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**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



ignoring any absorption in space and assuming that the power radiated by the star will be spread over a sphere of surface area .

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](http://www.physics.usyd.edu.au/teach_res/hsp/sp/mod7/m7black.pdf).



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

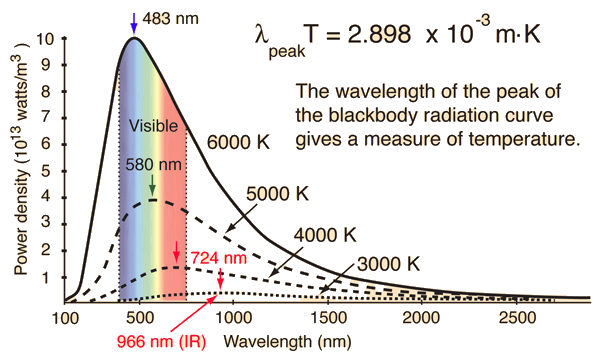


Fig. 1. Blackbody radiation curves.

The standard [spectral class classification](http://astro.unl.edu/naap/hr/hr_background1.html) 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:

**O**h **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).

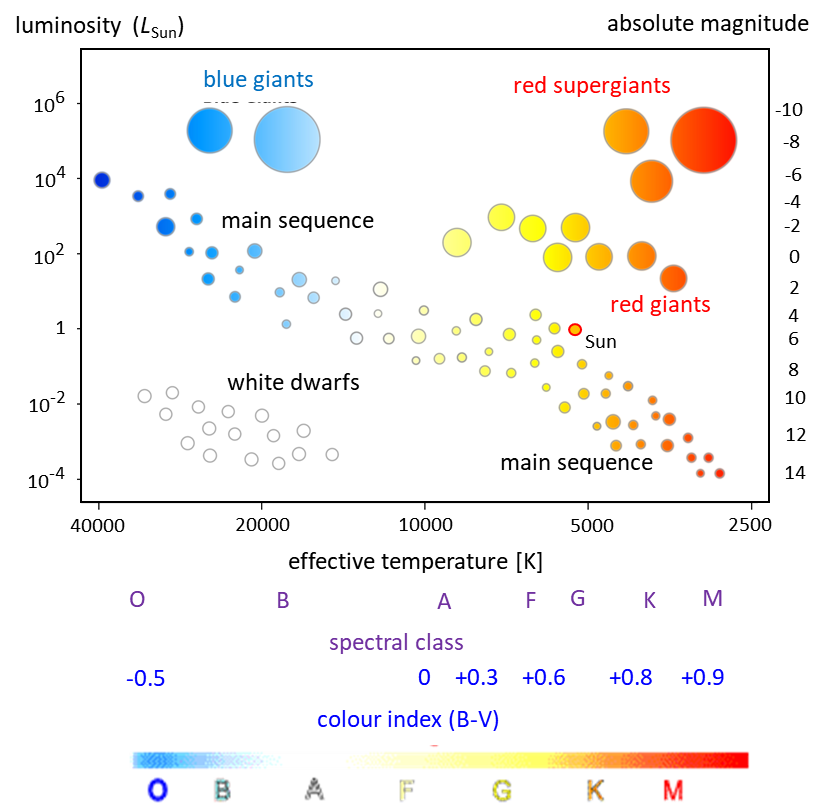


Fig. 1. Hertzsprung-Russell (H-R) diagram.

[Definition of absolute magnitude](http://astronomy.swin.edu.au/cosmos/A/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**.

