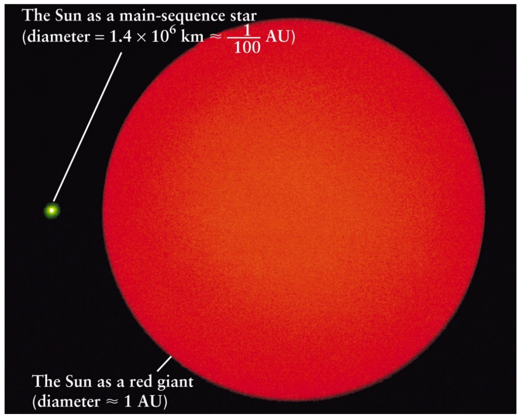
Red Giants



Universe by Freedman, Geller, and Kaufmann

Evolution on the Main Sequence

About 10 percent of a star's mass must be depleted of hydrogen before the star evolves away from the Main Sequence.

$$\tau \propto (10 \text{ x } 10^9 \text{ yr}) / \mathcal{M}^3$$

The more massive stars evolve the fastest. These stars spend only a few million years on the Main Sequence.

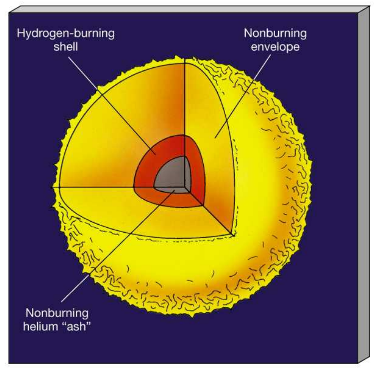
A star of 1 solar mass remains there for about 10 billion years.

An M0 V star (0.4 solar mass) has a Main Sequence lifetime of 200 billion years – longer than the age of the Universe.

Evolution on the Main Sequence

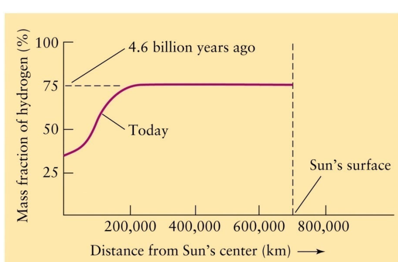
1. Over time there is a large build up of He in the core. This He is **not** participating in any fusion reactions. Because it is four times heavier than H, the He will *slowly* precipitate to the center region of the core.

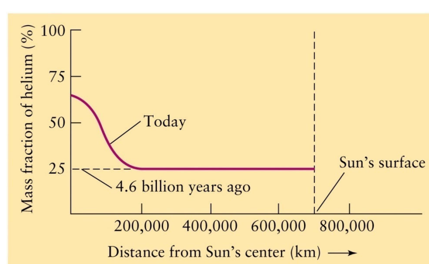
What was once a mixture of H and He becomes a homogenous **core** of He surrounded by a **shell** of H and He.



Astronomy Today, Chaisson and McMillan

Abundance Changes in the Sun



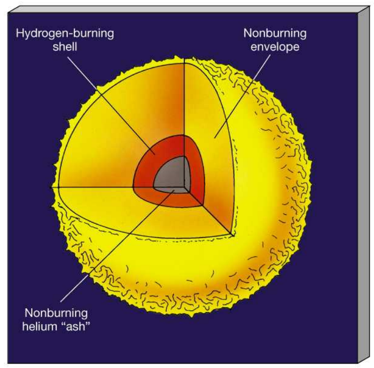


Universe by Freedman, Geller, and Kaufmann

Evolution on the Main Sequence

2. From this eventually-formed, central core of He, heat continues to escape.

Since there is no more nuclear energy generation (i.e., insufficient Pressure) to make up the deficit, the He core contracts gravitationally.



Astronomy Today, Chaisson and McMillan

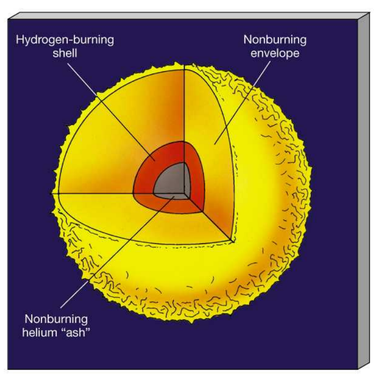
Evolution on the Main Sequence

3. As the core contracts, it heats itself – **as well as the layers just above it** – by converting potential energy.

Hydrogen is now fusing in a "**shell**". This shell produces most, but not all, the Pressure that fights the star's self-gravity.

