EVOLUTION OF STARS

HERTZSPRUNG-RUSSELL DIAGRAM

The total power radiated by a star is called its intrinsic **luminosity** L (**luminosity**). The **apparent brightness** (**apparent luminosity**) b of a star as observed on Earth is the intensity of the light at the Earth's surface which is perpendicular to the path of the light. If a star of luminosity L is at a distance R from the Earth, then its apparent brightness b is

$$b = \frac{L}{4\pi R^2}$$

ignoring any absorption in space and assuming that the power radiated by the star will be spread over a sphere of surface area $4\pi R^2$.

Generally, the more massive the star, the greater its luminosity

Another important parameter of a star is its surface temperature. The surface temperature T can be determined from the spectrum of electromagnetic frequencies it emits using the Wien Displacement Law.

$$\lambda_{peak}\, T = 2.898 \times 10^{-3} \ \text{m.K}$$

The surface temperatures of stars typically range from about 3 000 K (reddish) to about 50 000 K (UV).

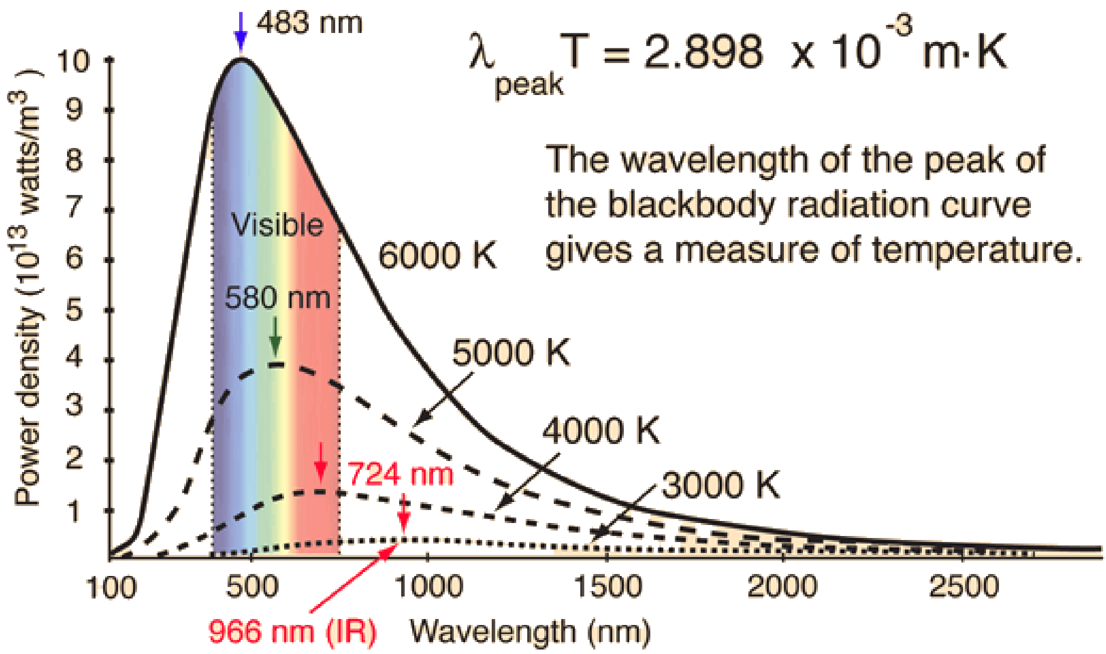

Fig. 1. Blackbody radiation curves.

The standard spectral class classification scheme is based on temperature. Most stars fit into one of the following types or spectral classes: O, B, A, F, G, K, M. These classes go from hot to cool with O the hottest and M, cool.

Spectral Type	**Surface Temperature [K] Colour**	**Spectral lines**
O	> 28 000 blue	He^+ lines strong UV continuum
B	10 000 – 28 000 blue-white	neutral He lines
A	7 500 – 10 000 white	strong H lines ionised metal lines
F	6 000 – 7 500 white-yellow	weak Ca^+ lines
G	4 900 – 6 000 yellow	Ca^+ lines metal lines
K	3 500 – 4 900 orange	Ca^+, Fe lines strong molecules CH, CN
M	< 3 500 red	molecular lines eg TiO metal lines

Many people use the mnemonic to help them:

Oh **B**e **A** **F**ine **G**irl (**G**uy) **K**iss **M**e

The **Hertzsprung-Russell diagram** (HR diagram) is one of the most important tools in the study of stellar evolution. Developed independently in the early 1900s by E. Hertzsprung and H. Russell. For most stars, its colour is related to the intrinsic luminosity and therefore to its mass. A useful way to present this relationship is by the so-called Hertzsprung–Russell (HR) diagram. It plots the temperature (colour - spectral type) of stars against their luminosity (absolute magnitude).

