astronomy
How to describe light?

Particles (photons) that travel in straight lines (optics)
waves of electromagnetic energy (things like diffraction)

How about this>>> 

Light is electromagnetic radiation. Moving charges generate self sustaining electric/magnetic fields that move away from the source object(s).

Light can be described with a wavelength and a frequency. 
\( \lambda \nu = c \) (c=speed of light)
\( E = hc/\lambda \)
Astronomical Observations

- **What do you want to collect?**
  - Photons coming from distant astronomical object
  - Problems: distance. Intensity of photons falls off as $1/r^2$. So few photons, atmosphere (in motion, absorbs and scatters photons), extraneous sources of photons

- **What is the process?**
  - Observations
  - Reduction/calibration
  - Analysis

- **Telescope**
  - Light bucket – help collect more photons
  - Brings light from distant objects to a focus

- **Detector**
  - Acquire data (photons) with high efficiency – don’t want to lose precious photons
    - Bad detector can make a big telescope small
    - Good detector can make a small telescope “big”
  - Modern times – form that can be analyzed by a computer
  - Different kinds of detectors
    - Position sensitive
    - Position insensitive – do not record position of photons

- **Calibration/Analysis**
  - Computerized
The Earliest Detector used for Astronomy: The Retina

Eye/brain: complete system of telescope, detector and processor
Eye – is the telescope (refracting)
• Retina – light sensing portion – detector(chemical)
  • Cones
    • Color (3 types of cones), detail
    • 7 million
    • Cluster near axis – 1000 per sq. mm
  • Rods
    • 100 million (2 microns wide)
    • All over retina
    • Low light
    • Inverted vision to see faint objects
• Located on back side of retina – lose 50%
• Reusable
  • Integration time – 100 -200 ms
• Overall QE – 15 % at 5000 Å
• Resolution 80 arc seconds (1/10th separation of Mizar and Alcor)
• Lined with black pigment
• Example of position sensitive

1 inch x 1 inch x 0.9 inch
Retina: about 40 mm wide
focal length – 16 mm, “aperture” varies 7-1.5mm
The Retina in Astronomy

- Early classification of stars by brightness
  - Greeks, Romans, and other early civilizations
  - Constellations
  - Trace tradition of naming stars
    - Example: Alpha Orionis (Betelgeuse)
    - Jupiter (Zeus)
- Early observations of positions of stars
  - Planets – means “wanderer”
  - Things like Aurora
- Early observations of variable stars
  - Largely ignored
  - Earth-centered universe
- The Milky Way
The Retina and the Telescope

- Galileo – did not invent the telescope, but he did improve it - 1609
- 1610– Galileo published his observations with his telescope
- Newly visible stars – example Pleiades
- Jupiter and its moons
- Mountains and craters
- Rings of Saturn
Galileo’s drawing of the moon

Galileo’s observations of sunspots

Galileo’s observations of Saturn
The Seven Sisters
Huygens’ observations of Saturn’s “phases”
Toscanelli’s observation of a comet
Photographic Emulsions

• Started being used around time of Civil War (primary astronomy detectors from 1880-1980)
• Chemical process
  • Silver halide crystal
  • Spread in an emulsion over film or glass plates
  • Crystals come in different sizes - sensitivities
    • Most sensitive crystal about 1 micron wide
  • Light (photon) creates defects in crystal
  • When developed, crystals with defects break down to metallic silver
• Irreversible – can’t reuse
• Nonlinear –
  • once enough defects in crystal, more light won’t make crystal more developable.
    • Number of developed grains is not directly proportional to number of captured photons
  • Developed grains can shadow other grains again leading to undercounting of photons
  • Also defects can “heal” themselves, not good for long exposures (i.e. low light levels in astronomical images
• Crystals not distributed evenly (grainy)
• Example of position sensitive

QE: ranges from 0.5% to 4%
Photographs in Astronomy

- **1840** – Henry Draper captured the first daguerreotype of the moon
  - Highly polished, iodine-fumed silver plate
  - 20 minute exposure

- **1882** – David Gill of Royal Observatory took a photograph of a comet and noticed lots of fainter stars.
  - Devoted 5 years of his life to taking pictures of the southern sky
  - 612 exposures, 30 minutes each
  - Cataloged 454875 stars

- Advantage → gathered light, the longer the exposure, the more light gathered.