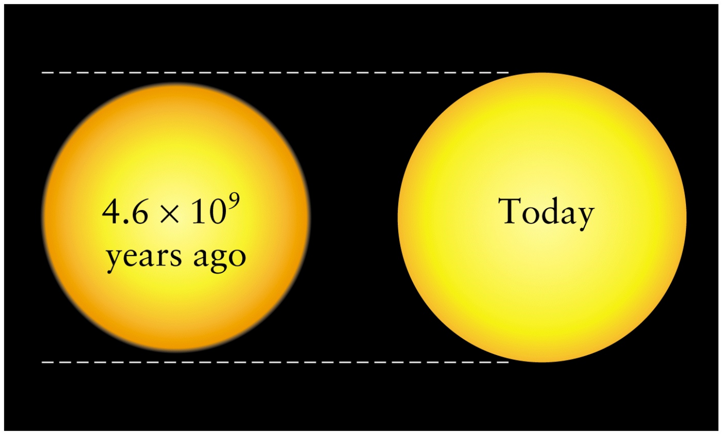
The change of the interior structure causes the star to leave the vicinity of the Main Sequence.

Why?



Astronomy Today, Chaisson and McMillan

Size Change

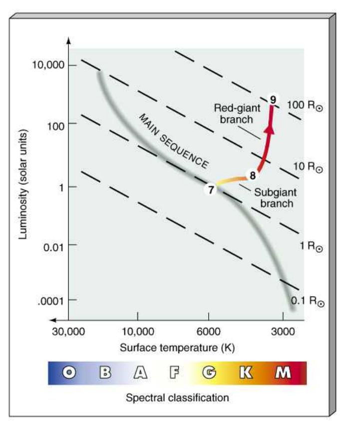


Universe by Freedman, Geller, and Kaufmann

Evolution to Red Giants

4. As the central He core contracts, it releases gravitational potential energy, which is **absorbed** in the H burning shell, making it burn faster. The ***bottom*** layer of the envelope above the shell ***heats up***, and the thermal motions cause the upper layers to expand immensely. However, in the outer layers, the density decreases. The ***outer*** layers ***cool***, and the star becomes red.

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

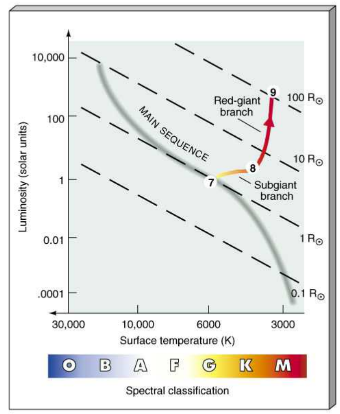


Astronomy Today, Chaisson and McMillan

Evolution to Red Giants

5. The He core continues to grow in mass, density, and temperature. The potential energy released from the contracting core continues to **heat up the H shell** to ever higher temperatures.

In these hot regions the conversion of H to He accelerates, causing most stars to increase in total luminosity.

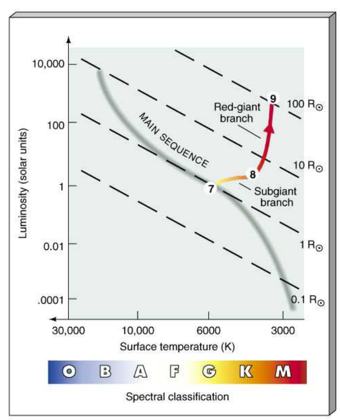


Astronomy Today, Chaisson and McMillan

Evolution to Red Giants

6. The increase in the amount of luminosity from the H-burning Shell is trying to make its way to the surface. There is too much for radiative diffusion to carry, and the entire envelope becomes convective.

As the star expands, the surface temperature cannot continue to fall to arbitrarily low values because of the **Hayashi Limit**. Its existence forces the evolutionary tracks of low-mass stars to travel almost vertically upward, making the size grow. [**Why?**]



Astronomy Today, Chaisson and McMillan

The Helium Core

7. The He core itself is still not a source of thermonuclear energy – that is, it is not *burning* – and continues to shrink and grow hotter. The core becomes extremely dense. With its increased mass and further release of gravitational energy, the core becomes still smaller, denser, and hotter. Eventually, its central temperature exceeds 100 million K.

