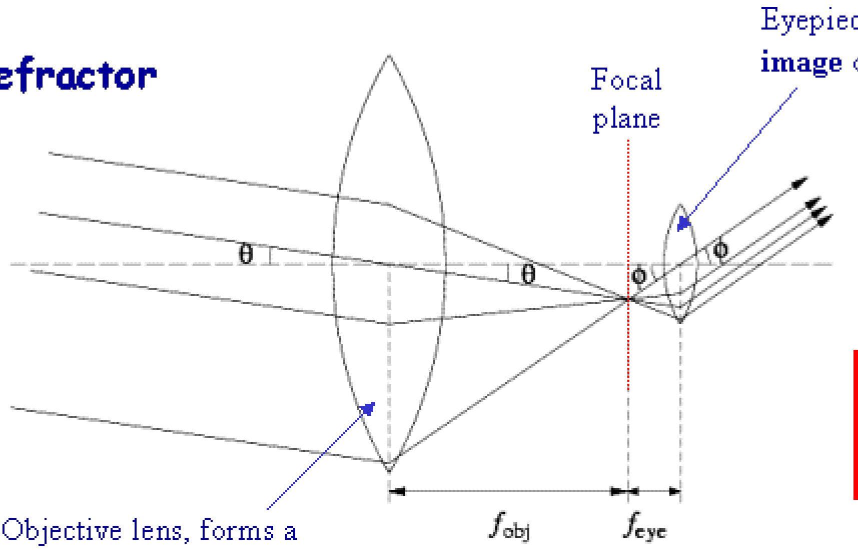
# 2. Detectors and Telescopes

A1Y Observational Astrophysics introduced the basic design features of optical telescopes: **refractors** and **reflectors**

## Refractor

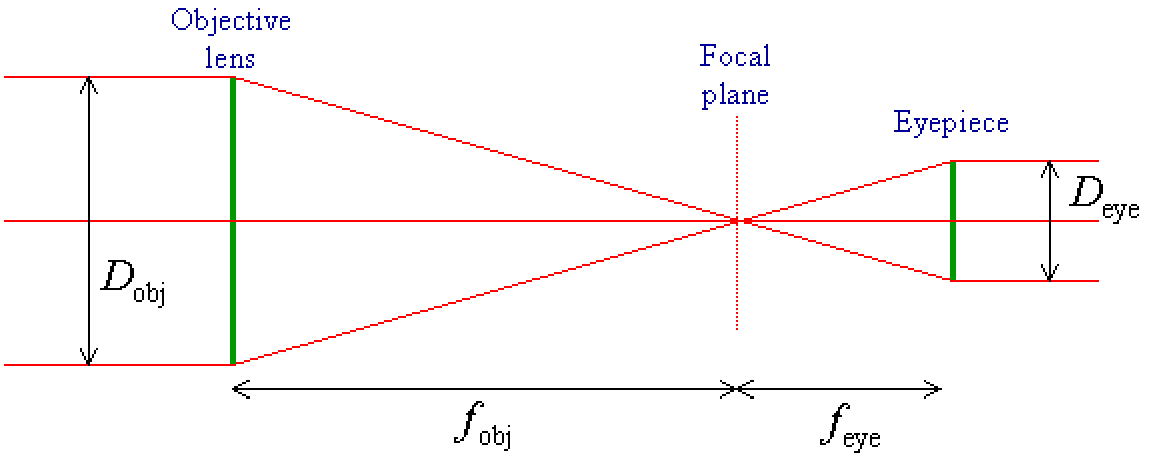



**Magnification** (ratio of the angular size of the virtual image to that of the source) given by

$$mn = \frac{f_{obj}}{f_{eye}} = \frac{D_{obj}}{D_{eye}} \qquad (2.1)$$

We can either view the virtual image through the eyepiece, or place a **detector** in the focal plane

## Virtual image viewed through eyepiece




Light collected in area $\pi\left(\frac{D_{obj}}{2}\right)^2$ of aperture covers only $\pi\left(\frac{D_{eye}}{2}\right)^2$ in eyepiece.

