CAIE Physics A-level

Topic 25: Astronomy and Cosmology

Notes

25 - Astronomy and Cosmology

25.1 - Standard Candles

The **luminosity L** of an astronomical object is the total power of the radiation it emits. The **flux f** is akin to intensity as a measure of the radiation power per unit area. The observed flux of an object is related to its luminosity by the inverse square law:

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

where d is the distance to the object.
The denominator in this equation can be derived by considering that a light source radiates equally in all directions, such that the flux at a given distance d from the star is equal to the power passing through a point on the surface of an imaginary sphere with d as its radius.

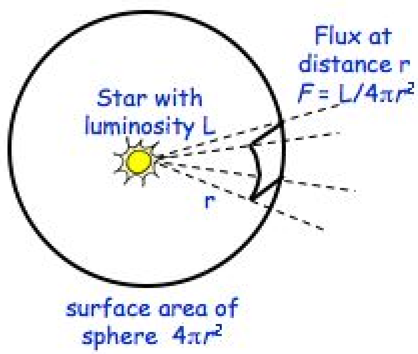


Image Source: https://astronomy.swin.edu.au/cosmos/F/Flux

If an object whose flux has been measured also has a known luminosity, then we can use the above flux-luminosity relation to determine the distance to the object. Such an object is called a **standard candle**, and is useful in determining the distances of far away galaxies.

For example if a distant galaxy contains a star with a known luminosity, and if we can measure its flux, then we can rearrange the equation to obtain

$$d = \sqrt{\frac{4\pi F}{L}}$$

and so the distance to the galaxy can be determined.

25.2 - Stellar Radii

A **blackbody** is a perfect emitter and absorber of all possible wavelengths of electromagnetic radiation. Stars can be modelled as blackbodies.

Wien's Displacement Law describes the relationship between the peak wavelength λ_{max} of a blackbody's emission and its temperature T. The law can be expressed as:

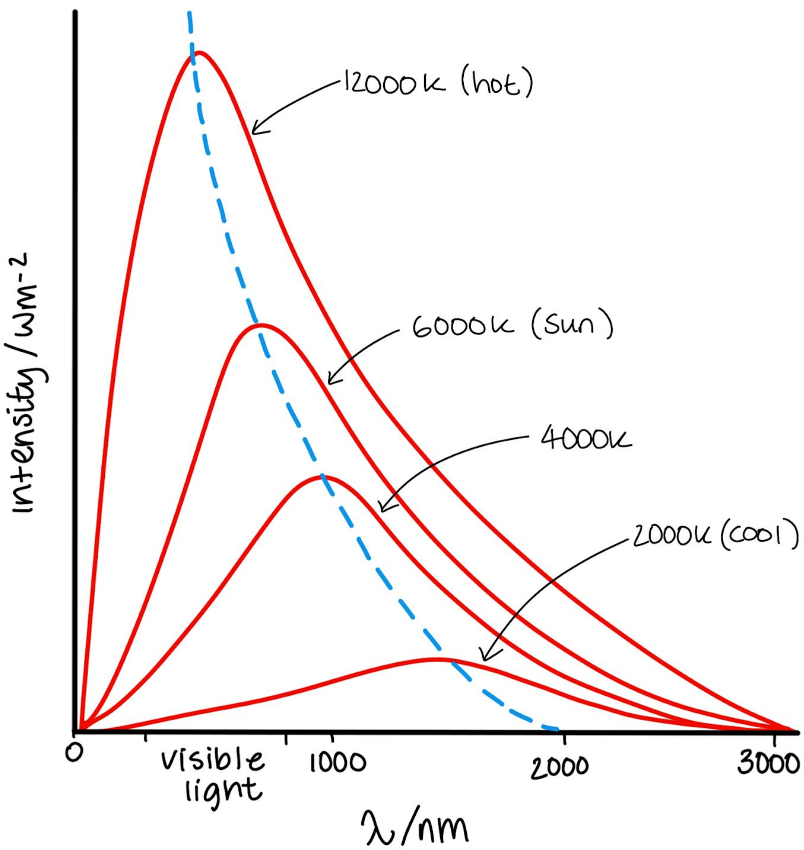
$$\lambda_{max} T = constant = 2.9 \times 10^{-3} m\ K$$

where the unit **m K** is **metres-Kelvin**, not milliKelvin.

Therefore

$$\lambda_{max} \propto 1/T$$

This means that the wavelength of peak emissions will decrease as the temperature of the body increases. In other words, the peak energy of the emitted photons will rise with temperature.



This law can be used to estimate the temperature of a blackbody emitter such as a star.
The **Stefan-Boltzmann Law** describes the relationship between the surface area (radius, r) and temperature, T, of a star and its luminosity L. It is given as follows:

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

where σ is the **Stefan-Boltzmann constant,** $\sigma = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$.