But before it begins to burn, **the extremely high densities** cause a major phase transition, environmental change, and evolutionary effect.

Degenerate Matter

No two electrons can be in the same place doing the same thing at the same time (**Pauli Exclusion Principle**).

The Pauli Principle permits only one electron in extremely small volumes (actually, two electrons are permitted if their "spins" are opposite).

Degenerate Matter

When all the available states of position and momentum are occupied, the electrons will resist further crowding with overwhelming pressure. Such electrons are said to be degenerate, and the gas is electron-degenerate.

The electrons can move about, but not with much freedom. A particular electron cannot change position or momentum until another electron in an adjacent state gets out of the way.

The pressure of the degenerate electrons halts the contraction of the core.

Degenerate Matter

In an ***electron-degenerate*** **gas**, the **nuclei** are not packed into contact.

The nuclei still move about freely among the electrons, they obey the usual perfect gas law, and they exert the normal pressure of particles of their mass and size.

The electron **pressure** dominates and controls the structure of the core.

The **temperature/speed** of the He nuclei continues to increase, though.

The Helium Flash

8. The gas in the core is electron degenerate, so it is **NOT** an Ideal Gas. The **Subgiant** star lacks a *safety valve* that was previously available when it was still on the Main Sequence – the core could expand causing the temperature to drop and nuclear reactions to slow.

Remember **Ideal Gas Law**: $\mathbf{P = n\,k\,T}$

where **P** is the pressure, **n** is the number of molecules per unit volume, **T** is the temperature, and **k** is equal to 1.38×10^{-23} J/K.

The Helium Flash

9. In the core, the pressure is primarily ruled by degeneracy effects. Raising the temperature slightly does not significantly alter the ***electron*** pressure. But the ***nuclei*** are still an ideal gas, so an increase in the overall temperature will increase the speed of these particles.

Then it happens! Nuclear fusion begins in the central core region, and significantly more energy is suddenly released. This raises the temperature still further.

Once He burning begins, this **runaway** generation of energy is known as **The He Flash**. It only lasts for a few seconds but is as bright at 10^{11} times the luminosity of the Sun!

The Helium Flash

10. The new energy released in this He flash is so great that it

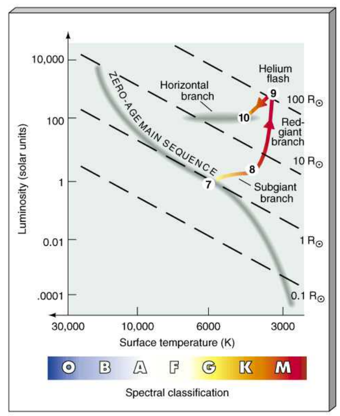
(a) first, removes the degeneracy,

(b) second, expands the core, and

(c) finally, slows energy generation.

Because the He Flash occurs quickly and basically then initiates the "safety value", the interior production of **luminosity slows** and the outer layers of the **star shrink rapidly**!

The surface temperature then increases, moving the star down and to the left on the HR diagram.



Astronomy Today, Chaisson and McMillan

Helium Burning

The main line of nucleosynthesis during He burning is found to consist of

$$3\ {}^{4}He \rightarrow {}^{12}C$$

$${}^{12}C + {}^{4}He \rightarrow {}^{16}O$$

$${}^{16}O + {}^{4}He \rightarrow {}^{20}Ne$$

The first one is known as the "triple-alpha" (3α) reaction. (A He nucleus is in fact the particle given off in an *alpha decay*, hence the designation.)

Helium Burning

The 3α particle reaction suggests why it is that ^{12}C is the fourth most abundant nuclear species. The third most abundant, ^{16}O, may be formed by the capture of yet another He particle. The fifth most abundant is apparently ^{20}Ne (its abundance is hard to determine), which presumably can be synthesized by the capture of another He particle by ^{16}O.

Continued successive He-particle captures can occur in principle, but calculations show that the increasing Coulomb barrier severely limits the number of He-particle captures at temperatures low enough for some He still to remain.

