Order of Business

1. Homework 2: available on class website, due Mon 2/11
2. Observing Project Part 1 - questions?
3. Other Questions?
4. Lecture

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

quantum:
individual photons interact with detector material to create signal

thermal:
absorption of photons causes an increase in detector temperature

Bolometers

Wednesday, January 30, 2019
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

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

Brain automatically corrects for several things:
- inversion of images
- large chromatic aberration
- spherical aberration
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: \(~24\text{mm onto retina}\)

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

<table>
<thead>
<tr>
<th></th>
<th>Table Values</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>

### Graphs
- **Sensitivity Function**: Shows the sensitivity of the eye to different wavelengths, indicating higher sensitivity in the blue-green range.
- **Visual Acuity**: Demonstrates the relationship between visual acuity and light intensity, highlighting the role of rods and cones.
- **Retroreflective Surface**: Illustrates how a retroreflective surface (mirror) in nocturnal animal eyes increases photon absorption by the retina, with a $6x$ increase in cats compared to humans.

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*Figure 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.*
Detection Characteristics of the Eye - but which eye?

- **human eye**
- **butterfly eye (UV+vis)**
- **bumblebee eyes (UV+vis)**
- **IR**

UV 375nm, UV 365nm, UV 325nm
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 or 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

\[ e^- \text{ becomes trapped in crystal defect} \]

nearby Ag\(^+\) combines with e\(^-\) \(\rightarrow\) 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

perfect crystals are not wanted here -- defects are necessary!
sulphur impurities often induced
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 negative
## Photographic Detection Characteristics

<p>| | |</p>
<table>
<thead>
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</tr>
</thead>
<tbody>
<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
Photomultiplier Detection Characteristics

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

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Photocathode</th>
<th>Input Window</th>
</tr>
</thead>
<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>
</tr>
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</table>
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

Conduction band
Valence Band

Free Electrons
Holes

The large energy gap between the valence and conduction bands in an insulator means that at ordinary temperatures, no electrons can reach the conduction band.

In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.
## CCD Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<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>
**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.