

Astronomy and Cosmology

Chapter 15 / A2 Level / Apollo Physics 9702



Basic Astronomy Vocabulary

Galaxy

A huge collection of dust, gases and stars bounded by gravitational force.

- Spiral galaxy
- Barred spiral
- Elliptical galaxy
- Lenticular galaxy
- Irregular galaxy
- Peculiar galaxy

Star

A huge cloud of gas, mostly hydrogen and helium, that produces light and heat using fusion reactions.

Meteoroid

A small rock or stone moving in space. When it enters Earth's atmosphere, it becomes a meteor.

Comet

A collection of frozen gas, dust, rock and ice. Due to heat, a gas and dust trail is left behind forming a tail.

Asteroid

A large-size stone that floats in space. Meteoroids are small stones broken out of asteroids. They can

have an orbit around a star.

Black hole

A place in space where gravity is so strong that even light cannot escape. It is produced when a star dies.

Planet

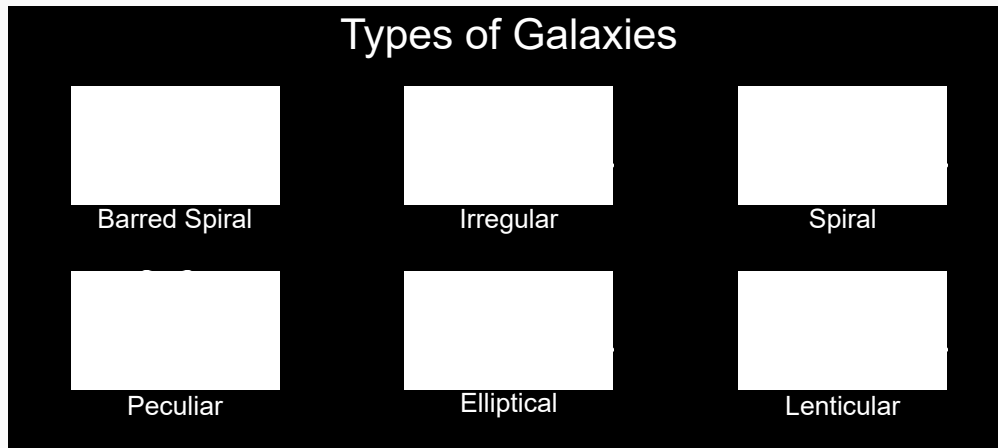
A celestial body that:

1. orbits a star,
2. is spherical due to sufficient gravity,
3. has no debris around it; it has a clear orbit.

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Pluto is a dwarf planet because it orbits along with other masses in the Kuiper belt.

Types of Galaxies



Luminosity and Radiant Flux Intensity

Stellar and interstellar

- **Stellar:** related to stars.
- **Interstellar:** between stars.

Luminosity

The word luminous means glowing or emitting energy.

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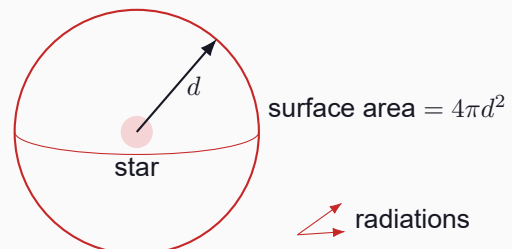
Luminosity is the total power of the radiation emitted by the star.

- The radiation includes light and all electromagnetic radiations.
- Luminosity is affected by surface area of the radiant body and the surface temperature.
- Sun's luminosity: approximately 4×10^{26} W.
- Proxima Centauri: approximately 4×10^{23} W.

Radiant flux intensity

Radiant flux intensity is the luminosity incident per unit surface area normal to that surface.

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



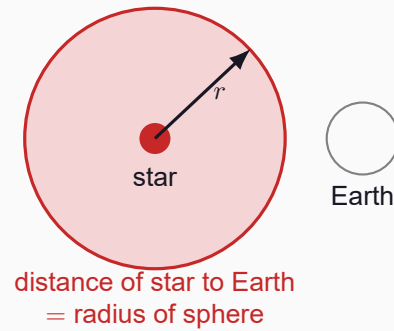
Where L is luminosity in W and d is the distance from the centre of the star to the surface.

Standard Candles

A body of known luminosity is called a **standard candle**. Luminosity is not just for light but for any radiation, for example heat.

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Common standard candles: Type Ia supernovae and Cepheid variables.



Worked example: luminosity of the Sun

The radiant flux intensity of solar radiation at Earth's surface is about 1400 W.m^{-2} . The mean Earth-Sun distance is $1 \text{ AU} = 1.50 \times 10^{11} \text{ m}$. Estimate the luminosity of the Sun.

$$I = 1400 \text{ W.m}^{-2},$$

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

$$1400 = \frac{L}{4\pi(1.5 \times 10^{11})^2},$$

$$L \approx 3.96 \times 10^{26} \text{ W}.$$

Black Body Radiation

$$\alpha + \rho + \tau = 1$$

Symbol	Meaning
α	absorbed fraction
ρ	reflected fraction
τ	transmitted fraction

- A body appears transparent because $\tau = 1$, $\alpha = 0$, $\rho = 0$. All radiation can pass through.
- A body is opaque because $\tau = 0$ and $\alpha + \rho = 1$. Some radiation gets absorbed and some gets reflected.
- Coloured opaque objects absorb all radiations and reflect only the colour which appears to be the colour of the object. Example: a red box appears red because all colours are absorbed and red is reflected.
- A black object appears black because all radiations are absorbed and no radiation is reflected back.