- British astronomer Isaac Roberts revealed the spiral nature of the Andromeda galaxy – start of realizing that our galaxy was not the only one.

- **1850s** → spectroscopy

- Main detector in astronomy until the 1980s.

- Emulsion placed on glass plate of various sizes – light tight box – attached to camera and then telescope
Drawing of Eta Argus (now Eta Carinae)

Approximate distances and magnitudes of the principal stars and nebulae surrounding Eta Argus. Taken at Hobart Town, February 1871.

Francis Abbott, 1871, Tasmania

Early Photograph of Eta Argus (now Eta Carinae)

Henry Russell, 1891, Sydney Observatory
The Digital Age

- Photomultiplier Tube – position insensitive
  - Used to precisely measure the brightness of stars at different wavelengths
  - Photoelectric effect
  - Output – voltage dependent on number of photons striking the photocathode
  - Voltage – Analog to Digital converter – binary number

- Proportional counters – position insensitive
  - Geiger counters
Photomultiplier Tubes
What is a CCD?

- CCD = Charge Coupled Device
  - Replaces photographic film and photomultiplier tubes
  - Consists of a thin silicon wafer divided into thousands (or millions) of tiny light sensitive squares (photosites). Each photosite corresponds to an individual pixel in the final image.
  - Turns light (photons) into electrons (charge) – photoelectric effect – analog device
  - Each photosite has a positively charged capacitor that attracts the electrons.
  - Uses movement of charge within the device
  - Output – voltage from each photosite dependent on number of photons that penetrated the silicon surface
  - Output voltage converted to a digital signal (electronics)
  - Instead of taking a picture – records an image

- Most astronomical instruments today use CCDs
  - Astrometry
  - Photometry
  - Imaging
  - Spectroscopy
Developed in 1969 by AT & T’s Bell Labs
Each photosite has a capacitor (or electrode) etched on it – acts like its own individual “camera”.
What does a CCD look like?

CCDs are manufactured on silicon wafers using the same techniques used to manufacture computer chips. Scientific CCDs are very big, only a few can be fitted onto a wafer. This is one reason that they are so costly. Also, the wafers are very fragile.

The photo below shows a silicon wafer with three large CCDs and assorted smaller devices. A CCD has been produced that fills an entire 6 inch wafer! It is the world's largest integrated circuit.
How does a CCD work?

- At beginning of exposure
  - Capacitors are positively charged and disconnected (bias)
  - Shutter is opened
- Photons enter silicon crystal lattice and are absorbed – raising some electrons from a low-energy valence band to a high energy conduction band (in other words, some electrons are liberated from their silicon atoms)
- Electrons are attracted to nearest positively charged capacitor – partially discharges capacitor (changes voltage).
  - Degree of discharge is proportional to number of photons that hit each photosite during the exposure
- At end of exposure, the electrons at each photosite are passed to a charge-sensing node, amplified, and passed to read-out electronics to be digitized and sent to the computer.
More details of a CCD

- For silicon – energy difference between valence (tightly bound electrons) and conduction band (free electrons) is 1.1 ev.
- Only photons with energy greater than 1.1 ev will be detected (11000 Angstroms, in the infrared).
- At shorter wavelengths, silicon becomes more reflective, so photons never enter silicon crystal. Blue cut off is about 3000 Angstroms.
- CCDs are linear (# of electrons is proportional to number of photons) as long as you don’t have too many electrons. Charge can leak from one photosite to the next if there are too many electrons → bleeding.
- Photosites are arranged in rows and columns. Size of photosites varies.
Basic Structure of a CCD