$\Rightarrow$ **Flux density** ( $\mathrm{W\,m^{-2}\,Hz^{-1}}$ ) ***increases*** by a factor $\left(\frac{D_{obj}}{D_{eye}}\right)^2$

Angular diameter of source = $\theta$ $\Rightarrow$ Solid angle of source = $\pi\left(\frac{\theta}{2}\right)^2$

Angular diameter of virtual image = $\theta \times mn$ $\Rightarrow$ Solid angle = $\pi\left(\frac{\theta}{2}\right)^2 (mn)^2$

$\Rightarrow$ From eq. (2.1) **Solid angle** ***also increases*** by a factor $\left(\frac{D_{\text{obj}}}{D_{\text{eye}}}\right)^2$

From eq. (1.20)

$$I_\nu = \frac{S_\nu}{\Omega_S}$$

Specific intensity (surface brightness) of virtual image in eyepiece unchanged

(ignores light losses – see later)

## Detector in focal plane

Performance determined by detector itself (see next section) and the telescope design.

We define

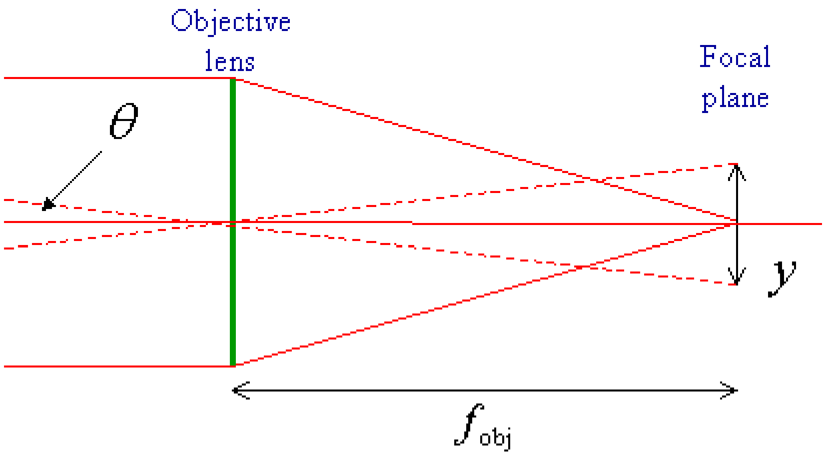
**Illumination** $J$ = energy per second, per unit area in focal plane

Same units as flux

Energy per second collected by telescope aperture:-

= **flux density x bandwidth x area**

$$E = S_{\bar{\nu}}\, \Delta\nu\, \pi \left(\frac{D_{\text{obj}}}{2}\right)^2 \qquad (2.2)$$




Diameter of image in focal plane,

$$y = f_{\text{obj}} \tan\theta$$

$$\approx f_{\text{obj}}\,\theta$$

$$\text{Area of image} = \pi\left(\frac{f_{\text{obj}}\,\theta}{2}\right)^2 \qquad (2.3)$$

$$J = \frac{S_{\bar{\nu}}\,\Delta\nu}{\theta^2}\left(\frac{D_{\text{obj}}}{f_{\text{obj}}}\right)^2 = \frac{\pi}{4} I \left(\frac{D_{\text{obj}}}{f_{\text{obj}}}\right)^2 \qquad (2.4)$$

Here we have substituted from eqs. (1.12) and (1.20), and defined the **Intensity** $I = I_{\bar{\nu}}\,\Delta\nu$

We define the **Focal ratio** $F = \dfrac{f}{D}$ (sometimes written as $f/F$)

The factor $\pi/4$ in eq. (2.4) is of order unity (and would be slightly different anyway if the source is not circular)