Definition and properties of a black body

A black body is therefore considered a perfect absorber of all radiations and does not reflect any radiation.

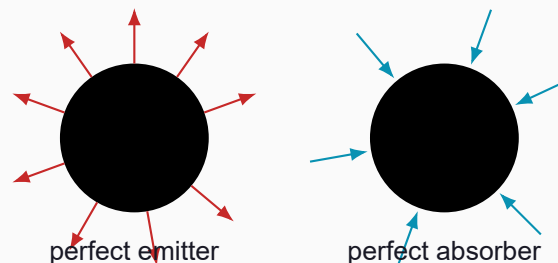
1. It completely absorbs incident radiation irrespective of wavelength. A black body is black because it does not reflect any radiation.
2. It is a perfect emitter. No other surface can emit more radiation than a black body at the same temperature.
3. It emits in all possible directions. A black body is a perfectly diffused emitter.

A black body acts either as a perfect absorber or a perfect emitter at a specific time. It does not act as both at the same time.

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A black body is basically a reference surface with which real surfaces are compared to determine how good an absorber or emitter that object is.

- Black objects are treated as black bodies.
- A tie is a black body for infrared radiations as a perfect absorber.
- A star is also a black body for infrared radiations as a perfect emitter.
- Stars are close to black-body objects.

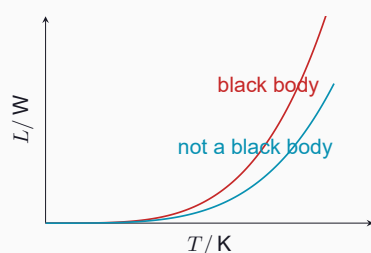


Stefan-Boltzmann Law

Luminosity of a black body at temperature T is directly proportional to its surface area and to T^4 .

$$L = \sigma AT^4$$

Quantity	Meaning
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$
A	surface area, $A = 4\pi r^2$
T	absolute temperature in K
L	luminosity in W



- The equation is applied considering surrounding temperature as 0 K.
- If surrounding temperature is higher, luminosity decreases.
- If two stars have the same luminosity, $L \propto A/T^4$; a hotter star must have a smaller radius and vice versa.

$$L = \sigma A (T^4 - T_s^4)$$

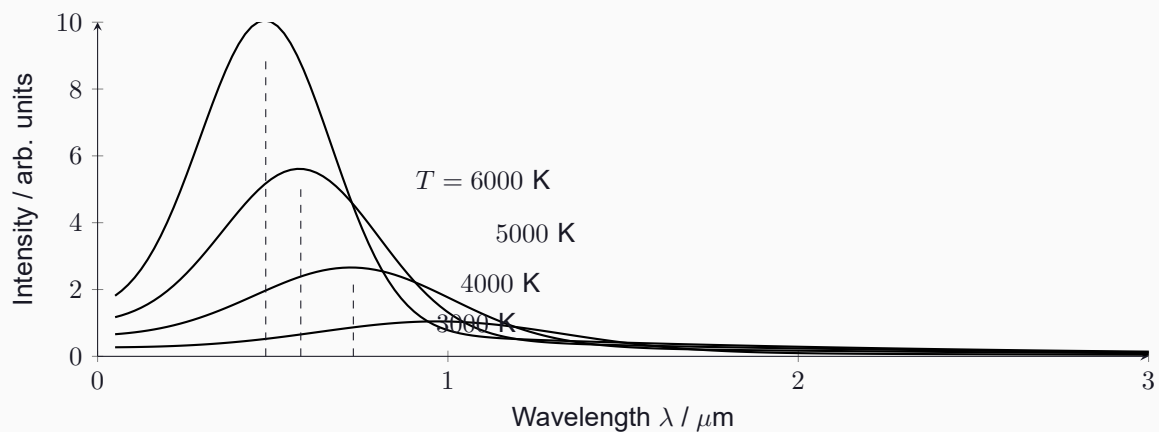
if the surroundings are at temperature T_s , not zero kelvin.

Wien's Displacement Law

The wavelength at peak intensity is inversely proportional to thermodynamic temperature.

$$\lambda_{\max} \propto \frac{1}{T}, \quad \lambda_{\max} = \frac{b}{T}, \quad \lambda_{\max} T = 2.9 \times 10^{-3} \text{ m.K}$$

- T is surface temperature in kelvin.
- $\lambda_{\max}$ is the wavelength having maximum intensity.
- At higher temperature, photon energy is higher, so intensity and the number of photons are higher.
- Higher temperature produces shorter wavelength.
- Colour of light from a hot object moves from red to blue and then to white.
- Brightness of light increases due to increasing intensity.