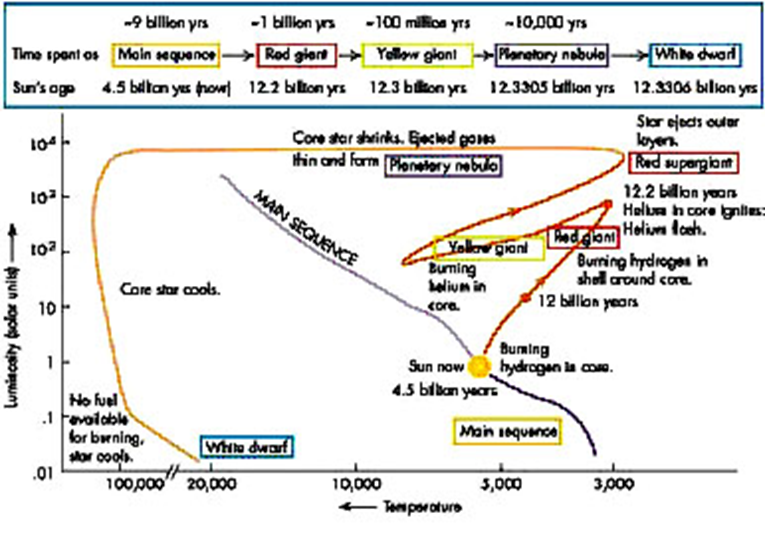
Depending on its initial mass, every star goes through specific evolutionary stages dictated by its internal structure and how it produces energy. Each of these stages corresponds to a change in the temperature and luminosity of the star, which can be seen to move to different regions on the HR diagram as it evolves.

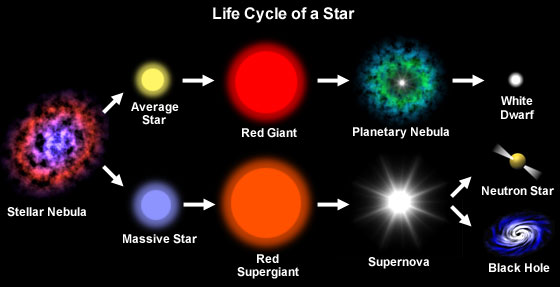
This reveals the true power of the HR diagram – astronomers can know a star’s internal structure and evolutionary stage simply by determining its position in the diagram.

Three evolutionary stages shown by 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](http://www.physics.usyd.edu.au/teach_res/hsp/sp/mod7/m7black.pdf), 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



Total power radiated from surface of star (thermal radiation) *Pradiated*  [watts W]

Stefan-Boltzmann constant *σ* = 5.6705x10-8 W.m-2.K4

Emissivity of star surface *ε* = 1

Surface area of star *A*  [m2] Radius of star *R* [m]



Surface temperature of star *T*

[measured in kelvin K: *T* K = 273.15 + *T* oC]

Hence,



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 .    Estimate the luminosity of the Sun given that the distance between the Sun and Earth is      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 2.0x10-12 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  **Solution**  The luminosity *L* of the Sun and the Solar constant  are connected by the relationship          STAR  Peak wavelength  Surface temperature *T* of star    From the HR diagram: main sequence star with surface temperature 10 000 K, its luminosity *L* is approximately the same as our Sun    The apparent brightness *b* of the star and its luminosity *L* are connected by the equation  *R* is the distance between the star & Earth  Therefore, the distance to the star [ m and light years ly ] is    The luminosity *L* of the star is connected to its radius a          Radius of Sun  So, the radius of the star is smaller than the radius of the Sun |

Why are there different types of stars?

How is a star born?

A star is born when gas clouds of mainly hydrogen contract under the force of gravity. The mass of the cloud clusters into globules causing an increase in the rate of contract and an increase in kinetic energy of the gas molecules to form protostars.



When the kinetic energy of the gas molecules exceeds the Coulomb repulsion between the molecules, nuclear fusion reactions occur. In our Sun, the “burning” of hydrogen occurs mainly via the **proton-proton cycle** in which four protons fuse to from a helium nucleus with the release of gamma rays and neutrinos.