Rows and columns make an array of photosites

Photons \rightarrow \text{electrons}

Electrons accumulate in photosites (voltage)

One column for reading

Amplifier

Analog to digital converter (voltage to numbers)
CCDs come in different “configurations”

- Back Illuminted and front illuminated
- Number of pixels
  - ST2000XM 1024x1023 pixels
    - Each pixel is a 7.4x7.4 micron square
    - Size is 9.2 x 9.2 mm
  - Ap7p 512X511 pixels
    - Each pixel is 24 microns
    - Size is 12.3x12.3 mm
  - Alta U47 1024X1024 pixels
    - Each pixel is 13 microns
    - Size of 13.3x13.3 mm
- Resolution!
- Bigger is more expensive
Santa Barbara (SBig) ST2000XM

Most common type of CCD

Front-illuminated CCD
1) Silicon layers on bottom
2) Insulating layer
3) Electrodes on top

**How it works:** Incoming photons strike the silicon. If the photons have the right energy, they liberate electrons from the silicon atoms. The electrodes (capacitors), called “gates”, are given a positive charge and attract the freed electrons. At the end of each exposure, each gate has a remaining net charge that indicates how many photons struck that region of the silicon.

**Front Illuminated CCD** – disadvantage is a lot of reflection of photons by the gates (capacitors) – QE ~ 40-60%
Thinned Back-side Illuminated CCD
Increased blue sensitivity

Strength of electric field proportional to $1/r^2$

Anti-reflective (AR) coating

- p-type silicon
- n-type silicon
- Silicon dioxide insulating layer
- Polysilicon electrodes

The silicon is chemically etched and polished down to a thickness of about 15 microns. Light enters from the rear and so the electrodes do not obstruct the photons. The QE can approach 100%.

These are very expensive to produce since the thinning is a non-standard process that reduces the chip yield. These thinned CCDs become transparent to near-infra-red light and the red response is poor. Response can be boosted by the application of an anti-reflective coating on the thinned rear-side. These coatings do not work so well for thick CCDs due to the surface bumps created by the surface electrodes.

Almost all Astronomical CCDs are Thinned and Backside Illuminated.
Overview

- First, turn the CCD on
- Electrodes on each pixel are given an initial positive voltage.
- Open the shutter
- Photons land on pixels of the CCD
- If they have the right energy, the photons liberate electrons from the silicon atoms.
- The negatively charged electrons are attracted to the nearest positively charged electrode.
- The electrons change the initial voltage on each electrode slightly. This change in voltage from pixel to pixel will become the image.
Getting the Image from the Camera to the Computer—Same process no matter what kind of CCD

After CCD is exposed to light, each photosite has a slightly different voltage that depends on how many photons landed on each photosite.

The Serial Register is used to “read” the CCD voltages.

Includes analog to digital converter, amplifiers, computer.
Reading the CCD

1

2

3

Image shifts down one row
The Bucket Brigade

- Rain (Photons)
- Buckets (Photosites)
- Vertical conveyor belts (CCD columns)
- Measuring cylinder (Output amplifier)
- Horizontal conveyor belt (Serial register)
After each bucket has been measured, the measuring cylinder is emptied, ready for the next bucket load.
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder.
After each bucket has been measured, the measuring cylinder is emptied, ready for the next bucket load.
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.
Eventually all the buckets have been measured, the CCD has been read out.
Charge Transfer (how charges move)

Edge-on view of CCD chip

Etched into surface of silicon

Edge-on view of CCD chip
Charge Transfer in a CCD 5.

How the voltages are applied: clocking pattern.
Charge Transfer in a CCD (how the charges move)

Charge – transfer efficiency → how many electrons are lost in transfer (99.99% efficient per transfer)
Bininning

1x1 Binning → 9 µ

2x2 Binning → 18 µ

3x3 Binning → 27 µ
Saturation – How many electrons can a CCD detect?

