Order of Business

1. Homework 2: available on class website, due Wed 2/7
2. Observing Project Part 1 - required weekend reading
   HLCO Observing Manual will be posted before 6pm Friday
3. Questions?
4. Lecture

Today’s topic: Detectors
Text: Chapter 8
Detector Types (UV-optical-IR)

**quantum:**
individual photons interact with detector material

**thermal:**
absorption of photons causes an increase in detector temperature

Bolometers
Detector Characteristics

Dynamic range - range between faintest and brightest detectable sources

Linearity range - range over which response to incident photons is linear

Quantum efficiency - ratio of detected photons to incident photons
The First Astronomical Detector - The Eye

Sketch by William Parsons, Earl of Rosse

HST image
The Eye

Brain automatically corrects for several things:
- inversion of images
- large chromatic aberration
- spherical aberration

Cornea refracts and focuses

Iris controls pupil size = amount of light

Lens focuses onto retina’s light-sensitive cells (rods & cones)

Signal sent through optic nerve to brain for processing
Uncorrected Aberrations

Brain has limited (or no) ability to correct for:

- myopia/hyperopia
- astigmatism (off-round eye)
- color blindness (absence of cone pigment)
- other age-related or disease-related degeneration of the eye
Optical Parameters of the Eye

Primary diameter:
3-4mm (bright light), 5-7mm (fully dilated)

Focal length: ~24mm onto retina

Angular resolution
Theoretical limit: 20arcsec
Typical value achieved: 1-2arcmin
(limited by density of receptors on the retina)
### Detection Characteristics of the Eye

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>peak Q.E.</strong></td>
<td>5% (night vision)</td>
</tr>
<tr>
<td></td>
<td>0.5% (normal vision)</td>
</tr>
<tr>
<td><strong>dynamic range</strong></td>
<td>$10^5$ (instantaneous)</td>
</tr>
<tr>
<td></td>
<td>$10^8$ (total)</td>
</tr>
<tr>
<td><strong>linearity range</strong></td>
<td>N/A - eye is inherently non-linear (logarithmic)</td>
</tr>
</tbody>
</table>

- Retroreflective surface (mirror) in nocturnal animal eyes increases photon absorption by retina ($x6$ in cats vs humans)
- **Fig. 16.6.** Comparison of CIE 1931 and CIE 1978 eye sensitivity functions $P(\lambda)$ for the photopic vision regime. Also shown is the eye sensitivity function for the scotopic vision regime, $P(\lambda)$, that applies to low ambient light levels.

![Graph showing visual acuity vs log L (millilamberts)](image1)

![Diagram of the human eye](image2)
Detection Characteristics of the Eye - but which eye?

- **human eye**
- **butterfly eye (UV+vis)**
- **bumblebee eyes (UV+vis)**
- **UV 375nm**
- **UV 365nm**
- **UV 325nm**
- **IR**
Photographic Plate

glass plate with photographic emulsion

first astronomical image in 1840
widely used from 1879 to mid-1980s

**Pros**
- first objective records of astronomical observations
  (unlike hand-drawn images)
- exposure times could be varied
- quantitative measure of brightness
- relatively cheap

**Cons**
- easily broken
- must be developed properly
- low quantum efficiency
- difficult to calibrate (every emulsion different)
Photographic Emulsion Basics

crystals of silver bromide and silver iodide suspended in gelatin

Ag atoms donate e- to Br or I  
→ Ag⁺ and Br⁻ or I⁻
Emulsion Exposure to Light

incoming photon knocks electron free from I or Br

e- becomes trapped in crystal defect

nearby Ag+ combines with e- → Ag

multiple Ag atoms may become trapped in the same location (depends on number of incident photons in the region)

latent image - clumps of neutral Ag trapped within lattice structure
Developing the Emulsion

developers very slowly convert AgBr or AgI to Ag

pure Ag acts as catalyst, so latent image Ag clumps (>10 atoms) are quickly amplified by factor of $\sim 10^9$

fixer - strips away remaining AgBr and AgI crystals (those with no latent image)
## Photographic Detection Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>peak Q.E.</td>
<td>~2-4%</td>
</tr>
<tr>
<td>dynamic range</td>
<td>~100</td>
</tr>
<tr>
<td>linearity range</td>
<td>N/A - photography is inherently non-linear (logarithmic)</td>
</tr>
</tbody>
</table>