Energy Generation

The question of energy generation in He burning is a complicated one. In principle it is easy enough, for all one must do is multiply the rate of each reaction by the energy release and then sum. Since all rates have already been determined, they need only be multiplied by the Q values:

$$Q(3\alpha \rightarrow {}^{12}C) = 7.274 \text{ MeV}$$

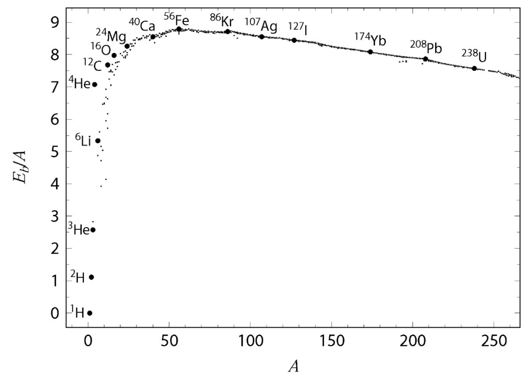
$$Q({}^{12}C + \alpha \rightarrow {}^{16}O) = 7.161 \text{ MeV}$$

$$Q({}^{16}O + \alpha \rightarrow {}^{20}Ne) = 4.73 \text{ MeV}$$

$$Q({}^{20}Ne + \alpha \rightarrow {}^{24}Mg) = 9.31 \text{ MeV}$$

Binding Energy

Binding Energy is the energy released due to an accompanying loss in mass when nucleons are combined into atomic nuclei (i.e., **fusion**).

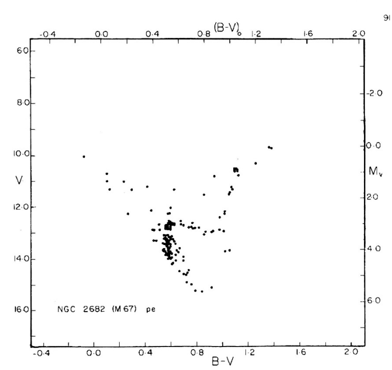


Modern Stellar Astrophysics, Ostlie and Carroll

Red Giant Phase

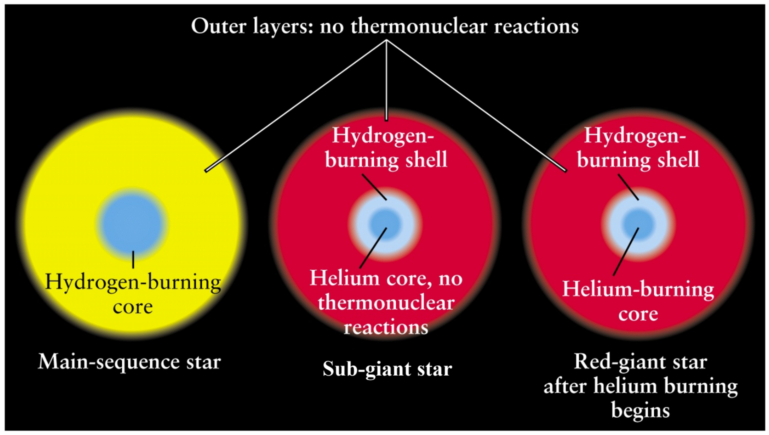
11. After the He flash, the core contains an ordinary, non-degenerate electron-He plasma, which is stably fusing He into C. Surrounding the core is a H-burning shell.

This is the **Red Giant Phase** [often incorrectly called the *Horizontal Branch*].



Atlas of Open Cluster CM Diagrams, Hagen

Interior Changes

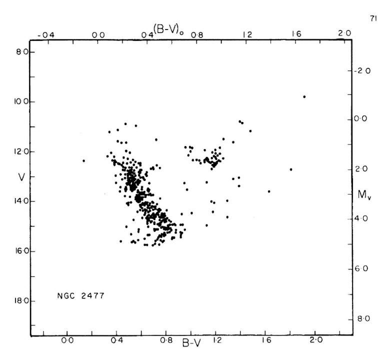


Universe by Freedman, Geller, and Kaufmann

Red Giant Phase

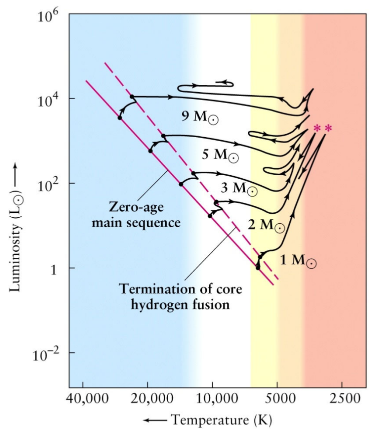
The star now becomes stable. The Red Giant Phase lasts about 1/10 as long as did the Main Sequence time.

This is why there are a large number of Red Giants.



Atlas of Open Cluster CM Diagrams, Hagen

Evolutionary Tracks



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