Thus we generally write

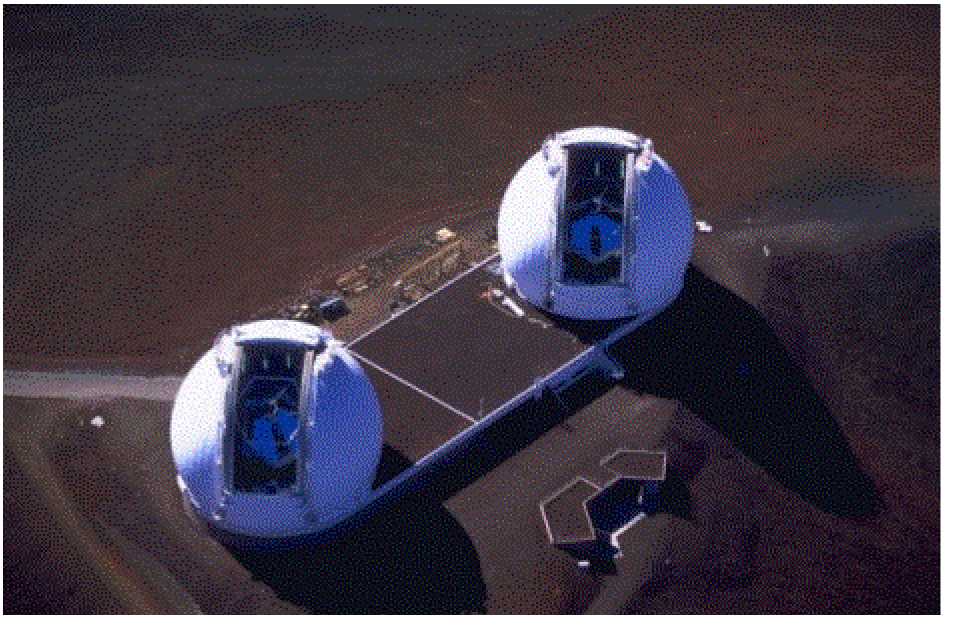
$$J \sim \frac{I}{F^2} \qquad (2.5)$$

Increasing the illumination reduces the time required to collect a given number of photons in our detector

Example: Keck Telescopes on Mauna Kea

2 x 10m diameter mirrors of focal length 17.5m $\Rightarrow$ $F = 1.75$

( or can be written as $F = f/1.75$ )



## Detector in focal plane

Optimal telescope design needs to consider competing factors:-

- **Increasing aperture diameter** $\Rightarrow$ increased illumination
  better angular resolution (see later)
  **BUT** more expensive to build

- **Increasing focal length** $\Rightarrow$ increased image size in focal plane
  covers more detector 'pixels'
  **BUT** decreased illumination
  longer exposures needed

- **Fixed focal ratio** $\Rightarrow$ illumination constant (as intensity conserved, ignoring light losses)

# Overview of Detectors

The techniques used to detect light energy vary considerably across the electromagnetic spectrum.

Note that in (astro)physics the energy of a photon is often expressed in **electron volts**

| | |
|---|---|
| **1 eV** = | energy required to move an electron across a potential difference of 1 Volt |

$$\left(1\,\mathrm{eV} = 1.602 \times 10^{-19}\,\mathrm{J}\right)$$

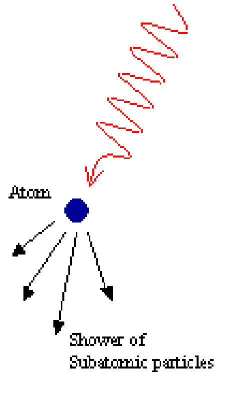
$$E = h\nu = \frac{hc}{\lambda} = \frac{1.24 \times 10^{-6}}{\lambda\,(\mathrm{m})}\,\mathrm{eV} \qquad (2.6)$$

## 1. Extremely high energy Gamma rays

$$\lambda \leq 10^{-18}\,\mathrm{m} \qquad E \geq 10^{12}\,\mathrm{eV}$$

We don't detect these photons directly, but we can see the effect which they have on atoms in the Earth's atmosphere.

