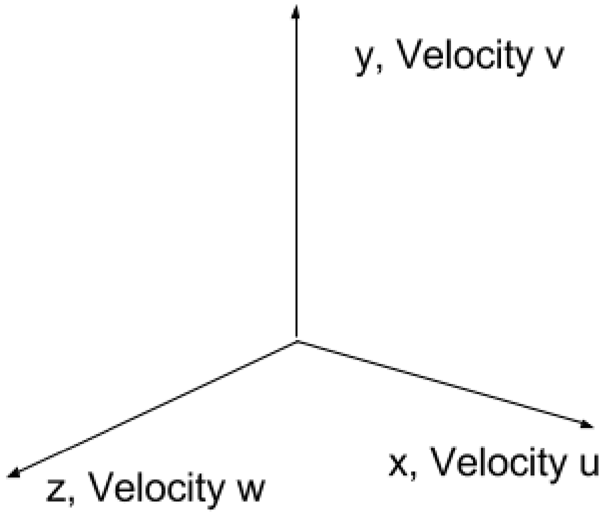
Physics (Nuclear Physics, Thermal Physics, Astronomy and Cosmology)

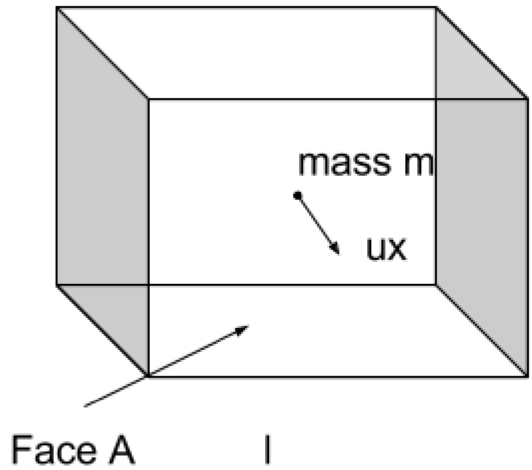
Thermal Physics

- **Thermal Energy**
  - For a change in temperature $Q = mc\Delta T$
    - Where c is the specific heat capacity of the material
  - For a change in state $Q = ml$
    - Where l is specific the latent heat of the material
- **Ideal Gases**
  - Assumptions about ideal gases
    - Molecules are point particles, volume of each particle is negligible compared to the volume of the gas
    - They do not attract each other
    - They are in continual random motion
    - Collisions with other particles and the container walls are elastic (no loss of kinetic energy in the collisions)
    - Each collision with the container surface is of much shorter duration than the time between impacts
  - Gas laws
    - Are experimental relationships between p, V, T and mass
    - Absolute zero is the lowest possible temperature (0K)
    - There are two forms of the equation:
      - $pV = nRT$, for n moles
      - $pV = NkT$, for N molecules
    - Molar mass is the mass of one mole of the substance
    - Explanation for gas laws
      - $P \propto T$ as an increase in temperature results in the average speed of the molecules increasing and with that the frequency and strength of collisions therefore increasing the pressure
      - $P \propto 1/V$ as an increase in the volume of the container will reduce the frequency of collisions therefore reducing the pressure
      - $V \propto T$ as an increase in temperature will cause the frequency of collisions to increase in order to keep the pressure constant the size of the container must increase

- Derivation of pressure of an ideal gas

Consider this …




Particle with mass m, velocity component $u_x$ as shown
Before colliding with face A it has momentum $mu_x$
After colliding with face A it has momentum $-mu_x$

The change in moment is therefore

$$\Delta p = -mu_x - mu_x = -2mu_x$$

The time taken to return to face A

$$\frac{2l}{u_x}$$

The force on the particle due to the collision is the rate of change of momentum

$$F = \frac{-2mu_x}{\frac{2l}{mu_x}} =- \frac{mu_x^2}{l}$$

From Newton's third law

The force on face A = $\frac{mu_x^2}{l}$

The total force due to N particles colliding with the face is

$$F = \sum_{i=1}^{i=N} \frac{mu_i^2}{l} = \frac{m}{l}(u_{x_1}^2 + u_{x_2}^2 + u_{x_3}^2 + \ldots + u_{x_N}^2)$$

Mean squared velocity in x direction = $\overline{u^2}$

$$\overline{u^2} = \frac{u_{x_1}^2 + u_{x_2}^2 + u_{x_3}^2 + \ldots + u_{x_N}^2}{N}$$

$$N\overline{u^2} = u_{x_1}^2 + u_{x_2}^2 + u_{x_3}^2 + \ldots + u_{x_N}^2$$

Therefore the total force on A

$$F = \frac{Nm\overline{u^2}}{l}$$

For all three directions we define a mean square velocity

$$\overline{c^2} = \overline{u^2} + \overline{v^2} + \overline{w^2}$$

Because the motions are random we can also say $\overline{u^2} = \overline{v^2} = \overline{w^2}$