The $4\pi r^2$ term represents the surface area of the star. Physically, the Stefan-Boltzmann law states that the bigger and hotter the star, the brighter it will be.

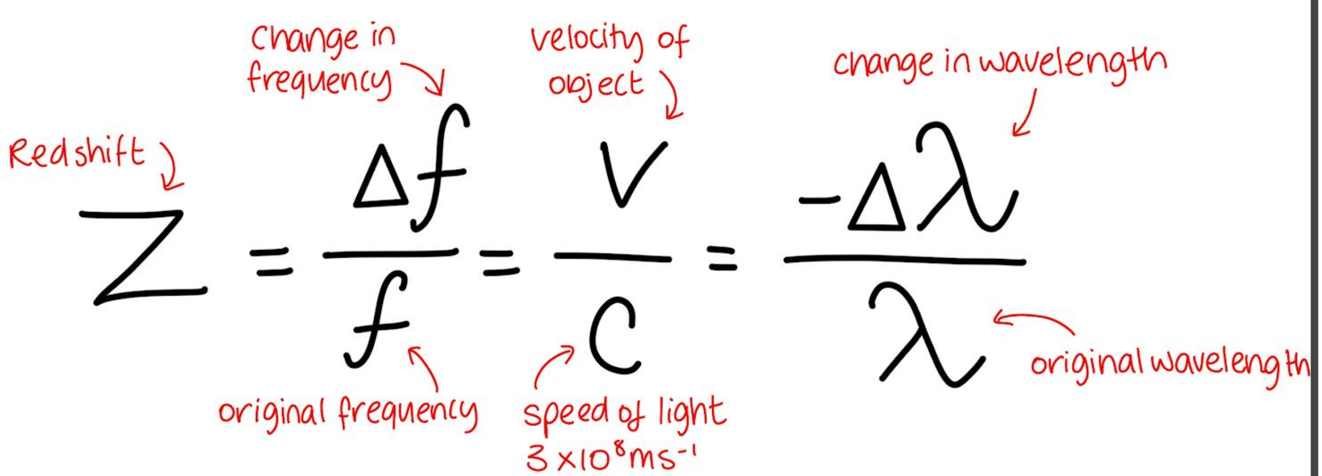
The Wien and Stefan-Boltzmann laws can be combined if one knows the luminosity from the flux-luminosity relation in the previous sections. Having estimated the temperature from Wien's Law, you can rearrange the Stefan-Boltzmann law to calculate the radius of the star.

25.3 - Hubble's Law and the Big Bang Theory

In 1929 Edwin Hubble observed numerous galaxies and found that their emission lines showed an **increase in wavelength** compared to their known values. This is known as **redshift** because the light emitted by the galaxies is being shifted to the longer, and therefore 'redder', wavelengths.

Redshift is an instance of the **Doppler Effect** where the relative motion of emitting objects causes a change in the observed wavelength of the radiation. In this case, the wavelengths are longer because the galaxies are **moving away** from us.

The redshift can be related to the fractional change in wavelength and the **recessional velocity v** of the galaxy:



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

The recessional velocities of the galaxies are plotted against their distances (in Megaparsecs) from us in the graph below- a linear relationship is shown. This means that **the further away a galaxy is from us, the faster it is receding from us**.

The constant of proportionality relating the two quantities is called the **Hubble Constant** H_0 where $v = H_0 d$.

H_0 is usually expressed in $km\ s^{-1} Mpc^{-1}$ as a result of the units used to measure the velocity and distances. Typical estimated values range from $65\ -\ 75\ km\ s^{-1}\ Mpc^{-1}$.