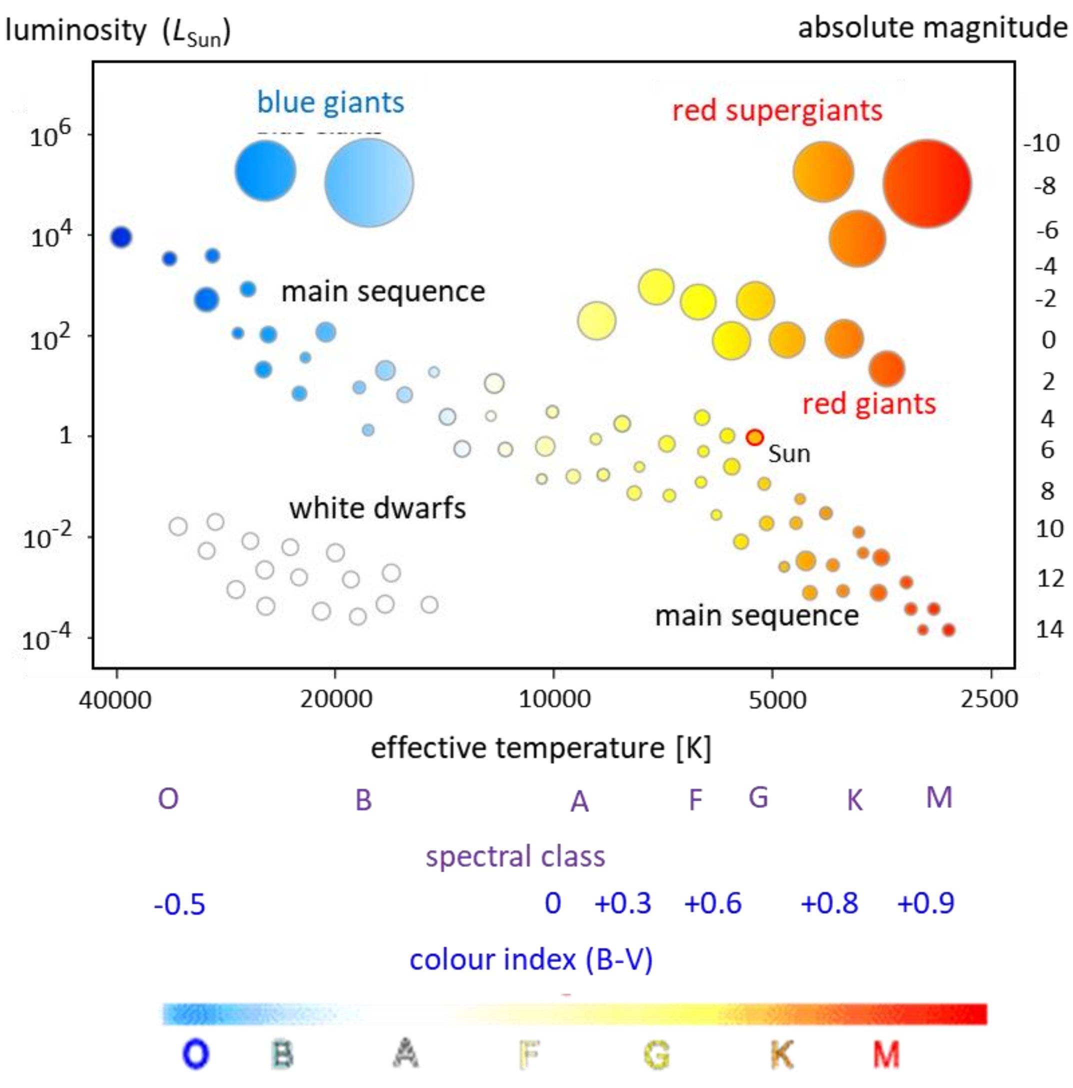

Fig. 1. Hertzsprung-Russell (H-R) diagram.

Definition of absolute magnitude

Starting at the lower right we find the coolest stars and by Wien's Displacement Law, their light output peaks at long wavelengths, so they are reddish in colour. They are also the least luminous and therefore of lowest mass. Farther up toward the left we find hotter and more luminous stars that are whitish, like our Sun. Still farther up we find even more luminous and more massive stars, bluish in colour. Stars that fall on this diagonal band are called **main-sequence stars**. There are also stars that fall outside the main sequence. Above and to the right we find extremely large stars, with high luminosities but with low (reddish) colour temperature: these are called **red giants**. At the lower left, there are a few stars of low luminosity but with high temperature: these are the **white dwarfs**.

Depending on its initial mass, every star goes through specific evolutionary stages dictated by its internal structure and how it produces energy. Each of these stages corresponds to a change in the temperature and luminosity of the star, which can be seen to move to different regions on the HR diagram as it evolves. This reveals the true power of the HR diagram – astronomers can know a star's internal structure and evolutionary stage simply by determining its position in the diagram.

The three evolutionary stages) of the HR diagram:

1. Most stars, including our Sun, are found along a region called the **Main Sequence**. Main Sequence stars vary widely in effective temperature but the hotter they are, the more luminous they are. So, the main sequence stretches from the upper left (hot, luminous stars) to the bottom right (cool, faint stars) dominates the HR diagram. It is here that stars spend about 90% of their lives burning hydrogen into helium in their cores.