proton 1H1 *mP* = 1.00727645232093 u

deuterium 2H1 *mD* = 2.01355319821093 u

helium-3 3He2 *m*3= 3.01493216025186 u

helium-4 4He2 *m*4= 4.001506094311861 u

electron *me* = 5.4857990907x10-4 u

1 u = 931.4940954 MeV/*c*2

mass defect  = *mProducts - mReactants*

*Q-*value 

*Q* < 0 exothermic reaction: energy released

*Q* > 0 endothermic reaction: energy absorbed

(1) 1H1 + 1H1   2H1 + e+ + 

*Q*1= (2.014102 + 5.489x10-4 – 1.007825 – 1.007825 )(931.5) MeV

*Q*1= - 0.42 MeV

(2) 1H1 + 2H1  3He2 + 

*Q*2= (3.01493216025186 - 1.00727645232093

- 2.01355319821093)(931.5) MeV

*Q*2= - 5.49 MeV

(3) 3He2 + 3He2  4He2 + 1H1 +1H1

*Q*3= (4.001506094311861 + 1.00727645232093 +1.00727645232093 - 3.01493216025186

-3.01493216025186)(931.5) MeV

*Q*3= - 12.86 MeV

The net result of the proton-proton cycle is that four protons combine to form one 4He2 nucleus plus two positrons two neutrinos and two gamma rays (it takes two of each of the first two reactions to produce the two 3He2 for the third reaction):

2(1H1 + 1H1)  2(2H1 + e+ + ) 2 = - 0.84 MeV

2(1H1 + 2H1)  2(3He2 + ) 2 = - 11.98 MeV

3He2 + 3He2  4 He2 + 1H1 +1H1  = - 12.86 MeV

(4) 4(1H1 )  4He2 + 2e+ + 2  + 2   = - 24.68 MeV

The total energy released for the net reaction is 24.38 MeV. But, the two positrons (reaction 1) will quickly annihilate with two electrons to release more energy

2(2*mec*2) = (4)( 5.4857990907x10-4)( 931.4940954) MeV

= 2.04 MeV

So, the total energy released is **26.75 MeV**.

Reaction 1 which produces the deuterium 2H1 has a very low probability and thus occurs very infrequently and this limits the rate at which the sun produces energy.

In stars that are more massive than the Sun, it is more likely that the energy output comes principally from the **CNO** (carbon) cycle. One possible sequence of the CN) cycle is

carbon *m*(12C6)= 11.99670852054558 u

*m*(13C6)= 13.00006335561558 u

nitrogen *m*(13N7)= 13.001898549636509 u

*m*(14N7)= 13.999233945066509 u

*m*(15N7)= 14.99626883951651 u

oxygen *m*(15N08)= 14.99867697872744 u



The two positrons will annihilate with two electrons releasing a further 2.04 MeV. so, the total energy released in the CNO cycle is **26.74 MeV**.

The theory of the proton-proton cycle and the CNO cycle as the source of energy for stars was first proposed by Hans Bethe in 1939. Both cycles involve the transformation of four protons into a helium-4 nucleus.

**NUCLEAR FUSION**

So, the energy source for stars is nuclear fusion which mainly involves the fusion of four protons to form a helium-4 nucleus. To accomplish nuclear fusion, the positively charged nuclei involved must first overcome the electric repulsion to get close enough for the attractive nuclear strong force to take over to fuse the particles. This requires extremely high temperatures. We can do some simple computations to estimate the kinetic energies of the particles and the temperature for fusion to occur.

What is the kinetic energy of a gas at room temperature (300 K) in J and MeV?

The average translation kinetic energy  for a gas is related the temperature of the gas



Boltzmann constant = 1.38066x10-23 J.K-1

at 300 K 

Considering the Coulomb barrier *UC* due to the electric repulsion to be the electric potential energy of two-point charges (with atomic numbers *Z*1and *Z*2and with radii *R*1 and *R2*), then the energy required to reach a separation is given by



The radius *R* of a nuclear is approximated by the expression



*A* is the mass number of the nucleus

Hence, to penetrate this barrier the kinetic energy of each particle is



and the temperature *T* of the plasma (ionized gas) of the star is



This estimated for the temperature is an overestimate since we have used the average temperature. In the plasma, many of the nuclei will be moving with energies much greater than the average. The particles involved in the fusion process have a wave nature and so can **tunnel** through the barrier with an energy much lower than that given by the Coulomb barrier.

What are the approximate energies and temperatures required for nuclear fusion to occur in the proton-proton cycle and the CNO cycle?

Proton-proton cycle: fusion of two protons



The energy of a particle involved in a nuclear fusion reaction is about 10 000 000 times greater than the energy of a gas molecule moving about at room temperature. The energies involved in nuclear fusion reactions are enormous and this is why a star can shine for billions of years using hydrogen as the “fuel”.

