3. Overview of Optical Detectors

(This section is mainly revision of material covered in the A1Y Observational course, so we will proceed fairly rapidly).

We will summarise the basic characteristics of:

- Photographic plates
- Photomultipliers
- Image Intensifiers
- Charged Coupled Devices (CCDs)

This list is roughly chronological: i.e. photographic plates were the earliest detector technology to be developed; CCDs are the most recent.

3.1 Photographic plates

From the late 19th century until the late 20th century photographic plates were the usual optical detectors

(prior to that astronomers had to be good artists!)

A photographic plate is a thin emulsion of silver bromide crystals. The photographic process consists of:-

1) Exposure to radiation

   This results in the chemical separation of Ag and Br

2) Development

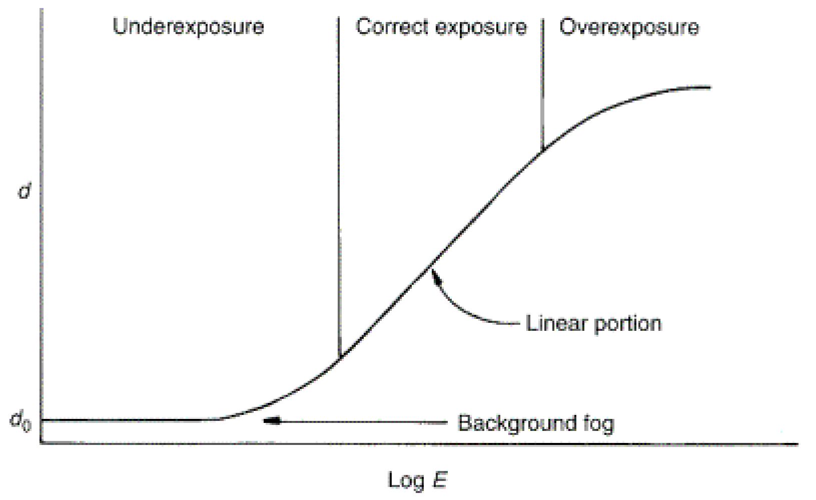
   This enhances the separation process

3) Fixing

   This washes out the Br, leaving Ag grains, which make up the ***image***

3.1 Photographic plates

Characteristic curve of a photographic emulsion



The exposure, E, is defined as the illumination, J, multiplied by the exposure time, t.

The image strength is measured by the density, d, of Ag grains.

For an underexposed image, d tends to a constant low background value. ('Fog')

Over a short range of exposures the density increases linearly with the log of the exposure.

For larger values of the exposure, the image saturates and the density no longer increases - no further information recorded.

Weaknesses of Photography

- Low **quantum efficiency** (= fraction of incident photons which produce a response) of ~ 0.001
- Non-linear response: strength of image not proportional to number of photons
- Wavelength sensitivity: biased towards **blue** colours

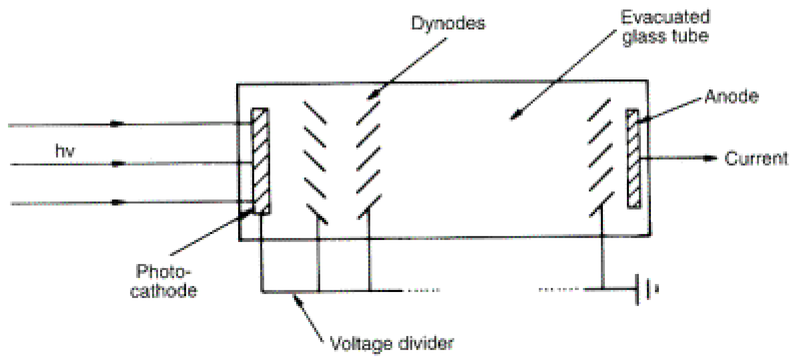
Strengths of Photography

- Large area - e.g. **Schmidt camera plates** (40cm × 40cm)
- Small 'pixel' (i.e. Ag grain) size: ~ 10 microns

$\Rightarrow$ Schmidt plates have about 40000 × 40000 pixels

But electronic detectors are catching up fast!