- not all photons will hit crystals
- need ~10 Ag atoms for catalyzation to occur (latent image to develop)
**Photomultipliers**

**Pros**
- first digital records of astronomical observations
- linear response
- decent quantum efficiency
- very precise
- easily calibrated

**Cons**
- loss of spatial resolution
- time consuming observations and calibrations

still used today
(e.g., neutrino detectors)
Photomultiplier Basics

1. photoelectric effect - incoming photon releases electron from photocathode

2. secondary emission - free electron releases additional electrons from dynodes

photoelectric photometer at the Laboratorio di Astrofisica Spaziale, c.1975
Photomultiplier Detection Characteristics

<p>| | |</p>
<table>
<thead>
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</thead>
<tbody>
<tr>
<td>peak Q.E.</td>
<td>10-40%</td>
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<tr>
<td>dynamic range</td>
<td>~1000</td>
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<tr>
<td>linearity range</td>
<td>~1000</td>
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</table>

### Photomultiplier Detection Characteristics

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Photocathode</th>
<th>Input Window</th>
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<tbody>
<tr>
<td>-71</td>
<td>GaAs</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-73</td>
<td>Enhanced Red GaAsP</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-74</td>
<td>GaAsP</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-76</td>
<td>InGaAs</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>Non</td>
<td>Multialkali</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-1</td>
<td>Enhanced Red Multialkali</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-2</td>
<td>Bialkali</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-3</td>
<td>Cs–Te</td>
<td>Synthetic Silica</td>
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Charge-Coupled Devices (CCDs)

Pros
- digital records of observations
  - linear response
- very high quantum efficiency
  - easily calibrated
- good spatial resolution

Combine the best of photography and photomultipliers

CCDs revolutionized astronomy in the 1970s-1980s

"JPL management recognized that scientists should become familiar with the capabilities and unique features of the CCD... Expeditions to various observatories with the new camera system paid off as the CCD performed beyond anyone's expectations. New scientific discoveries were usually made each time the camera system visited a new site."

Janesick & Elliott 1992, ASP Conference Series Vol. 23
Photographic plate image

CCD image with same exposure time
Semiconductors

The photoelectric effect can knock electrons from the valence band to the conduction band, leaving behind “holes”.

- 1.1 ev, silicon
- 0.7 ev, germanium
## CCD Characteristics

<table>
<thead>
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<th>Feature</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>peak Q.E.</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>dynamic range</td>
<td>~few x 10000</td>
</tr>
<tr>
<td>linearity range</td>
<td>~few x 10000</td>
</tr>
</tbody>
</table>

![Image of quantum efficiency graph]

![Image of radiation wavelength graph]
**CCD Characteristics**

**photon absorption length** - distance that photons must travel before ~63% are absorbed by the material

Each absorbed photon releases an electron in the silicon.

Coatings often used to increase sensitivity, especially in the blue.

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**Diagram:**
- **std AR**
- **UV AR**
- **unthinned**

**Graph:**
- **Y passes through CCD**
- **~300μm**
- **~15μm**

**Absorption length (μm)** vs **wavelength (μm)**

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Wednesday, January 31, 2018
CCD Bucket Brigade

Charge is transferred along the detector one row at a time.

Charge from row is collected in the output register, and each pixel is read out and recorded.

Repeats until all pixels have been read and recorded.

Result is a grid of numbers with values related to the total quantity of incident photons on that pixel.

→ brightness only, no color information

\[
\begin{array}{cccccccc}
0 & 2 & 5 & 2 & 0 \\
1 & 5 & 10 & 5 & 1 \\
0 & 2 & 5 & 2 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{array}
\]
CCD Readout Animated

Clocking Parallel Register

white = many electrons

gray = few electrons
Three-phase CCD Structure

pixels defined by electrodes or gates, not silicon chip

amplifier connected to A/D converter, which is linked to computer

gain = \frac{e^-}{counts}