Therefore $\overline{c^2} = 3\overline{u^2}$

$$\overline{u^2} = \frac{1}{3}\overline{c^2}$$

So the total force is

$$F = \frac{Nm\overline{c^2}}{3l}$$

The pressure on face A = $\frac{F}{l^2}$

Therefore

$$F = \frac{Nm\overline{c^2}}{3l^3}$$

Because $l^3 = V$

$$P = \frac{Nm\overline{c^2}}{3V} \text{ or } PV = \frac{Nm\overline{c^2}}{3}$$

Because $PV = \frac{1}{3}Nm\overline{c^2}$ and $PV = NkT$

$$NkT = \frac{1}{3}Nm\overline{c^2}$$

$$kT = \frac{1}{3}m\overline{c^2}$$

$$\frac{3}{2}kT = \frac{1}{2}m\overline{c^2}$$

The mean KE of a particle = $\frac{3}{2}kT$

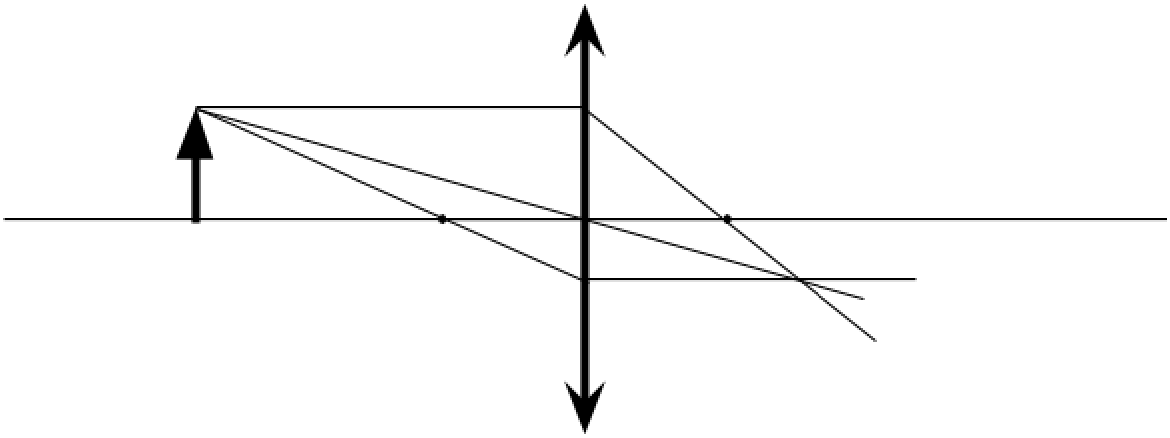
Internal energy of 1 mole of gas is

$$E = \frac{3}{2}N_AkT \text{ or } E = \frac{3}{2}RT$$

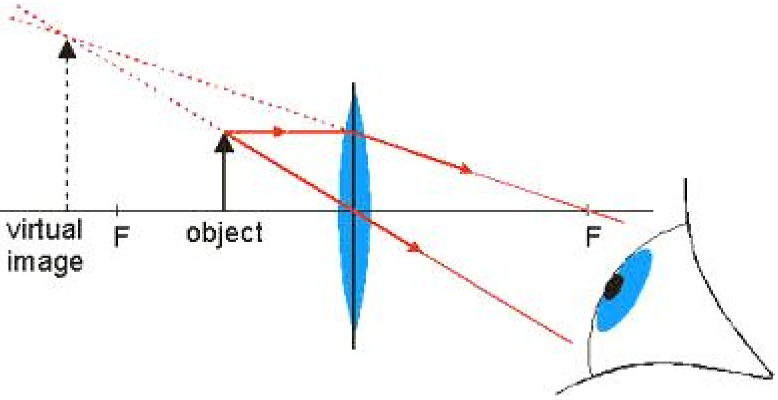
<u>Optics</u>

- Lenses
  - **Principle axis** - A line that passes at right angles through the optical centre of the lens
  - **Principle focus** - This is the point on the principle axis where rays parallel to the principal axis converge

- When for any object between 1 and 2 focal length
  - **Inverted**
  - **Magnified**
  - **Real**



- **When for any object less than the focal length**
  - **Magnified**
  - **Virtual**
  - **Upright**




- **The Lens Formula**

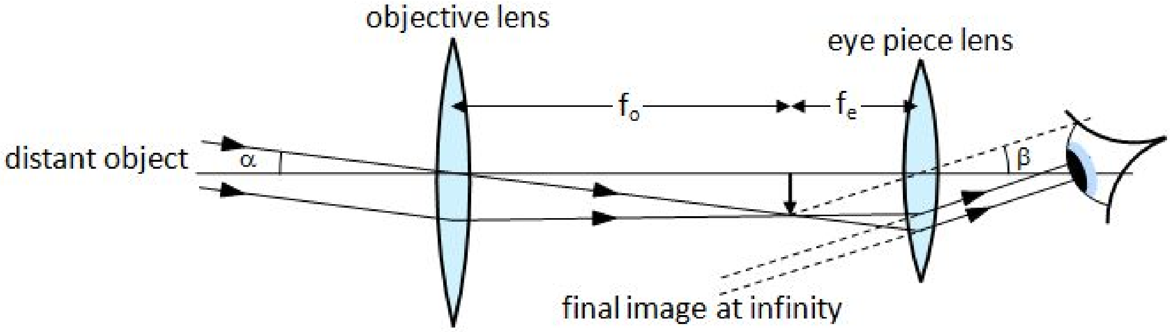
$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

  - U = object distance, V = image distance and f = focal length of lens
  - Use the real positive sign convention
    - Distance to real objects and images and the focal lengths of converging lens are positive
    - Distance to virtual objects and images and the focal lengths of diverging lens are negative
- **Linear Magnification**

$$m = \frac{h_i}{h_o} = \frac{v}{u}$$

  - $h_i$ = image height, $h_o$ = object height, v = image distance, u = object distance

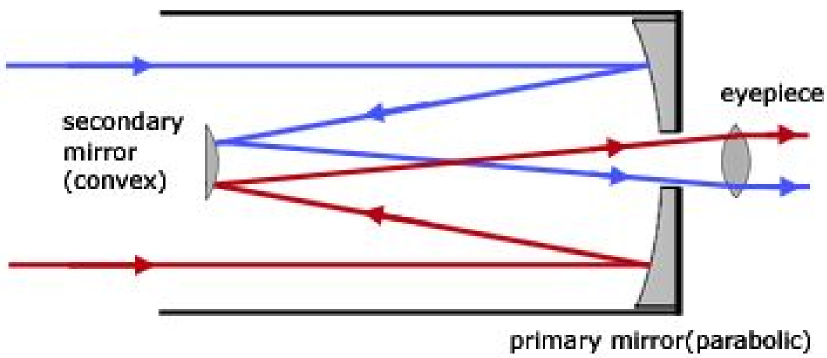
- **Normal Adjustment**




  - In normal adjustment the image is formed as if it were at infinity
  - The Angular magnification when in normal adjustment:

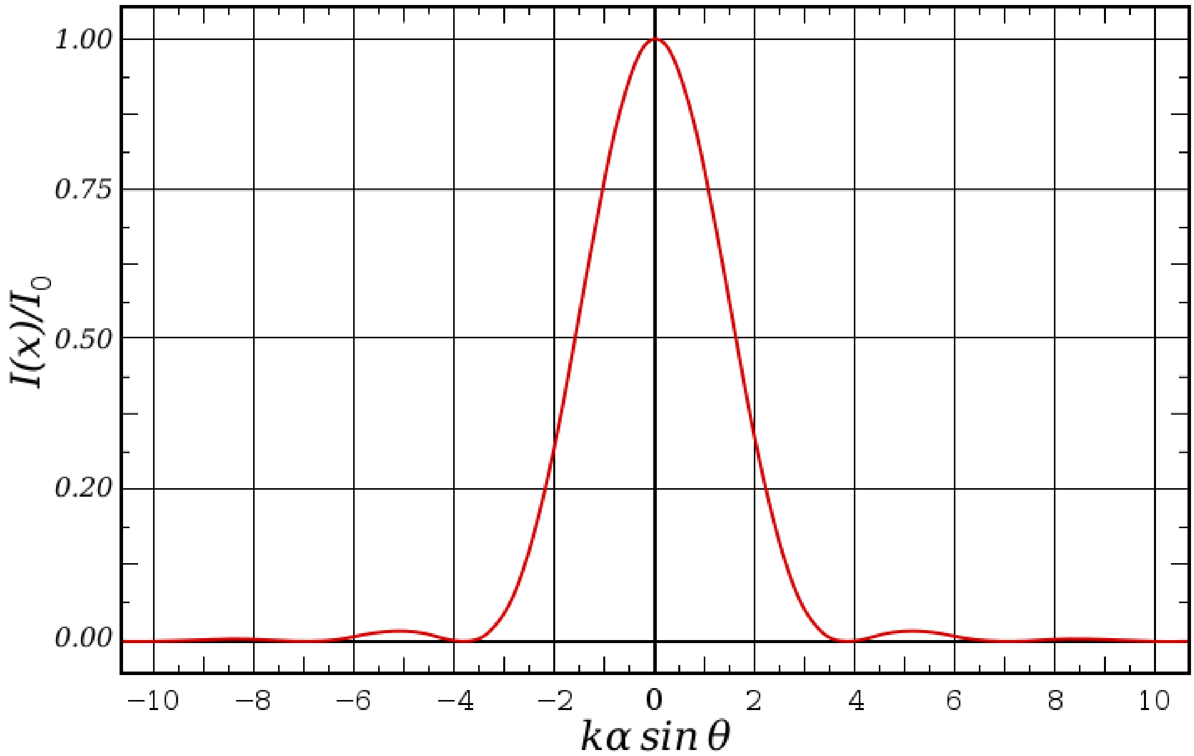
$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}} = \frac{f_o}{f_e}$$

  - Where $f_o$ = objective lens's focal length, $f_e$ = eye lens's focal length
- **Reflecting Telescopes**
  - **Cassegrain Reflecting telescope**




- **Problems with refracting telescopes**
  - **Spherical aberrations**
    - Rays further from the principle axis have a different focal point
    - This can be reduced
      - Covering parts of the lens
      - Parabolic lenses are used, but are very expensive
  - **Chromatic aberrations**
    - Different wavelengths of light refract at different angles in the lens
    - Blue light focuses closer to the lens than the red light
    - Cured by using an achromatic lens, but are expensive
- **Differences between refracting and reflecting telescopes**
  - Telescopes require a large diameter objective lens and therefore greater light gathering power.
    - There are issues producing large lenses:
      - They are physical heavy
      - Shape may distort
      - Have to be supported
      - Two surfaces must be ground
      - Spherical and chromatic aberrations

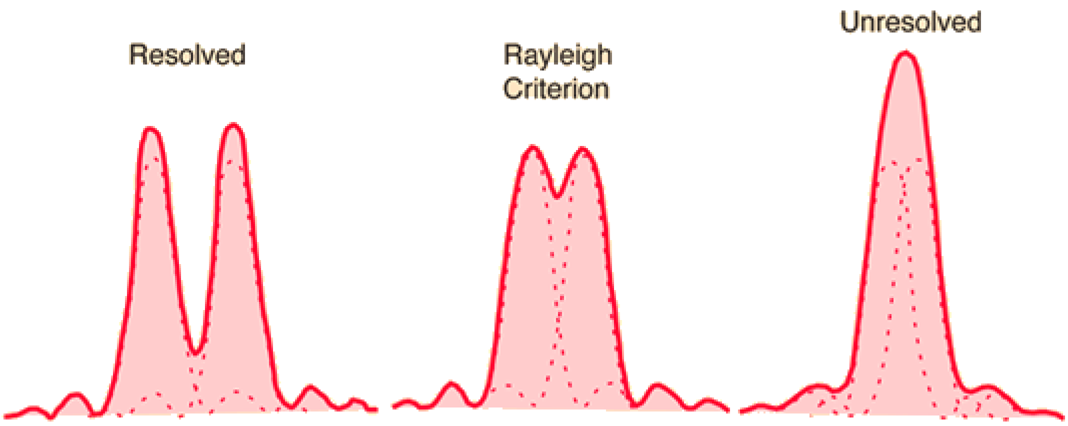
        - Large mirrors
            - Only one surface to grind
            - No chromatic aberrations
            - Spherical aberrations cured by making the mirror parabolic
            - Easy to support
    - Reflectors tend to be smaller than similar performance refractors
    - Reflectors can be high maintenance be mirrors are open to the air
    - Secondary mirrors and supports reduce light for imaging and contrast of the image
    - Mirrors do not refract and therefore no chromatic aberrations
    - No spherical aberrations will occur because the lenses are parabolic
- **Diffraction pattern produced by circular aperture**