Red Shift and Hubble's Law

Red shift

When stars or galaxies move away from the observer, the observed frequency of light coming from it decreases. Hence a red shift is seen in its colour. The shift in frequency or wavelength is directly proportional to speed of recession.

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}, \quad \frac{\Delta f}{f} = \frac{v}{c}$$

This formula is applicable when v is much smaller than c . It is used to calculate the speed of the star or galaxy.

Hubble's Law

The speed of recession v of a star is directly proportional to the distance d of the star from Earth.

$$v = Hd$$

where:

- v is speed of recession,
- H is Hubble's constant,
- d is distance between source and observer at that instant.

$$H = 2.2 \times 10^{-18} \text{ s}^{-1}$$

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This idea of galaxies receding proves the Big Bang Theory: the universe is expanding. The presence of cosmic microwave background radiation also supports the Big Bang Theory.



Age of the Universe

How old is the universe?

$$\begin{aligned} v &= Hd, \\ c &= \frac{d}{T} \quad \text{for the fastest galaxy moving at } v = c, \\ c &= Hd, \\ T &= \frac{1}{H}. \end{aligned}$$

Using $H = 2.2 \times 10^{-18} \text{ s}^{-1}$,

$$T = \frac{1}{2.2 \times 10^{-18}} = 4.55 \times 10^{17} \text{ s}.$$

Converting into years,

$$T = \frac{4.55 \times 10^{17}}{365 \times 24 \times 3600} = 1.44 \times 10^{10} \text{ years}.$$

Worked Examples: Stefan-Boltzmann and Wien's Law

Example 1: luminosity and radius of a star

Given $\sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$, a star has luminosity $6.0 \times 10^{28} \text{ W}$ and surface temperature 3400 K.

(a) Show that its surface area is about $7.9 \times 10^{21} \text{ m}^2$.

$$L = \sigma AT^4$$

$$6.0 \times 10^{28} = 5.67 \times 10^{-8} \times A \times (3400)^4$$

$$A \approx 7.8 \times 10^{21} \text{ m}^2.$$

(b) Calculate its radius and the ratio of its radius to the radius of the Sun, using $r_{\text{Sun}} = 7.0 \times 10^8 \text{ m}$.

$$A = 4\pi r^2 \Rightarrow 7.8 \times 10^{21} = 4\pi r^2$$

$$r \approx 2.5 \times 10^{10} \text{ m}$$

$$\frac{r_{\text{star}}}{r_{\text{Sun}}} = \frac{2.5 \times 10^{10}}{7.0 \times 10^8} \approx 35.7.$$

Example 2: peak wavelength

If a star has peak intensity at wavelength 620 nm,

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

$$T = \frac{2.9 \times 10^{-3}}{620 \times 10^{-9}} \approx 4677 \text{ K}.$$

Example 3: larger diameter

If a star has twice the Sun's surface temperature and its diameter is four times the Sun's diameter:

$$L \propto AT^4.$$

Because diameter is four times, area is $4^2 = 16$ times. Because temperature is twice, T^4 is $2^4 = 16$ times. Therefore:

$$L_{\text{star}} = 16 \times 16 L_{\text{Sun}} = 256 L_{\text{Sun}}.$$

Worked Examples: Red Shift and Hubble's Law

Example 1: shifted spectral line

A spectral line of a star is displaced from its laboratory value of 434 nm by +0.087 nm. Determine whether it is moving towards or away from Earth and find the speed.

$$\Delta\lambda = +0.087 \text{ nm} \Rightarrow \text{red shift, so the star recedes.}$$

$$\begin{aligned}\frac{\Delta\lambda}{\lambda} &= \frac{v}{c} \\ \frac{0.087}{434} &= \frac{v}{3.0 \times 10^8} \\ v &\approx 6.0 \times 10^4 \text{ m.s}^{-1}.\end{aligned}$$

Example 2: recession speed and distance of a galaxy

The same spectral line is measured at 398.6 nm in a distant galaxy and 393.3 nm in the laboratory. Given $H = 2.2 \times 10^{-18} \text{ s}^{-1}$:

$$\begin{aligned}\Delta\lambda &= 398.6 - 393.3 = 5.3 \text{ nm} \\ \frac{5.3}{393.3} &= \frac{v}{3.0 \times 10^8} \\ v &\approx 4.04 \times 10^6 \text{ m.s}^{-1}.\end{aligned}$$

Using Hubble's law:

$$\begin{aligned}v &= Hd \Rightarrow d = \frac{v}{H} \\ d &= \frac{4.04 \times 10^6}{2.2 \times 10^{-18}} \approx 1.8 \times 10^{24} \text{ m}.\end{aligned}$$

Example 3: light year

$$\begin{aligned}1 \text{ light year} &= c \times (365 \times 24 \times 3600) \\ &= 3.0 \times 10^8 \times 365 \times 24 \times 3600 = 9.46 \times 10^{15} \text{ m} \\ \frac{1.76 \times 10^{24}}{9.46 \times 10^{15}} &\approx 1.86 \times 10^8 \text{ light years}.\end{aligned}$$

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Cosmic microwave background radiation is the relic radiation left from the early hot universe and is taken as evidence for the Big Bang model.