They **collide** with atoms and produce a shower of subatomic particles, moving very close to the speed of light in a vacuum.




These particles can be moving **faster** than the speed of light in air.

This produces **Cerenkov Radiation**
Analogous to the 'sonic boom' produced by e.g. Concorde

## 2. High energy Gamma rays

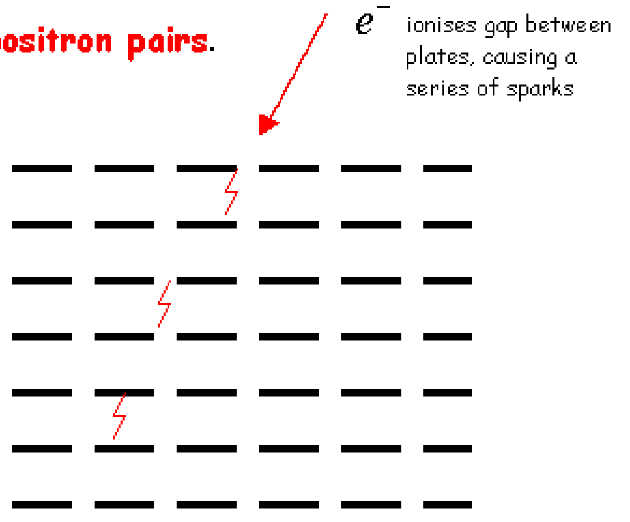
$$\lambda \sim 10^{-14}\ \text{m} \qquad E \sim 100\,\text{MeV}$$

We need to get above (most of) the atmosphere to detect these photons – from e.g. a balloon platform or rocket.

The photons produce **electron-positron pairs**.

We can track the path of the electrons through an array of **spark chambers** – conducting plates held at high potential difference.

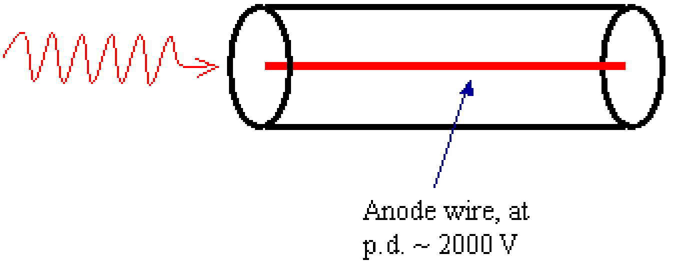
Gives limited 3-D info on direction of incoming photon




## 3. Low energy Gamma rays and X-rays

$$0.05\ \text{nm} < \lambda < 1\ \text{nm} \qquad 1\,\text{keV} < E < 20\,\text{keV}$$

We use a **proportional counter**: a tube filled with inert gas.




- X-ray enters tube
- Ionises gas atom, liberates electron
- Electron accelerates towards anode, ionising further atoms and liberating more electrons

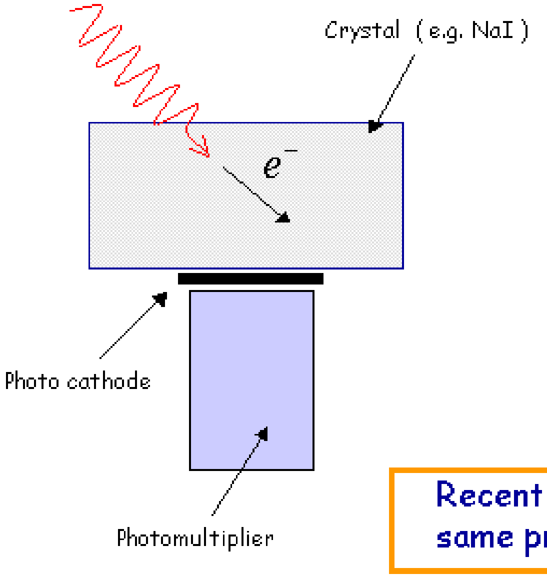
→ **Cascade**

(Similar to photomultiplier for optical / UV photons. See later)