    - Made up of a bright central maxima
- **Rayleigh Criterion**
    - The smallest angle resolvable is found by

$$\theta_R \sim \frac{\lambda}{D}$$

    - Where λ = wavelength of the light, D = Diameter of the objective

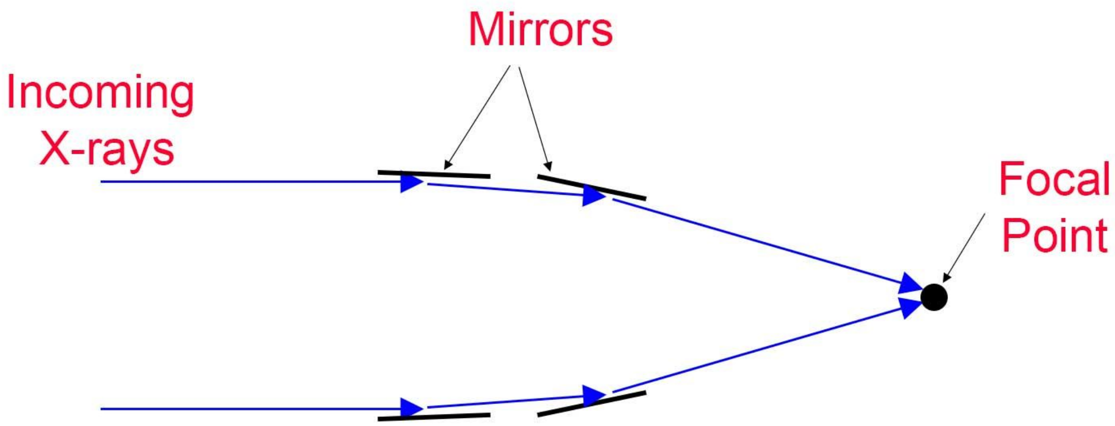



- Two objects are just resolvable when their central maxima and first minima coincide
- **Charge Coupled Device (CCD)**
  - CCDs are used to capturing images
  - Operation of a CCD
    - Light photons strike the photosite (pixels) and release electrons, by the photoelectric effect
    - 1 Photon releases 1 Electron
    - Electrons are stored in potential wells until the end of imaging
    - Each photosite's electrons content is 'read' sequentially to a computer screen
    - The image is on a computer screen and represents accurately the brightness of the object
  - Advantages of CCDs
    - Since 1 photon releases 1 electron the image brightness closely resembles the object
    - Imaging time is significantly less than for film
    - Records in real time
    - They are sensitive to a wider range of wavelengths than the eye
    - They link naturally to computers whereas photographic film does not
    - They have a high quantum efficiency > 70%:

$$Quantum\ Efficiency = \frac{Number\ of\ photons\ involved\ in\ imaging}{Total\ number\ of\ incident\ photons}$$

    - Easily capable surviving in cold environments (eg. space)
  - Disadvantages of CCDs
    - They are costly
- **Radio telescope**
  - Consists of a parabolic dish with an aerial at the focal point of the dish
  - Atmosphere transmits wavelengths 1mm to 10m
  - Radio waves are not absorbed by gas so allow things that are hidden in optics to be seen
  - Advantages and disadvantages:
    - Radio and optical can be done from the ground
    - Resolving power of radio is much lower than optics as wavelength large and therefore inaccurate

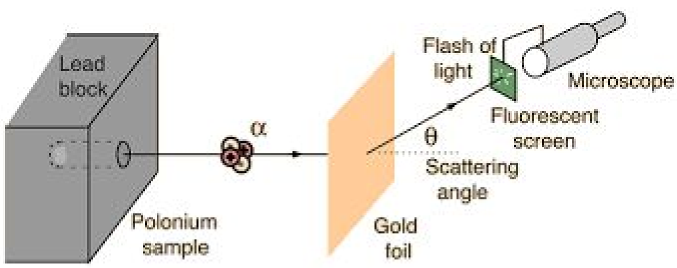
- **Infrared telescope**
  - Consists of a large concave reflector which focuses infrared radiation onto a detector at the focal length of dish
  - Infrared absorbed by water vapour and therefore done high up
  - Will detect the infrared of itself so must be cooled to ~2°K
  - Advantages and disadvantages:
    - Can be ground based like optical but be high up
    - Resolving power better than radio but worse than optical
- **Ultraviolet telescope**
  - Must be done above the atmosphere as UV is absorbed by the atmosphere
  - Glass absorbs UV therefore a mirror is used to focus UV onto a UV detector
  - UV emitted by hot objects eg. stars, quasars and some gas clouds
  - High resolving power
- **X-ray telescopes**
  - Must be above atmosphere as atmosphere absorbs all X-rays
  - X-rays are reflected by highly polished metal at a grazing angle




- **Gamma ray telescopes**
  - Must be above the atmosphere as it is absorbed entirely by the atmosphere

Radioactivity

- **Rutherford Scattering**




  - Foil is in a vacuum so that the alpha particles are not absorbed
  - Before the experiment the atom was thought of the "plum pudding model" a positive padding with negative electrons
  - He observed that:
    - Most of the alpha particles passed through the gold without being deflected

        - Some of the alpha particles through large angles - Not expected
        - A small amount of alpha particles were deflected backwards - Not expected
- **Alpha Radiation**
    - Made up of helium nuclei, two protons and two neutrons
    - Range of < 10cm
    - Blocked by paper
    - Equation:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

- **Beta Plus Radiation**
    - Made up of positrons
    - Range of 1m
    - Stopped by thin aluminium sheet
    - Equation:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e^{+} + \nu_e$$

- **Beta Minus Radiation**
    - Made up of electrons
    - Range of 1m
    - Stopped by thin aluminium sheet
    - Equation:

$$^{A}_{Z}x \rightarrow {}^{A}_{Z+1}y + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu_e}$$