2. **Red giant** and **supergiant** stars occupy the region above the main sequence. They have low surface temperatures and high luminosities which, according to the Stefan-Boltzmann Law, means they also have large radii. Stars enter this evolutionary stage once they have exhausted the hydrogen fuel in their cores and have started to burn helium and other heavier elements.

3. **White dwarf** stars are the final evolutionary stage of low to intermediate mass stars, and are found in the bottom left of the HR diagram. These stars are very hot but have low luminosities due to their small size.

The Sun is found on the main sequence with a luminosity of 1 and a temperature of around 5400 K.

Why do these three groups differ so much in **luminosity**?

The answer to this question depends upon the Stefan-Boltzmann relationship: The total power radiated from the surface of a star increases with temperature

$$P_{\text{radiated}} = \varepsilon \sigma A T^4$$

Total power radiated from surface of star (thermal radiation)

$P_{radiated}$ [watts W]

Stefan-Boltzmann constant σ = 5.6705x10^{-8} W.m^{-2}.K^{4}

Emissivity of star surface ε = 1

Surface area of star A [m^2] Radius of star R [m]

$$A = 4\pi R^2$$

Surface temperature of star T

[measured in kelvin K: T K = 273.15 + T °C]

Hence,

$$P_{\text{radiated}} = 4\pi \sigma R^2 T^4$$

If two stars have the same effective temperature but one star is more luminous (greater power output) than the other, then, it must have a larger radius and a greater surface area

For stars of the same temperature,

the more luminous stars are bigger

Exercise 1

The intensity of the radiation from the Sun reaching the Earth is known as the solar constant I_0.

$$I_0 = 1362 \text{ W.m}^{-2}$$

Estimate the luminosity of the Sun given that the distance between the Sun and Earth is

$$R_{SE} = 1.496 \times 10^{11} \text{ m}$$

A main sequence star has a peak wavelength in its emission spectra of 289.8 nm.

What band of the electromagnetic spectrum does the peak wavelength belong to?

Estimate the surface temperature of the star.

It measured apparent brightness is $2.0 \text{x} 10^{-12}$ W.m^{-2}.

Estimate the distance of the star from the Earth.

Estimate the radius of the star and compare its value with the radius of the Sun.

Hint: use the HR diagram (figure 1).

Stefan-Boltzmann constant $\sigma = 5.6704 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$

Solution

The luminosity L of the Sun and the Solar constant I_0 are connected by the relationship

$$I_0 = \frac{L_{Sun}}{4\pi R_{SE}{}^2} \quad L_{Sun} = I_0\left(4\pi R_{SE}{}^2\right) \quad R \equiv R_{SE} \quad b \equiv I_0$$

$$I_0 = 1362 \text{ W.m}^{-2} \qquad R_{SE} = 1.496\times10^{11} \text{ m}$$

$$L_{Sun} = (1362)(4\pi)\left(1.496\times10^{11}\right)^2 \text{ W} = 3.83\times10^{26} \text{ W}$$

Peak wavelength $\lambda_{peak} = 289.8\times10^{-9}$ m

Surface temperature T of star

$$T = \frac{2.898\times10^{-3}}{289.8\times10^{-9}} \text{ K} = 1.0\times10^4 \text{ K}$$

From the HR diagram: main sequence star with surface temperature 10 000 K, its luminosity L is

$$L \sim L_{Sun} = 3.83\times10^{26} \text{ W}$$

The apparent brightness b of the star and its luminosity L are connected by the equation

$$b = \frac{L}{4\pi R^2}$$ R is the distance between the star & Earth

Therefore, the distance to the star [m and light years ly[is

$$b = 2\times10^{-12}\ \text{W.m}^{-2} \quad L = 3.83\times10^{26}\ \text{W}$$

$$R = \sqrt{\frac{L}{4\pi b}} = 4\times10^{18}\ \text{m}$$

$$1\ \text{ly} = \left(3\times10^{8}\right)\left(3600\right)\left(24\right)\left(365\right)\ \text{m} = 10^{16}\ \text{m}$$

$$R = \frac{4\times10^{18}}{10^{16}} = 400\ \text{ly}$$

The luminosity L of the star is connected to its radius a

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

$$\sigma = 5.6704\times10^{-8}\ \text{W.m}^{-2}.\text{K}^{-4}$$

$$T = 1.0\times10^{4}\ \text{K} \quad L = 3.83\times10^{26}\ \text{W}$$

$$a = \sqrt{\frac{L}{4\pi\ \sigma T^4}} = 2.3\times10^{8}\ \text{m}$$

Radius of Sun $R_S = 6.96\times10^{8}\ \text{m}$

So, the radius of the star is smaller than the radius of the Sun

$$\frac{a}{R_S} = \frac{2.3\times10^{8}}{6.96\times10^{8}} = 0.3$$

[VISUAL PHYSICS ONLINE]

If you have any feedback, comments, suggestions or corrections please email:

Ian Cooper School of Physics University of Sydney

ian.cooper@sydney.edu.au