Detectors – Introduction

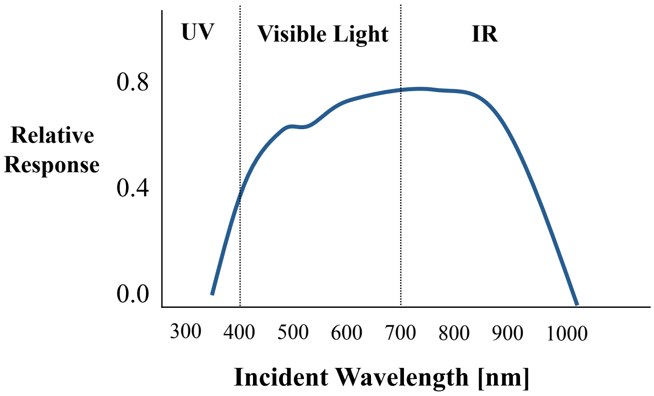
Photography
Photo-emissive detectors (Photo-multiplier Tubes)
Charge Coupled Devices (CCDs)

Detector Performance

- Spectral response
  - Total wavelength range over which photons can be detected with reasonable efficiency
- Spectral bandwidth
  - Wavelength range over which photons detected at any one time
- Linearity
  - Degree to which output signal is proportional to number of incoming photons
- Dynamic range
  - Maximum range of signal over which output represents incoming photon flux
- Quantum efficiency
  - Fraction of incoming photon stream that is converted into signal
- Noise
  - The uncertainty on the output signal (ideally just Poisson noise due to photon counting)
- Number of pixels
  - Number of detectors elements in an array (influences angular resolution and FoV)
- Time response
  - Shortest time interval over which changes in photon arrival rate can be detected

Spectral Response

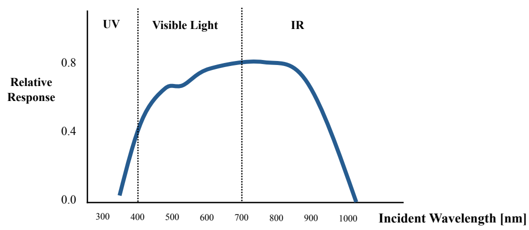
Total wavelength range over which photons can be detected with reasonable efficiency

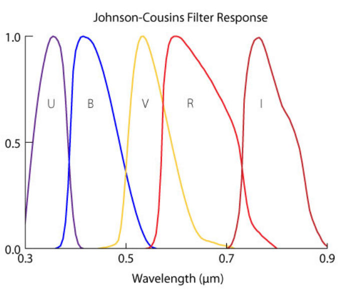


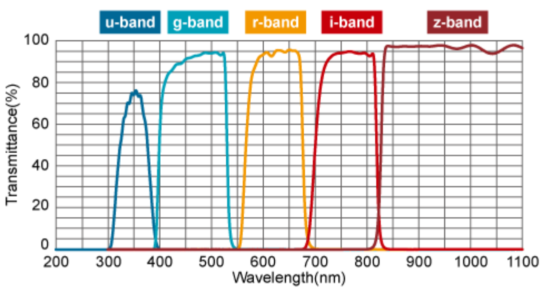
- Spectral response of "optical" observations with CCD detectors is limited in the UV by atmospheric transmission and in the IR by detector response

Spectral Band-width

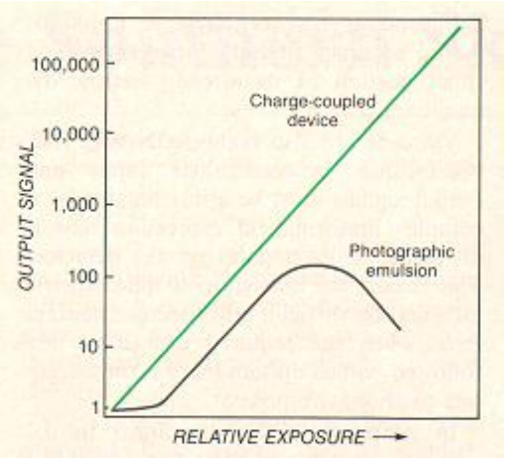
Wavelength range over which photons detected at any one time







Linearity and Dynamic Range



Linearity:

- Degree to which output signal is proportional to number of incoming photons
- CCDs are extremely linear detectors

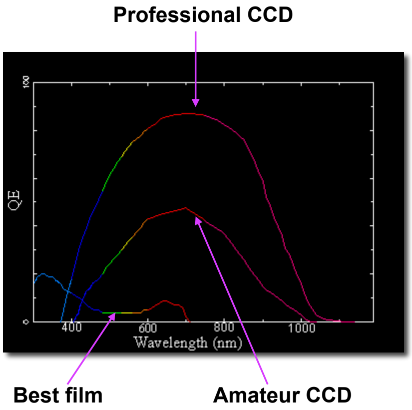
Dynamic range:

- Maximum range of signal over which output represents incoming photon flux
- Ratio between brightest and faintest detectable signal
- The dynamic range of CCDs is about 100 times larger compared to films

Quantum Efficiency

Fraction of incoming photon stream that is converted into signal

- Quantum efficiency (QE) is a measure of the efficiency of a detector in turning incoming photon stream into a measurable signal
- CCDs have a higher QE than both photographic film and photomultiplier tubes
- Higher QE means more data can be gathered in a shorter time, or that in the same time you can measure a fainter signal.

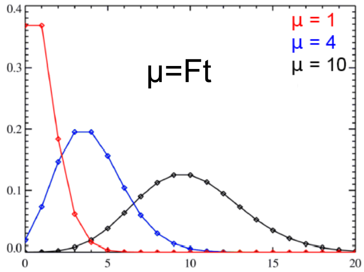


Noise – uncertainty on the output signal

Primer on Poisson statistics

- At optical wavelengths, hv>>kT, so we treat the energy incident on a detector as a stream of individual photons
- N, the number of photons arriving in a time interval t varies, for a fixed average flux F (photons/sec)
- Emission of photons by as astrophysical source is a random process described by Poisson statistics
- The probability that N photons are counted in an observation time t is therefore given by:

$$P(N|F,t) = \frac{(Ft)^N \exp(-Ft)}{N!}$$



Noise – uncertainty on the output signal

Primer on Poisson statistics

- The mean of the Poisson distribution is μ
- The standard deviation (spread) of distribution is √μ
  - Corresponds to uncertainty on N
- So for μ=10, fractional spread is

$$\boxed{\sqrt{\mu}/\mu = 33\%}$$

- And for μ=100, fractional spread is

$$\boxed{\sqrt{\mu}/\mu = 10\%}$$

- So for higher numbers of photons (bright sources or long exposures) statistical noise is smaller fraction of source signal

Number of pixels

Number of detectors elements in an array

- Detector elements sample the focal plane – they chop it up into bits
- If the sampling is too coarse (bits too big) then information is lost
- If the sampling is too fine (bits too small) then the field of view is unnecessarily small
- Nyquist sampling is optimal: 2.3 pixels per "resolution element"
- The size of the resolution element is determined by the diffraction limit and seeing

Time Response

Shortest time interval over which changes in photon arrival rate can be detected

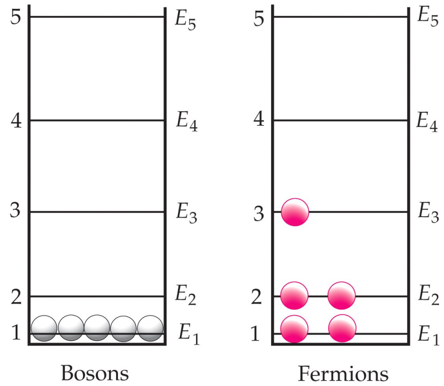
- The eye responds in 0.1 seconds
- Photographic time response depends on the frequency with which you change photographic plate: minutes to hours
- CCD time response is typically >1 minute, in part to minimize read noise
- Very few astronomy applications require the time response offered by the eye

Band Theory of Solids

Reminder of Pauli Exclusion Principle

There can be at most two electrons with the same set of values for their *spatial* quantum numbers.