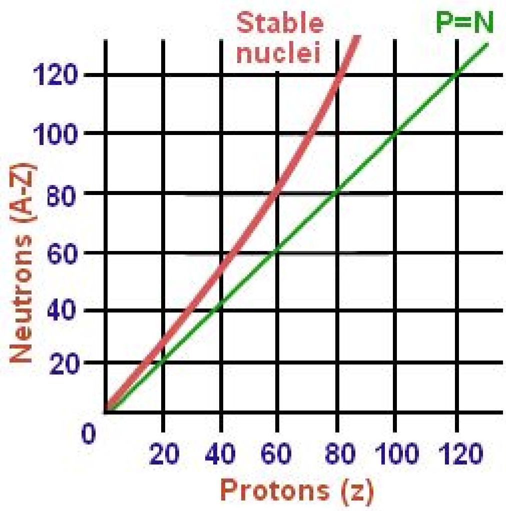
- **Gamma Radiation**
    - Made up of photons with energy of MeV
    - Follows the inverse square law
    - Stopped by thick lead
    - Equation:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$$

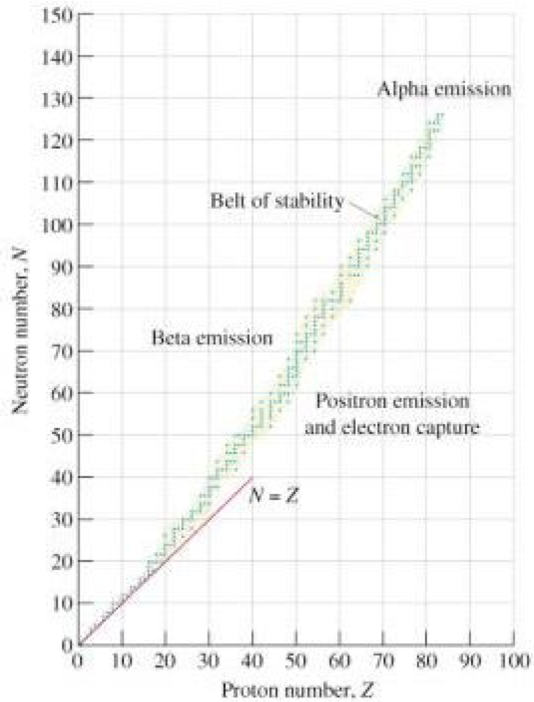
- **Inverse Square Law**
    - Equation:

$$I = \frac{k}{x^2}$$

- Where I is the intensity of the radiation, k a constant and x is the distance from the source
- **Sources of Background Radiation**
  - Gas in the air
  - Medical purposes
  - Ground and buildings
  - Food and drinks
  - Cosmic Rays
  - Nuclear weapons
  - Air travel
  - Nuclear power
- Radioactive decay is random
- The time for half the atoms in a sample to decay is the substance's half life
- The half life of carbon-14 can be used to date organic substances
- **Stability graph**




- **To return to stability atoms will do one of four things**




- **Nuclear Energy Levels**
  - After alpha or beta decay or electron capture a nucleus can be in an excited state
  - The nucleus will emit a gamma photon to return to its ground state, it lowest energy level
  - Technetium is used as a gamma source, it remains in an excited state for long enough to be separated.
  - When an atom stays in an excited state for a long period of time it is said to be **metastable**
  - The metastable technetium has a half life of 6 hours
  - By inserting metastable technetium into the body a gamma camera can be used to image the internals of the body
- **Closest approach**
  - By setting an alpha particle's kinetic energy and electrical potential energy equal the closest the alpha particle gets to the nucleus can be found
- **Radius of a nucleus**
  - By firing electrons through gold foil
  - Using the angle of the first minima the size of a nucleus can be found
  - The following formula is used:

$$r = \frac{0.61\lambda}{sin\theta}$$

  - The radius of a nucleus ~ $10^{-15}$
  - The radius of a nucleus only depends on the number of nucleons in it
  - The following formula is used to find the radius of a nucleus

$$R = r_o A^{\frac{1}{3}}$$

Where $r_o$ is a constant 1.05Fm and A is the nucleon number

  - We assume that the nucleus is spherical, and use the equation $\frac{4}{3}\pi r^3$ to find the volume

- Energy and mass are equivalent and are connected by the equation
$$E = mc^2$$
- In a nuclear reaction the energy released can be found by
$$Q = \Delta mc^2$$
- **Binding energy of the nucleus** is the work that is done to separate a nucleus into its constituent neutrons and protons
- **Mass defunct** Δm of a nucleus is defined as the difference between the mass of the separated nucleons and the mass of the nucleus
- The binding energy of the nucleus can be found using $E = mc^2$ ,
$$Binding\ Energy = \Delta mc^2$$
- The **Atomic Mass** unit is used as a conventional unit of mass
1u = 931.3MeV
- Binding energy per nucleon graph