3.2 Photomultiplier



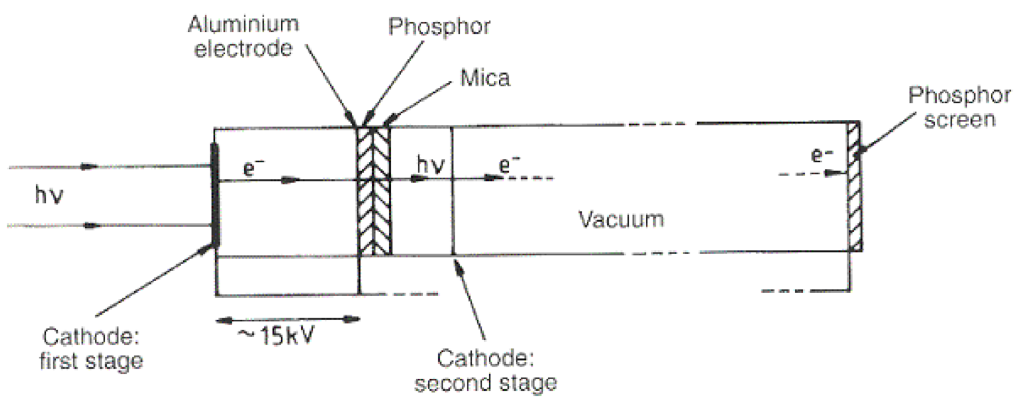
- Incident photon strikes a **photocathode**, held at a p.d. of ~ 1kV from the **anode** - at the other end of a vacuum tube.
- Cathode and anode separated by a series of **dynodes** at successively more positive potentials.
- Electrons emitted from cathode are accelerated towards first dynode, where they each have enough energy to release several more electrons.
- This is repeated at all dynodes → **Cascade** reaches anode

Each initial electron produces a D.C. current of up to 10^6 electrons

Typical quantum efficiency ~ 10% but little directional information

⇒ Poor imaging capability

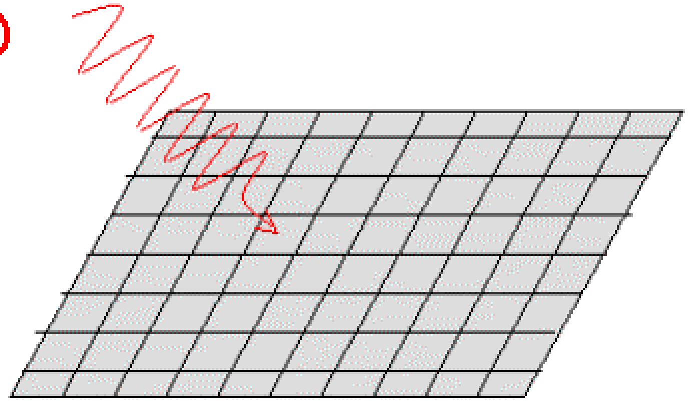
3.3 Image Intensifier



- Electrons emitted from the first cathode accelerated down evacuated tube by a voltage difference of ~ 15 kV and strike a phosphor screen ⇒ **image**
- The photons emitted from the phosphor strike a second cathode, and the process repeats - with the intensity of the image on the phosphor increasing at each stage. (The mica layer absorbs electrons not stopped in the phosphor).

Typical quantum efficiency is 20 - 30%

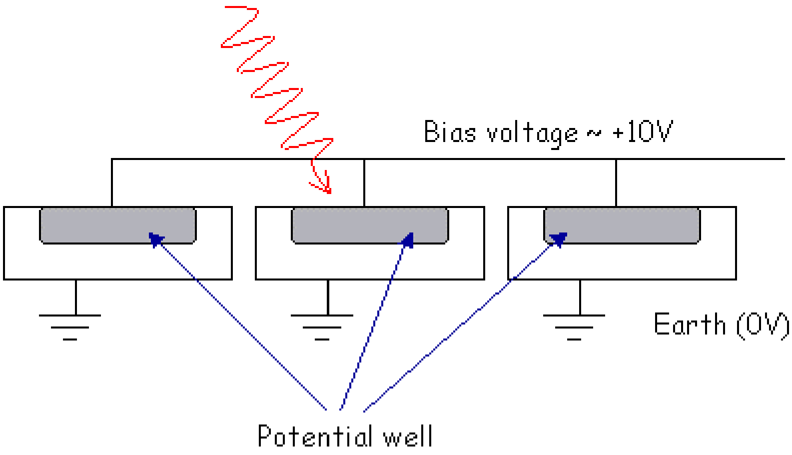
3.4 Charge Coupled Device (CCD)