## 3. Low energy Gamma rays and X-rays

$$\lambda < 0.05 \text{ nm} \qquad E > 20 \text{ keV}$$

For these photons a gas-filled tube is no good, as X-rays pass straight through. We use a **solid state detector** - **scintillation counter**.

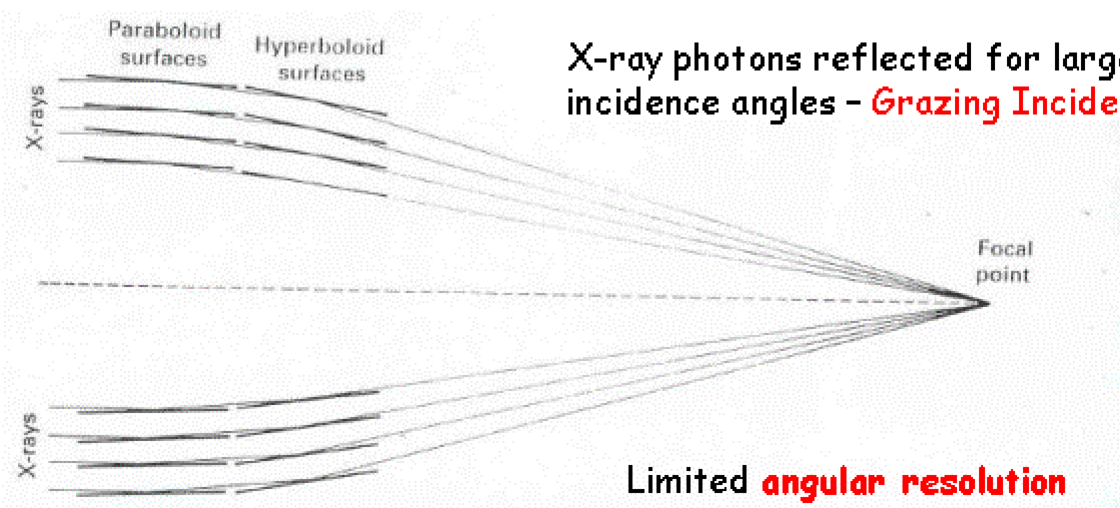



- X-ray enters crystal, ionises atom
- High energy electron excites many other electrons
- Impurity atoms in crystal lattice capture electrons
- Capture releases flashes of **visible light** detected by photomultiplier

Recently semiconductors have been used, with the same principle – e.g. Ge or Si with Li impurity

We can image X-rays using **grazing incidence optics**

For $E < 1$ keV




Series of nested surfaces of highly conducting material (e.g. Cu)

X-ray photons reflected for large incidence angles – Grazing Incidence

Limited **angular resolution**

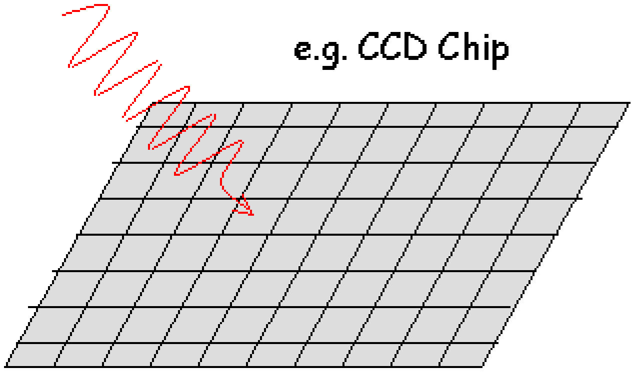
(but improving all the time – e.g. XMM Newton: 5 arcsec resolution; also X-ray spectra)