CNO cycle: fusion of a carbon-12 nucleus and a proton



The required energies and temperature for fusion to occur in the CNO cycle are much greater than those for the proton-proton cycle.

The nuclear fusion in occurs only in the interior of stars because of the higher temperatures required to sustain fusion reaction.

**EVOLUTION OF STARS**

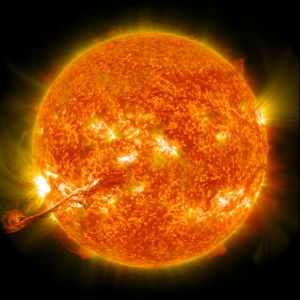
After the formation of protostars, the tremendous release of energy in these nuclear fusion reactions produces sufficient pressure to stop the gravitational contraction and the protostar stabilizers to become a young main sequence star. Exactly where the star sits on the main sequence band in the HR diagram depends upon its mass. The more massive the star, the further up and to the left it will be located on the HR diagram. From gas cloud to young main sequence star takes about 30 million years (3x107 y). Stars such as our Sun will remain as a main sequence star for about 10 billion years (1010 y).

At the core of the star, the hydrogen fuel is consumed, and a shell of helium is formed surrounding it. When much of the hydrogen is consumed within the core, the production of energy decreases, and the gas pressure is no longer sufficient to prevent the huge gravitational forces from once again causing the star to contract and the core to heat up. The hydrogen in the shell now burns (*burn* refers to high temperature nuclear fusion reactions and must not be confused with ordinary burning in air which is are chemical reactions) fiercely producing a rise in temperature which results in an expansion of the outer envelope of the star. The expansion of the nonburning envelop cools and the surface temperature of the star is reduced and produces a spectrum which has peaks at longer wavelengths. The star becomes redder, bigger and more luminous as it leaves the band of main sequence stars. So, the star will move to the right and upward on the HR diagram and enter the **red giant** stage.



Red giant star 1 Gruis in the southern constellation of Grus (The Crane). Notice the blue star 2 Gruis.

Our Sun has been a main sequence star for about 4.5x109 y and most likely remain as a main sequence star for another 5x109 y When our Sun leaves the main sequence, it is expected to grow in size as a red giant until it occupies the volume out to approximately the size of the Earth’s orbit. So, no need to worry about our Sun becoming a red giant star any time soon.

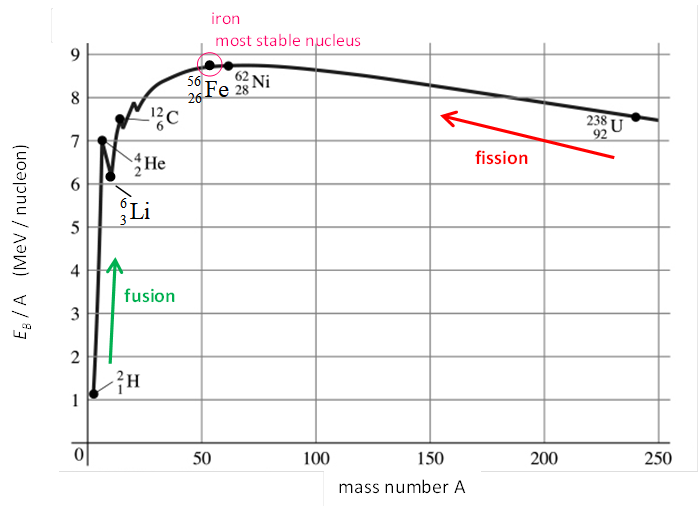


As the star’s envelope expands, the core is shrinking and heating up. When the core temperature reaches about 108 K, even helium nuclei with their greater charge and hence greater electrical repulsion can undergo fusion. The fusion of three helium-4 nuclei produces the isotope carbon-12



The first reaction is slightly endothermic and the 8Be4 nuclei is unstable and can decay back into two alpha particles within 10-16 s. So, the second reaction must occur very quickly after the first reaction for carbon-12 to be produced.