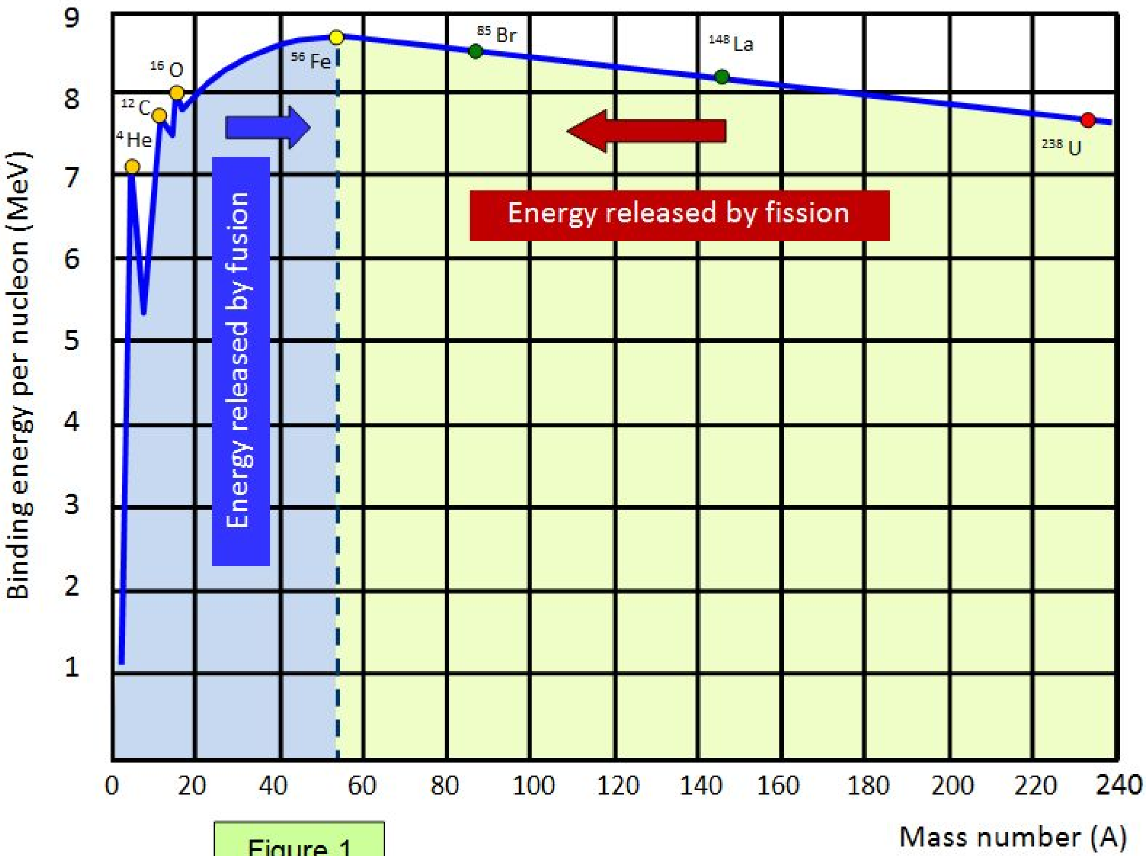



Figure 1

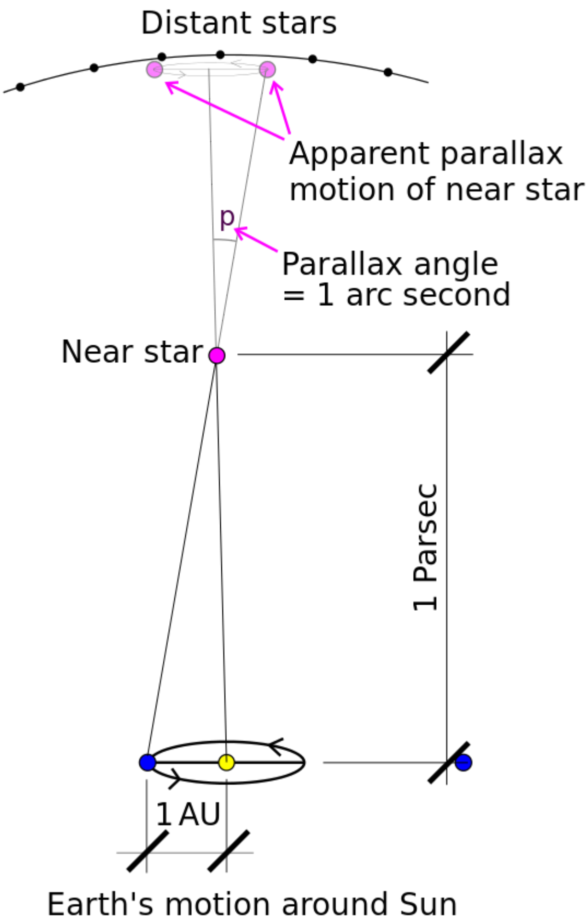
- Iron is stable
  - Atoms smaller than iron will undergo fusion to become iron
  - Atoms larger than iron will undergo fission to become iron
  - Both will release energy
- **Nuclear Fission**
  - A large nucleus splits into two fragments, which are more stable than the original nucleus
- **Nuclear Fusion**
  - Small nuclei fuse together to form a larger nucleus

- **Induced Fission**
  - A neutron is collided with a uranium-235 nucleus causing induced fission
  - The nucleus breaks into two smaller nuclei and two **fission neutrons**
  - The fission neutrons then collide with other uranium-235 nuclei causing a **chain reaction**
  - The **critical mass** is the smallest amount of mass needed to sustain a chain reaction
  - **Fuel rods**
    - Enriched uranium, contains increased percentage of uranium-235
    - Where the reaction occurs
  - **Control rods**
    - Made of Cadmium or Boron to absorb fission neutrons
    - Can be raised or lowered to change the rate of the reaction
    - By absorbing the neutrons they reduce the rate of the reaction
  - **Moderator**
    - Made of water or graphite
    - Slows the neutrons and increases the likelihood of fission with another nucleus
  - **Coolant**
    - Made of water
    - Removes the heat generated by the reaction
- **Safety features of the reactor**
  - **Steel** - withstand high pressures and temperatures and can absorb alpha, beta and neutrons.
  - **Concrete** - absorbs neutrons and gamma.
  - **Control** rods - can be raised and lowered to control rate of neutron production (and thus fission reactions).
  - **Fuel rods -** when removed they are radioactive and are therefore only handled remotely.
- Types of waste
  - **High Level Waste**
    - Used fuel rods
    - They are very hot and are therefore left under water to cool for many years
    - Useful fuel is extracted
    - Remaining is stored deep underground ~ 300m
  - **Intermediate Level Waste**
    - Low activity radioactive materials
    - Stored underground in concrete containers that shield the radiation
  - **Low Level Waste**
    - Lab equipment and cloths
    - Seal underground in trenches
- **ALARA** (As Low As Reasonably Possible) This is the level of acceptable exposure
- Radioactive material should be handled with tongs, gloves or robots
- A radiation badge is worn, this has photographic film that changes colour if radiation strikes it

  - Part of the film is covered by lead, part by aluminium and part is not covered
  - By examining where the film's colour has changed the type of radiation can be found

<u>Classification of stars</u>

- The brighter a star the lower its apparent magnitude
- A magnitude 1 star is about 100 times brighter than magnitude 6 star
- 1 parsec is a unit of astronomical measurement