# 4. UV and optical wavelengths

$$10\,\mathrm{nm} < \lambda < 1\,\mu\mathrm{m} \qquad 1\,\mathrm{eV} < E < 100\,\mathrm{eV}$$

1 micron

We will look in detail at how modern optical detectors operate in Section 3, but the basic principle is the **photoelectric effect**




- semi-conductor array of 'pixels'
- when a photon strikes a pixel, it knocks an electron out of semi-conductor
- Read out of current produced by each pixel gives an image

Same technology as digital cameras and camcorders, but astronomical CCDs usually cooled to reduce electrons from thermal 'noise'

Same technology for UV as for optical, but most UV light is absorbed by the **Ozone Layer**, so UV observations must be done from space

# 5a. Near infra-red wavelengths

$$1\,\mu\mathrm{m} < \lambda < 25\,\mu\mathrm{m} \qquad 0.04\,\mathrm{eV} < E < 1\,\mathrm{eV}$$

1 micron

Now common to use CCD technology here too (e.g. HST, James Webb Space Telescope, Keck, VLT)

But need advanced semiconductor detector materials with appropriate 'bandgap' – i.e. sensitive enough so that weak NIR photons can still 'kick' electrons out of semiconductor lattice, to produce a current.

Present technological limits are about

$$\Delta E \sim 0.01\text{eV} \quad \Rightarrow \quad \lambda \sim 100\,\mu\text{m}$$

Crucial to cool CCD to avoid background thermal noise

Recall **Wien's Law**

$$\lambda_{\max} T = 2.9 \times 10^{-3} \qquad (2.7)$$

($\lambda_{\max}$ in m, $T$ in K)

Thermal background (telescope, dome, astronomers etc) at $T \sim 300\text{K}$

$$\Rightarrow \quad \lambda_{\max} \sim 10\,\mu\text{m} \qquad (2.8)$$

Cooling to about 100 K takes thermal peak outside of near infra-red range

## 5a. Far infra-red wavelengths ( also known as 'submillimetre' )

$$300\,\mu\text{m} < \lambda < 1\text{ mm} \qquad 10^{-3}\text{ eV} < E < 4\times10^{-3}\text{ eV}$$

These photons are too weak for the photoelectric effect, but frequency very high, so radio techniques (see below) difficult

We use a **bolometer** which measures very accurately the increase in temperature of a crystal (e.g. Germanium) when the photons strike it.

Now **essential** to eliminate thermal background

e.g. SCUBA on the James Clerk Maxwell Telescope (Hawaii)

cooled with liquid helium to $T << 1\text{K}$

Bolometer array - gives (limited) imaging capability

## 6. Radio wavelengths

$$\lambda > 1\ \text{cm} \qquad E < 10^{-4}\ \text{eV}$$

Individual radio photons have tiny energies, so we treat light as a **wave**, produced by a varying electric and magnetic field.

Radio waves are detected by an **antenna** - changing E-M field induces an **AC current** in the antenna. Pre-amplifier then produces a voltage (~ 1 volt) proportional to the current.

For a radio wave of frequency $f$

$$V(t) = V_0 \sin(2\pi f t + \phi) \qquad (2.8)$$

Amplitude ($V_0$), Phase ($\phi$)

**Antenna** (e.g. dish or dipole - see A1Y)

- chooses direction of observation
- collects radiation
- converts radiation to AC signal

**Receiver** (this is the 'detector')

- amplifies the signal (by a factor known as the **gain**)
- selects frequency and bandwidth (compare e.g. optical filters)
- processes and records signal

Ready availability of phase information means we can combine radio waves observed from different telescopes - **Interferometry**

e.g. VLA: Very Large Array in New Mexico

Radio techniques are now being extended to **millimetre wavelengths**

e.g. ALMA: Atacama Large Millimetre Array in Chile