EXCLUSION PRINCIPLE IN TERMS OF SPATIAL STATES



Pauli Exclusion Principle

Bose-Einstein statistics

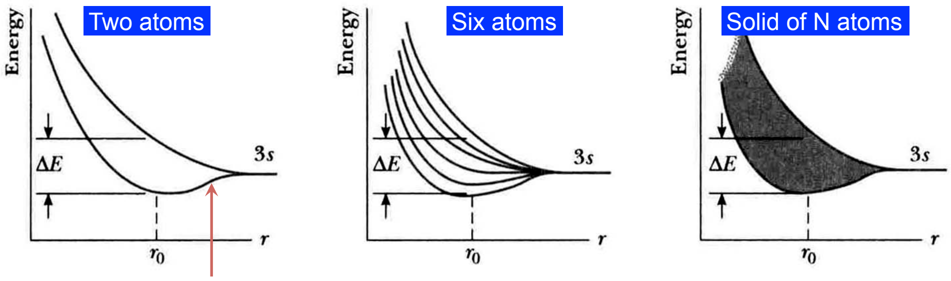
e.g. Photons

Fermi-Dirac statistics

e.g. Electrons

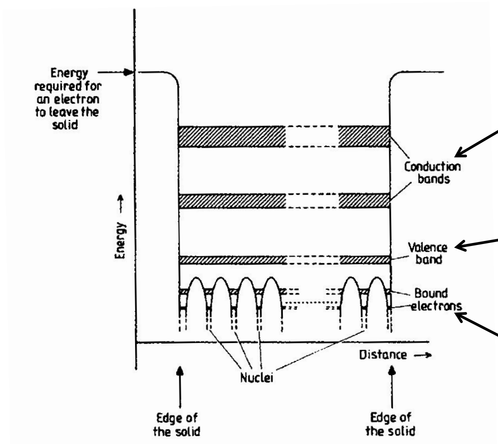
Band Theory of Solids

- For the total number N of atoms in a solid (10^{23} cm^{-3}), N energy levels split apart within a width ΔE
  - Leads to a band of energies for each initial atomic energy level (e.g. 1s energy band for 1s energy level).



Electrons must occupy **different energies** due to the Pauli Exclusion principle

Valence and conduction bands



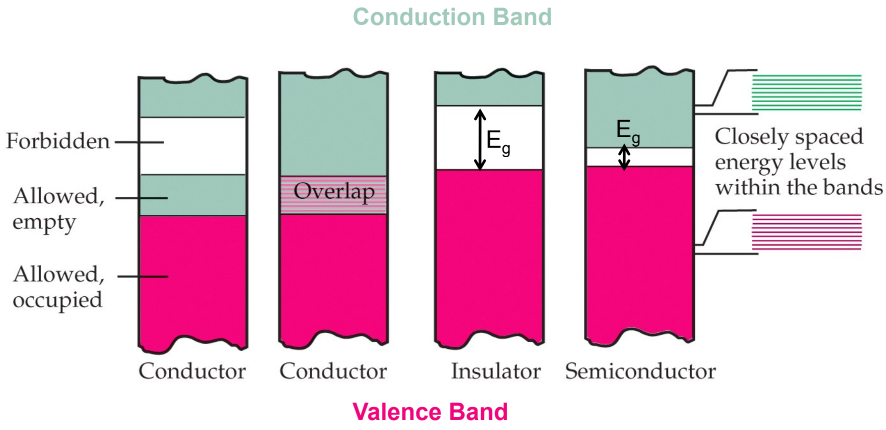
Electrons may be excited into the conduction bands at T>0

Electrons that form bonds between atoms are shared in the valence band

Innermost electrons are bound to individual atoms

A solid conducts electricity if its valence band is not full, or if electrons can move from the (full) valence band into allowed conduction bands

Valence and conduction bands



Detectors – Photography

Introduction

- Photography dominated professional astronomy for most of the 20th century
- Photography allows:
  - a permanent record of observations to be kept, stored and analyzed
  - longer exposure times to be used than the 0.1seconds of the eye
- Photography has important disadvantages:
  - E.g. quantum efficiency 10x worse than the eye!

Photographic plate

- Micron-sized grains of Silver halide (AgCl, AgBr, AgI) suspended in thin layer of gelatin on a glass or plastic backing
- When a photon strikes a grain, its energy is absorbed by the crystal lattice, and an electron is excited from valence to conduction band

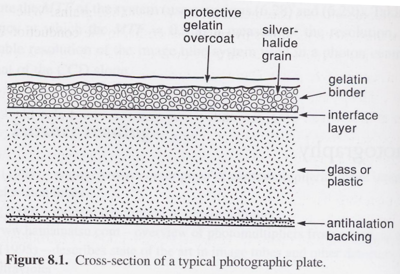


Figure 8.1. Cross-section of a typical photographic plate.

Photographic detection of photons

Photon elevates valence electron into conduction band:
$h\nu + Br^- \rightarrow Br + e^-$

Immobile hole:
- Recombine with an e^-) negate
- Ionize a silver atom) detection
- Migrate to grain surface: react with gelatin or form Br_2 and escape

Mobile electron
- Recombines with Br (negates detection)
- Wanders through the grain (Brownian motion)
- Trapped in flaw of crystal lattice, attracts Ag^+

$e^- + Ag^+ \leftrightarrow Ag$ (very unstable)

Ag atom acts as a trap for a second e^-:

$Ag + e^- \rightarrow Ag^-$

Ag^- can attract a Ag^+ from crystal lattice:

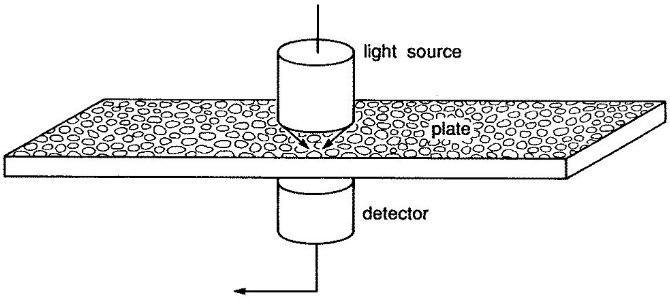
$Ag^- + Ag^+ \rightarrow Ag_2$

Ag_2 acts as center around which silver molecule grows under sustained exposure to light

Developing a photograph

- Pattern of exposed grains on the plate is called the “latent image”
- A chemical reducing agent (developer) is used to convert grains of AgBr into metallic Ag
- This process is catalysed by metallic Ag, so grains containing Ag react fastest with the developer
- Ultimately all AgBr grains would turn to Ag
- Development process is stopped by “fixing” the image, i.e. dissolving all the remaining AgBr away
- The dynamic range is limited: either a grain develops into Ag or not
- Shades of grey come from the concentration of (black) silver grains
- Development process amplifies the amount of metallic silver on a plate by a factor of 10^8-10^9 times that in the latent image

Measuring a photographic plate

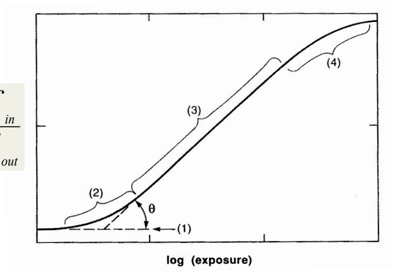


Density $$D = \log_{10} \frac{f_{in}}{f_{out}}$$ D=0.3 for 50% transmission

The Characteristic Curve

Density

$$D = \log_{10} \frac{f_{in}}{f_{out}}$$



Log (incident energy per unit area)

1 Gross fog
Minimum density even with no exposure

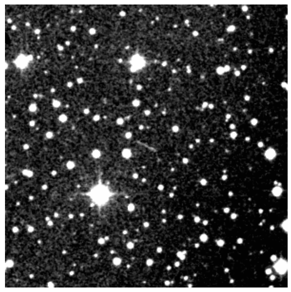
2 Under-exposure (toe)
Conduction e-s recombine before viable development centres form

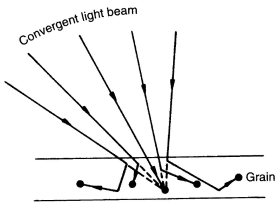
3 Linearity
Moderate exposure times: grain density is proportional to incident flux

4 Over-exposure (shoulder)
Majority of grains have become developable;
At high incident flux generates e-s faster than ions can migrate

Onset of non-linearity

- Saturation due to most grains becoming converted, or conduction electrons being produced more quickly than silver ions can migrate
- Also, photons get scattered in the emulsion and produce larger images at high flux





Extending sensitivity to λ>440nm

- Sensitivity of photographic plates extended to redder wavelengths by adding dyes
- Red sensitive dyes are adsorbed onto silver halide grains
- Dyes absorb light of their own characteristic frequency and then transfer the absorbed energy to the silver halide grains
- The latent image is then produced as normal
- The effect of dyes can be dramatic, as seen in the figure

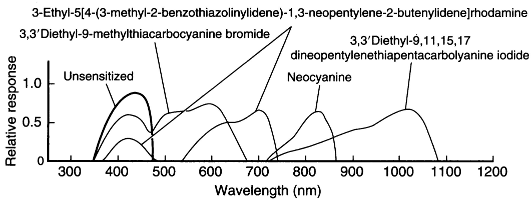


FIGURE 2.6 Effects of dyes upon the spectral sensitivity of photographic emulsion.

Photography

- Advantages:
  - Cheap
  - Large area, large number of pixels (upto six degrees square of sky, 10^9 pixels)
- Disadvantages:
  - Very inefficient (QE = 1 – 5%)
  - Response can be non-linear, saturates easily
  - Developing process subjective, sensitive
  - Limited dynamic range

Example problem

- The mean density measured on a developed photographic plate (in arbitrary units) is $D=\log(t_{exp})$ where t_{exp} is the exposure time. The noise in the density per pixel element is $\sigma_D=7/D^2$. The contrast parameter is measured to be: $\gamma=1$.
- Calculate the detective quantum efficiency (DQE) of exposures in which (a) 10^3 and (b) 10^4 photons per pixel element were incident on the plate.