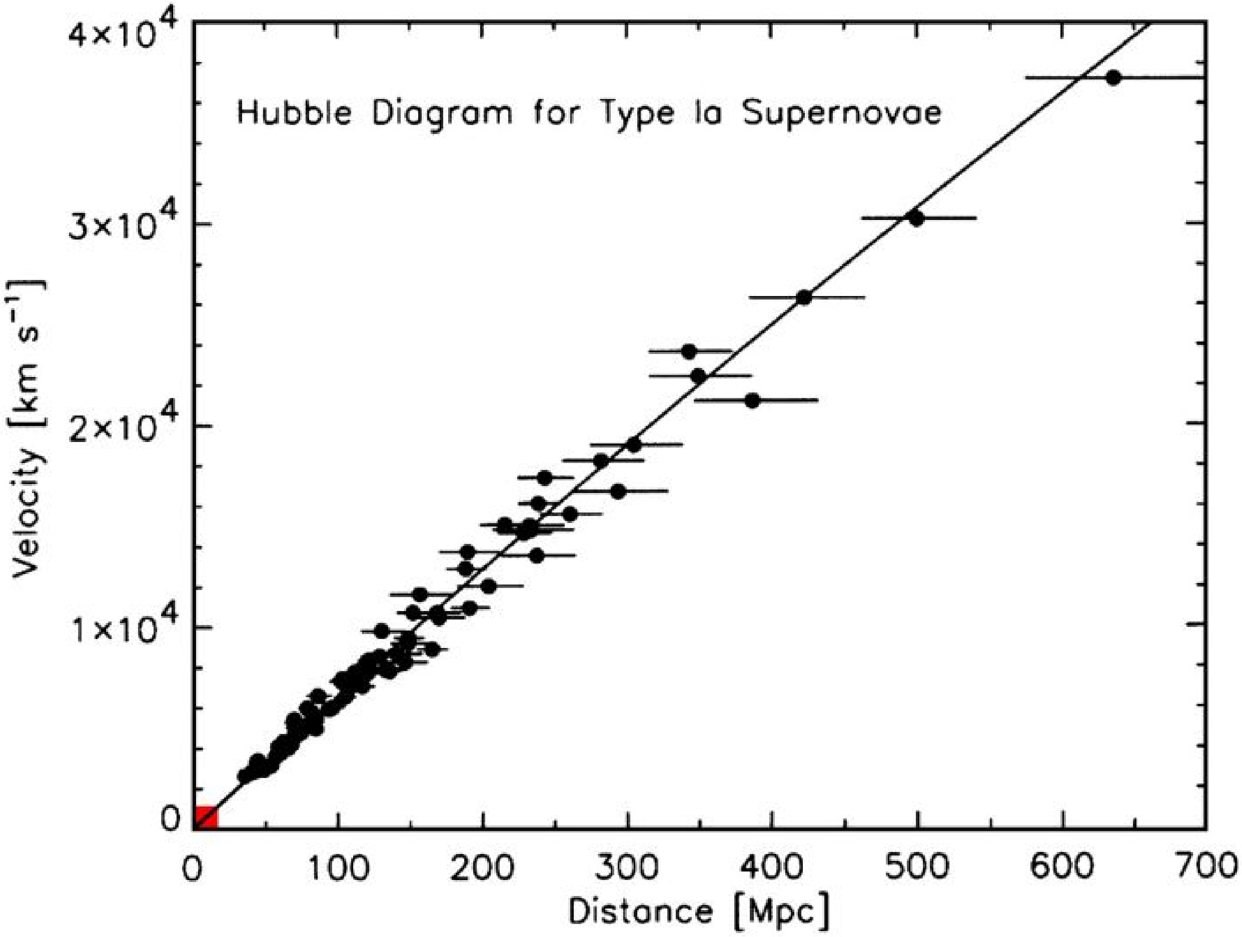


Image Source:
https://www.researchgate.net/figure/The-Hubble-diagram-or-the-velocity-distance-relation-plot-for-type-Ia-supernovae_fig1_331983227

The presence of galactic redshift showing that galaxies are all receding away from us implies that in the past they were all closer together than they are now.

The recession is not a phenomenon that only we observe, but rather an observer in any other galaxy would also be able to see the rest of the galaxies moving away from them. Imagine the expansion of a loaf of raisin bread from the perspective of a raisin: all the other raisins would be observed as moving away from you, but they would see the same from their perspective.

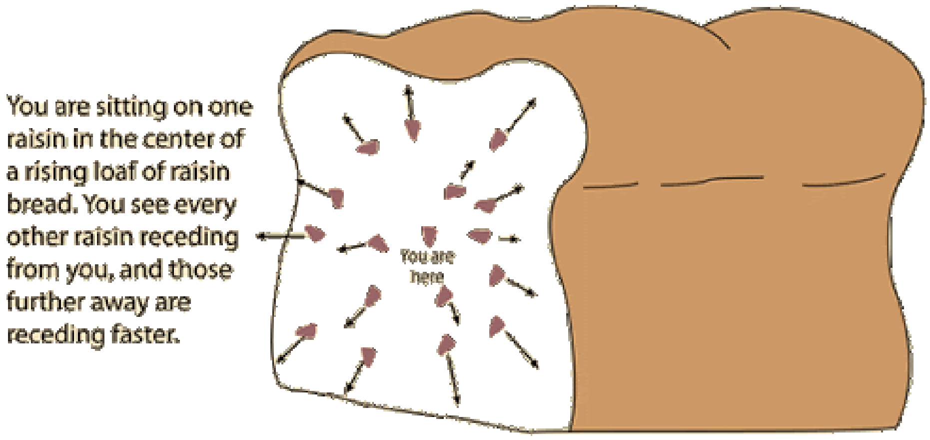


Image Source: http://hyperphysics.phy-astr.gsu.edu/Nave-html/Faithpathh/Myth61.html

If you were to wind back the clock you would see all galaxies moving closer to each other as you move back in time. This implies that, at some point, the matter in the Universe must have been concentrated down to a tiny point of massive density known as a **singularity**. The expansion of the Universe from this point is the key concept behind the **Big Bang Theory**- the commonly accepted theory describing the origin of the observable Universe.