Astronomy and cosmology

Luminosity and radiant flux intensity, the inverse square law, standard candles, Wien's displacement law, the Stefan-Boltzmann law and estimating a star's radius, redshift, the expanding Universe, Hubble's law and the Big Bang.

25.1 Standard candles

Luminosity and radiant flux intensity

Luminosity L is the total power of radiation emitted by a star, measured in watts.

Radiant flux intensity F is the radiant power per unit area arriving at an observer, in W/m². This is what we measure.

The inverse square law

The star's power spreads out over a sphere of area $4\pi d^2$:

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

So doubling the distance gives one quarter of the flux.

Standard candles

A **standard candle** is an object of **known luminosity**. Measuring the radiant flux from it, you can work out how far away it is, using $d = \sqrt{L/4\pi F}$.

Cepheid variable stars and type Ia supernovae are standard candles. If a standard candle is in a distant galaxy, then its distance gives the galaxy's distance.

> TRY IT
>
> **A standard candle has a luminosity of 3.8×10^{28} W and its radiant flux at Earth is 1.5×10^{-13} W/m². Find the distance.** $d = \sqrt{(3.8 \times 10^{28})/(4\pi \times 1.5 \times 10^{-13})} = 1.4 \times 10^{20}$ m.

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25.2 Stellar radii

Wien's displacement law

The hotter a star is, the shorter the wavelength at which it emits most strongly:

$\lambda_{\text{max}} \propto \frac{1}{T}$

So $\lambda_{\text{max}} T$ is constant, and its value is about 2.9×10^{-3} m K.

The Stefan–Boltzmann law

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

where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} and $4\pi r^2$ is the star's surface area. Doubling the temperature gives 16 times the power from each square metre.

Estimating a star's radius

1. Find the star's peak wavelength from its spectrum, and use Wien's law to find its surface temperature.
2. Find its luminosity from a standard candle or a measured flux and known distance.
3. Rearrange the Stefan–Boltzmann law: $r = \sqrt{L/(4\pi\sigma T^4)}$.

> **TRY IT**
>
> **A star has a peak wavelength of 400 nm and a luminosity of 6.0×10^{27} W. Estimate its radius.**
> $T = 2.9 \times 10^{-3}/4.0 \times 10^{-7} = 7250$ K. $r = \sqrt{(6.0 \times 10^{27})/(4\pi \times 5.67 \times 10^{-8} \times 7250^4)} = 1.7 \times 10^9$ m.

25.3 Hubble's law and the Big Bang theory

Redshift

The lines in the emission and absorption spectra of distant objects show an **increase in wavelength** from their known values. This is **redshift**, and it means they are moving away from us. For speeds much less than the speed of light:

$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$

> **TRY IT**

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A hydrogen line at 656 nm is observed at 660 nm from a galaxy. Find the galaxy's speed. $v = c\Delta\lambda/\lambda = 3.0 \times 10^8 \times 4/656 = 1.8 \times 10^6$ m/s, away from us.

The expanding Universe

Almost every distant galaxy shows redshift, and more distant galaxies show more of it. So galaxies are moving away from us and from each other, and the further they are, the faster they are receding. This leads to the idea that the **Universe is expanding**.

Hubble's law

$v \approx H_0 d$

The recession speed of a galaxy is approximately proportional to its distance, where H_0 is the Hubble constant. Only SI units (s^{-1}) are used.

The Big Bang

If the galaxies are moving apart now, then they were closer in the past. Running the expansion backwards, the whole Universe began from an extremely small, hot, dense state and has been expanding ever since. That is the **Big Bang theory**.

Since $v = H_0 d$, the time for a galaxy to reach distance d at its current speed is $d/v = 1/H_0$, which estimates the age of the Universe. With $H_0 = 2.3 \times 10^{-18}$ s^{-1}, it gives about 4.3×10^{17} s, or 14 billion years.

NOTE

Exam tip: for redshift and Hubble's law, take care with units: distances in metres, speeds in m/s, H_0 in s^{-1}. Redshift comes with distance across the Universe, and the speed here is the galaxy's speed away from us.

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