- The absolute magnitude of a star (M) is the magnitude of a star at a distance of 10 parsecs from the earth
- Distance, apparent and absolute magnitudes are linked by

$$m - M = 5log(\frac{d}{10})$$

- **Stefan's Law**
  - Allows us to calculate the power output of a star or black body

$$P = A\sigma T^4$$

Where P is the power, A is the area, $\sigma$ is Stefan's constant and T is the absolute temperature

  - For a star the following is used

$$L = 4\pi r^2 \sigma T^4$$

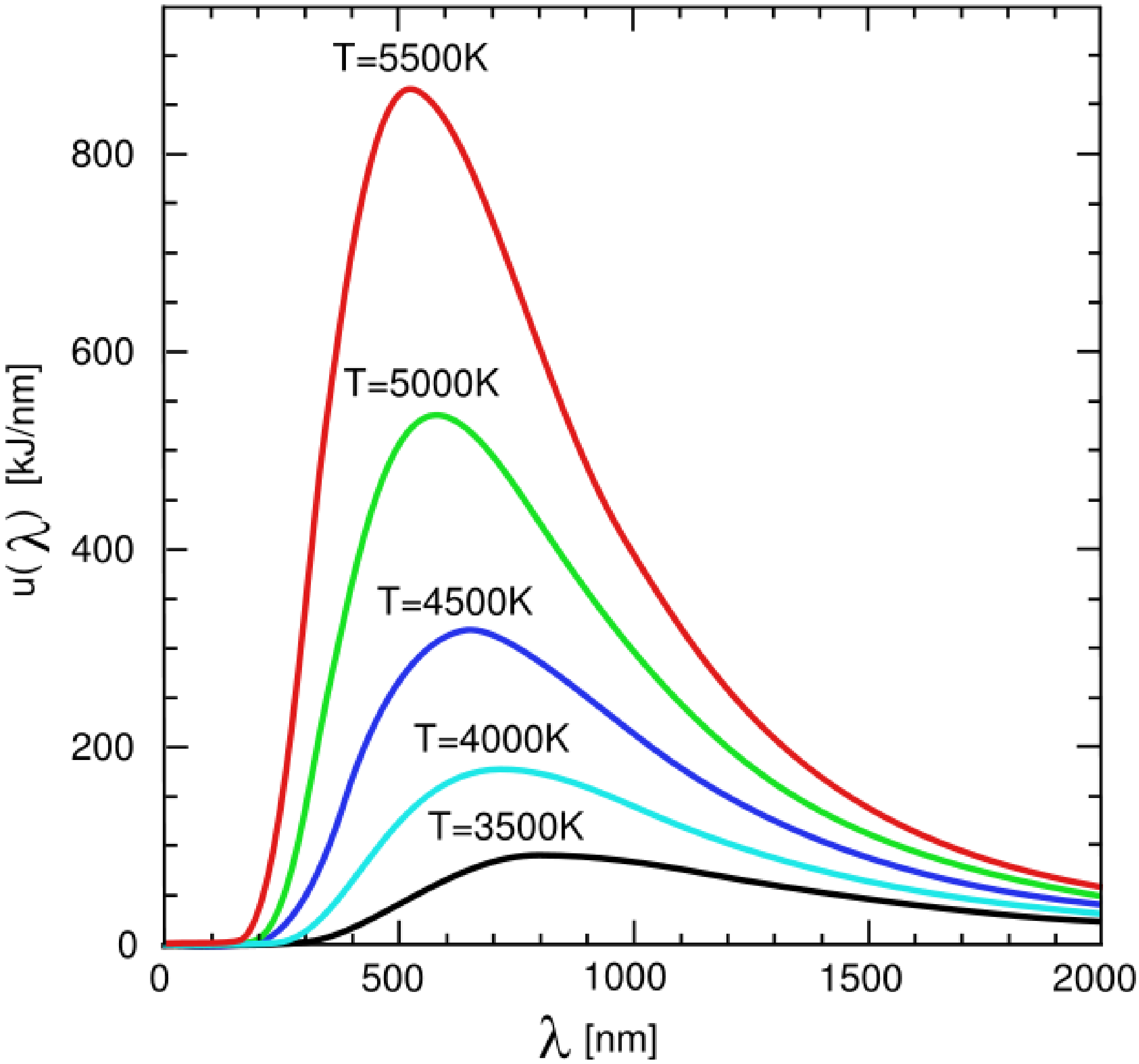
Where L is the luminosity and r is the radius

- The intensity of the light from an object is

$$I = \frac{L}{4\pi d^2}$$

Where L is the luminosity and d is the distance from the star

- **Black bodies**
    - Bodies that absorb all radiation and emit all characteristics wavelengths of radiation
    - The following are black body curves




- **Wien's Law**
    - The maximum wavelength emitted by a black body multiplied by its absolute temperature is a constant