- Depends on the structure of the CCD
- Depends on the electronics used
- Two types of saturation
  - Pixel saturation – depends on pixel dimensions
    - Ap7p – 300,000 electrons
    - Alta – 100,000 electrons
    - ST2000XM – 77,000 electrons
  - Electronic saturation – the voltage on each pixel is converted to a binary number (counts) – the electronics of both can count up to 65536 counts ($2^{16}$, 16bit)
    - Gain – number of electrons that get converted to 1 count
Saturation/blooming – occurs when finite charge capacity of the individual photosites is reached, or maximum charge transfer capacity of the CCD is reached.

Result is the overflow of electrons onto adjacent photosites.

Amount of charge that can be accumulated under each photosite: full well capacity
Figure 4

Vertical Overflow Drain Structure

Transfer Gate

Incoming Photons

Full Potential Well

Blooming

Photoelectrons

Drain

Electrostatic Potential
• Linearity
  • CCD is “linear” in its response to photons until it gets close to saturation
  • Linear means number of photons is directly proportional to number of counts
  • Counts × gain = photons

Figure 2
Quantum Efficiency

The number of photons absorbed
The number of photons that actually hit

Even the best CCDs don’t detect all the photons that fall on them, so this number is always less than 1.0.

This number is wavelength dependent, and depends on the type of CCD chip.
Quantum Efficiency ST-2000XM

A “thick” chip (frontside illuminated) – with electronics on the front so the photons must pass through.

Not sensitive to blue light (short wavelength) because electronics absorb the blue photons

Not sensitive to infrared light (long wavelength)

Best response – 5000 Angstroms about 45% of photons absorbed

Compare to your eye – 1%
Quantum Efficiency of Alta
Alta CCD Camera

Ap7p Specifications:

- Chip: SiTe SI-032AB back illuminated
- 512x512 pixels
- Pixel size: 24 microns
- Well depth > 300,000
- Dark count (pA/cm²) 50@20°C
- CTE=0.99999
Calibration

Every image contains:
1) Light from astronomical object
2) Added signal from bias
3) Noise from the electronics
4) Thermal noise
5) Vignetting (includes dust, etc.)
Calibration- Out with the Bad and Leaving the Good (Chap 6)

Step 1:

Defect Correction Map

Each black pixel has the value of 0
Each white pixel has the value of 3

In AIP, under “Calibrate”, load the defect file.

During calibration, will average over the columns on either side of the bad column

Details: pg 165 in book
Bias Frame

Step 2:

A constant “bias” voltage is added to the electrodes (to avoid negative numbers when voltage is converted to numbers).

To measure bias:
• Shortest exposure possible
• Shutter is closed
• A bias frame contains:
  • actual bias level
  • fixed pattern noise
  • extraneous interference
  • readout noise
Step 3: Thermal Noise

Temperature Dependent

- Lower temperature/ lower noise
- Both CCDs can run 40 to 50 degrees C below ambient
- About 5 electrons per pixel per sec (for a 2 minute exposure, that’s 600 extra electrons!)

Stable in a good CCD

Scaleable! Hooray! Don’t have to make a dark frame for every image.

Raw dark frame contains bias – must be removed!
Flat Field

Step 4:

- Nonuniformities between pixels (different quantum efficiencies)
- Vignetting (blocking the light path)
  - Dust
  - Physical things in the way
  - Reflections
- Illuminate CCD with a uniform light source
- Must use same optical configuration as the observation images
- Raw flat contains: photon noise
  - Bias
  - Thermal noise
The Art of Flatfields
Review Calibration Files

- Defect Map Correction
- Bias Frame
- Dark (thermal) Frame
- Flat field
To create your calibration frames

- Take multiple “raw” images for whichever frame you are creating.
- Average each set together to make a “master” calibration frame.
- Set up the Calibration function in AIP
- Select your files to calibrate.
What to do with your calibration frames?

- AIP will deal with the defect map
- Calibration can be set up automatically
- Subtract bias from image
- Subtract scaled thermal frame from image
- Divide by the flat field