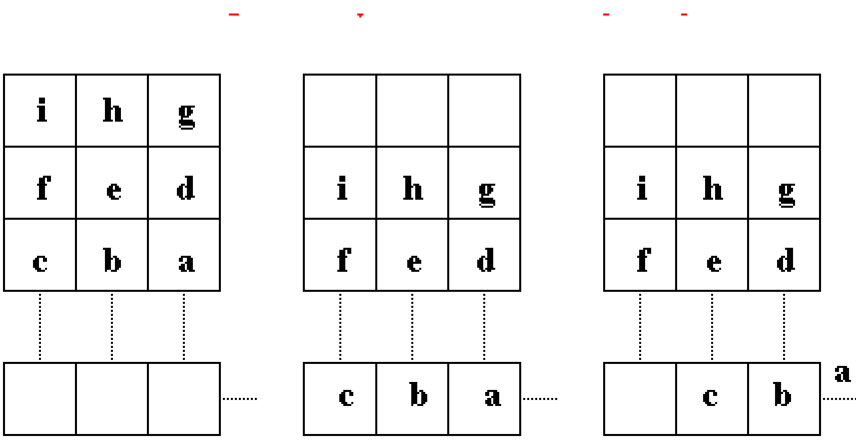
A CCD is a semiconductor array of light-sensitive pixels – typically about 20 μm across.

Arrays of 10^7 pixels standard.

'State of the Art' – mosaics of CCDs, approaching 10^9 pixels in total



- Electron released when photon strikes semiconductor
- Bias voltage draws electron into potential well; stored there during exposure



- Readout of stored charge via pulsed oscillation of bias voltage. Contents of potential wells moved across chip line by line to **line register**, then read out pixel by pixel
- Readout rate up to 10^8 pixels per second

Readout noise: very low, ~10 times less than for photomultipliers

Quantum efficiency: 50 – 70% (90% at 600 – 700nm)

- Number of electrons that a pixel (potential well) can store = **pixel capacity**

For long exposures, number of electrons produced by CCD chip may exceed the pixel capacity. The chip then **saturates** : electrons spill over into neighbouring pixels. (Analogous to saturation of a photographic plate)

Up until saturation, however, the pixel response is **linear**: i.e. number of electrons stored is proportional to number of incident photons.

Thus, CCDs have a large **dynamic range** = range over which detector response is linear.

$$\frac{\text{brightest object before saturation}}{\text{faintest object detectable}} \approx 10^4$$

Improving CCD performance

There are several sources of systematic error which need to be eliminated from CCD observations:-

a) Bias Value

This is the current due to charge in the CCD before any photons are collected.

Can be corrected for with a **BIAS FRAME**: an exposure of 0 seconds followed by readout of the CCD chip.

b) Dark (thermal) current

This is the electrons produced in the absence of light, due to thermal fluctuations in the CCD. The current will vary from pixel to pixel.

Can be reduced by cooling the CCD.

Residual current sensitive to temperature. Can be corrected for by a **DARK FRAME**: an exposure of the same time and at the same temperature as the real observation, but in total darkness.

c) Response factor

The current read out from each pixel differs from the 'true' current that would be read out from a uniform detector, due to inhomogeneities and variations in sensitivity across the CCD.

For a pixel at position (x,y), we can model this distortion by a response factor, $r(x,y)$

We can estimate $r(x,y)$ from a **FLAT FIELD** observation: an exposure for a **uniform light source** (e.g. uniform sky at twilight), for which the 'true' current should be constant.

We need a new flat field for every observing session, since CCD irregularities (due to e.g. dust) are constantly varying

We can summarise the relation between these systematic effects via the following expressions:-

'True' current that would have been measured with a uniform detector

$$\mathrm{I}(x,y,t,T) = \mathrm{I}_{\mathrm{true}}(x,y,t,T) \times r(x,y) + b(x,y) + d(x,y,t,T) \qquad (3.1)$$

Current measured from pixel (x,y) for an exposure of time t at temperature T

Bias current for pixel (x,y)

Dark current from pixel (x,y), for an exposure time t at temperature T

$$r(x,y) \propto \left[\mathrm{I}_{\mathrm{flat}}(x,y,t,T) - b(x,y) - d(x,y,t,T)\right] \qquad (3.2)$$

Current measured during **flat field** observation

The corrected image is constructed from $\mathrm{I}_{\mathrm{true}}(x,y,t,T)$