$$\lambda_{max} T = 2.9 \times 10^{-3}$$

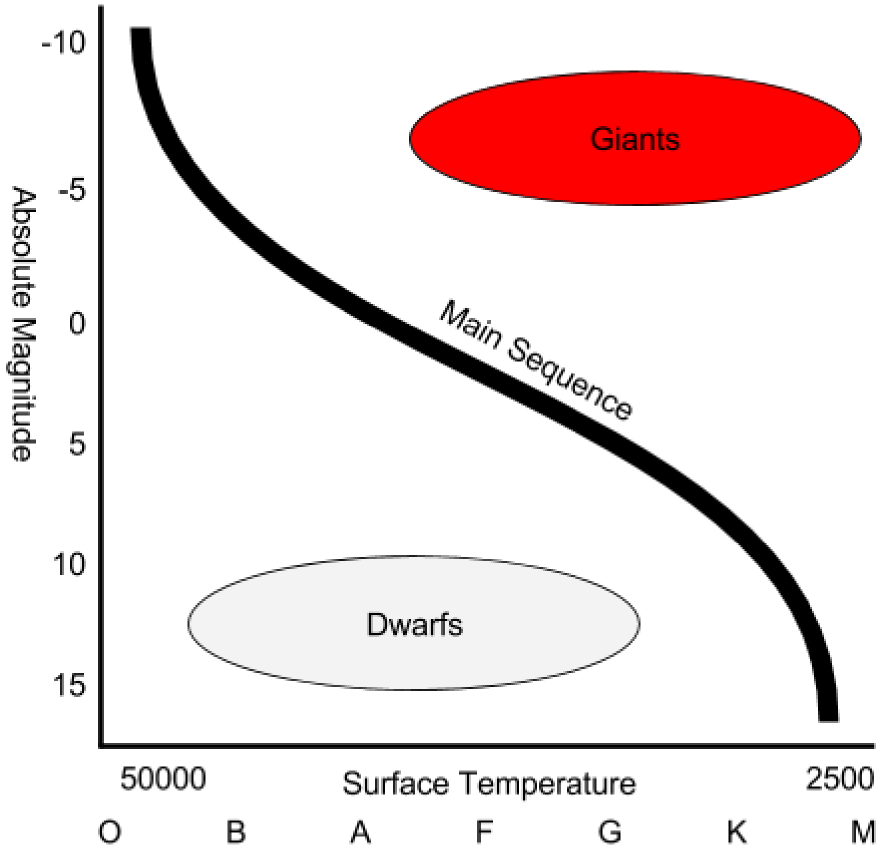
Spectral Classes

| Spectral Classes | Colour | Temperature | Prominent Absorption Lines |
|---|---|---|---|
| O | Blue | 25000 - 50000 | $He^+$, He, H |
| B | Blue | 11000 - 25000 | He, H |
| A | Blue-white | 7500 - 11000 | H (strongest), ionised metals |
| F | White | 6000 - 7500 | Ionised metals |
| G | Yellow-white | 5000 - 6000 | Ionised and neutral metals |
| K | Orange | 3500 - 5000 | Neutral metals |
| M | Red | < 3500 | Neutral atoms, TiO |

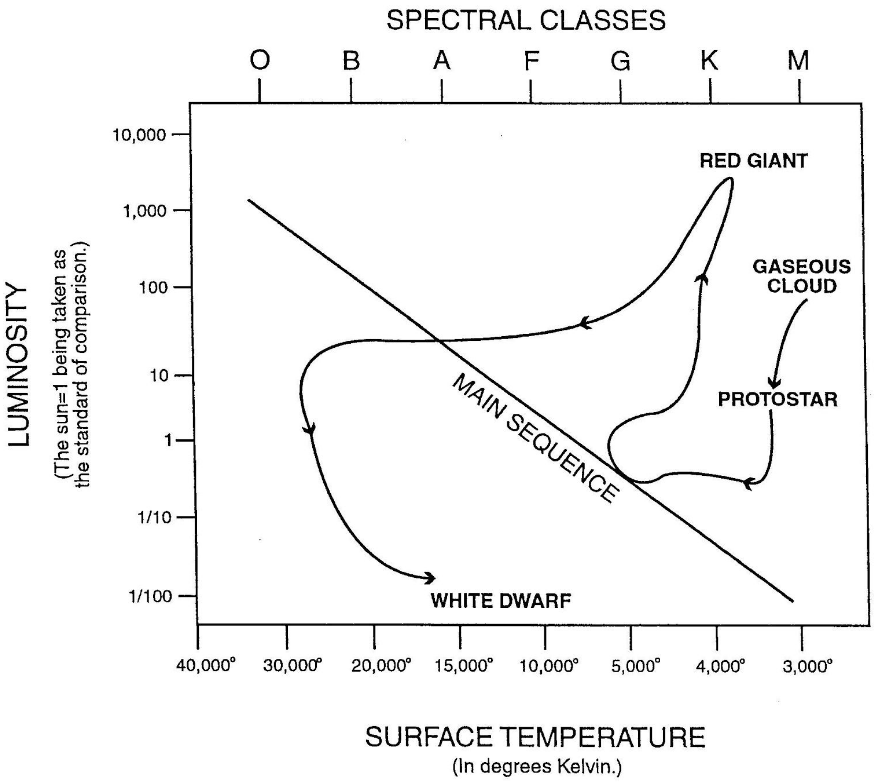
- The Hydrogen Balmer lines are energy changes that end in the n=2 state
    - For them to be present the star can't be too hot or too cold

Hertzsprung-Russell diagram

- The following is the hertzsprung-russell diagram




- The journey of our sun throughout its life




- **Supernovae** - These are stellar objects that have a rapid increase in absolute magnitude
- **Neutron Stars** - Very small dense star, made only of neutrons
- **Black holes** - Infinitely dense object, with an escape velocity larger that the speed of light
- **Quasars** - Strong radio sources
- Supernovae are used as **standard candles**, these are used to measure distances to galaxies. The luminosity of the supernovae is known so the distance can be calculated
- The universe is accelerating, making physicists think there may be a new type of energy called **dark energy**
- It is thought that most galaxies have supermassive black holes at their centres
- The radius of a black hole's event horizon can be found using the following formula

$$R_S = \frac{2GM}{c^2}$$

Cosmology

- If a light source is moving away from the observer it's light will be red shifted
- If a light source is moving towards the observer it's light will be blue shifted
- The Doppler shift of a light source is calculated as follows

$$z = \frac{\Delta f}{f} = -\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$$

- The velocity of an astronomical object is proportional to its distance

$$v = Hd$$

- The universe is expanding
- The big bang theory states that
    - The universe expanded from a single point

    - Around 15 billion years ago
- Evidence for the big bang
    - The big bang states that initial the universe was filled with short wavelength radiation, with the expansion of the universe this becomes longer wavelength radiation, consistent with **background cosmic microwave radiation**
    - There is a 3:1 ratio of hydrogen to helium, consistent with the early universe being hot as predicted by the big bang theory
- Quasars
    - The most distant measurable objects
    - Discovered as bright radio sources
    - Show large optical red shifts