This burning of helium causes major changes in the star, and the star now moves rapidly along the horizontal branch of the HR diagram. For stars with a mass greater than about 0.7 solar masses, as its core temperature increases nuclei as heavy as 56Fe26 and 56Ni28 can be produced within the star. Here, the process of **nucleosynthesis** where heavy nuclei are formed by the fusion of lighter ones ends since the average binding energy per nucleon begins to decrease for A greater than about 60.



For stars with a mass less than 1.4 solar masses (Chandrasekhar limit), no further fusion can take place and the star collapse under the action of gravity to become a **white dwarf** star (on the HR diagram the trajectory is from the upper left downward). A star such as our Sun will shrink to a about the size of the Earth. The white dwarf halts its collapse due to the repulsion between electron clouds (Pauli Exclusion Principle). The white dwarf star will continuous to lose energy, hence decreasing its temperature as it becomes dimmer and dimmer until its “lights go out”. The result is a **black dwarf** which is just a chunk of dark cold ash.

Massive stars (mass greater than 1.4 solar masses) follow a very different scenario. Gravity is so strong, contraction can continue resulting in extremely high core temperatures and pressure, so that fusion can continue to produce elements heavier than iron and collisions between nuclei can result in the destruction of heavy nuclei to form alpha particles, protons and neutrons.

The temperatures and pressures can become so greater that an energy-requiring endothermic reaction can force electrons and protons to from neutrons (inverse  decay).

e- + p+  n + 

We end up with an enormous nucleus made up of almost exclusively of neutrons. The size of the star is no longer limited by the Pauli Exclusion Principle applied to electrons, but rather applied to neutrons. The star then contracts rapidly to form an enormously dense **neutron star**. As the contraction continues to form the final core of the neutron star, a catastrophic explosion may occur where the entire outer envelope of the star is blow away, spreading its contents into the surrounding interstellar space. In this explosion it is believed that virtually all the elements of the periodic table are created. This explosion is observed as a **supernova**. In a supernova explosion, a star’s brightness is observed to suddenly increase billions of times in a period of just a few days and then fade away over a few months.

Examples of supernova events observed with the naked eye include:

* Feb 1987 in the Large Magellanic Cloud, 170 000 ly away.
* 1604 observed by Kepler and Galileo
* 1054 observed by Chinese astronomers and some of the remains as still visible in the Crab Nebula. In the midst is a **pulsar** (rotating neutron star that emits sharp pulses of electromagnetic radio at regular intervals).

The core of a neutron star contracts to a point at which all neutrons are close together as they are in a nucleus (density ~ 1014x density of materials of Earth). A neutron star that mas a mass of 1.5 solar masses would have a diameter of only 10 km.

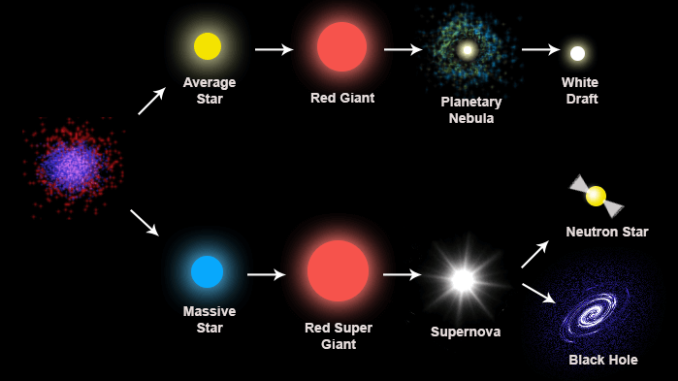


Supernova Remnant Menagerie

If the mass of the star is greater than about 3 solar masses, the gravitational force may force further contraction to even smaller diameters and ever increasing density, the force is so great that even the neutron Pauli Exclusion Principle can be overcome. Gravity is now so strong that light cannot escape (the escape velocity is greater than the speed of light). We now have a black hole. Since, no radiation can escape form the black hole, it would appear black. Black holes can be detector by observing the deflection of radiation passing not to near the black hole. If the radiation came too close, then it would be swallowed up, never to escape.

There may be a black hole at the centre of our galaxy and its estimated mass is several million solar masses.

[Black hole YouTube video](https://www.youtube.com/watch?v=FoExPq04OQQ)



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