Post-Main Sequence Stars

What happens when a main sequence star runs out of hydrogen in its core? The answers to this take us along the next stage of stellar evolution. As with most stages in a star's life, the exact post-main sequence is primarily dependent on its mass. We will start by looking at what happens to a a one-solar mass star like our Sun and then explore what happens to higher-mass stars.

Credit: *NASA*
An artist's impression of a red supergiant engulfing a Jupiter-like planet as it expands.

- Evolution of a Solar-Mass Star off the Main Sequence
  - Red Giant Branch (RGB)
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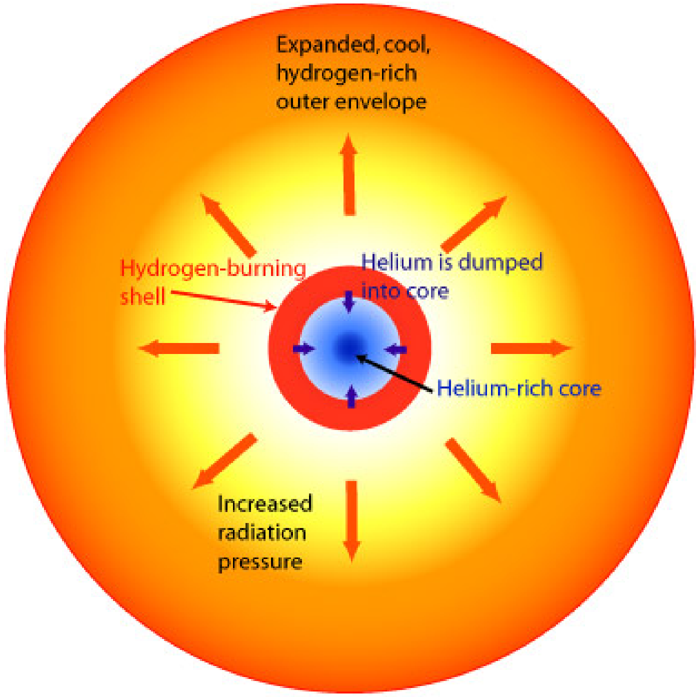
One-Solar Post-Main Sequence Evolution.

Stars such as our Sun move off the main sequence and up the red giant branch (RGB), fusing hydrogen into helium in hydrogen shell burning. A very short helium flash sees the start of helium core fusion and the star moves along the horizontal branch (HB). Once shell temperature is sufficient, helium shell burning starts and the star moves up into the asymptotic giant branch (AGB).

Moving Off the Main Sequence - Red Giant Branch

A star remains on the main sequence as long as there is hydrogen in its core that it can fuse into helium. So far we have assumed that a star on the main sequence maintains a constant energy output. In fact, as a main sequence star ages its luminosity increases slightly, resulting in it expanding and its outer layer cooling. This explains why the main sequence is a broad band rather than a narrow line - stars move up and to the right on this band as they age.

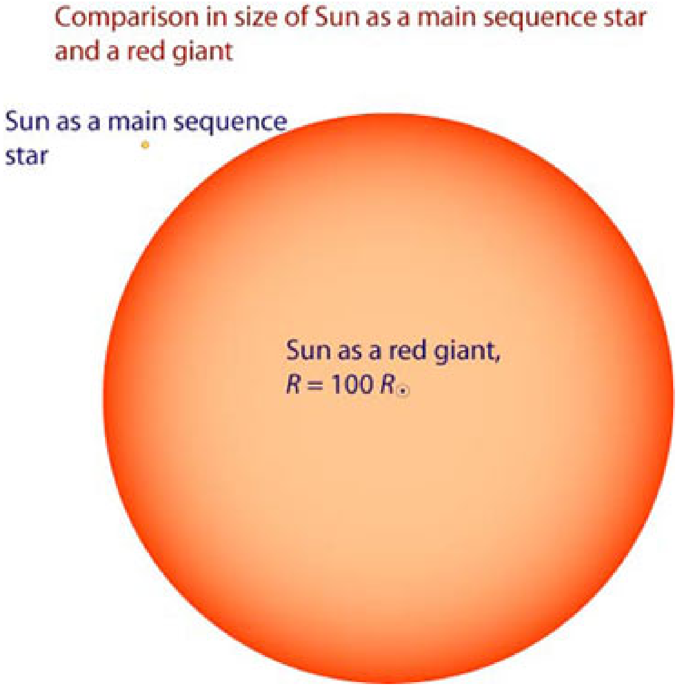
Eventually the hydrogen fuel in the core runs out and fusion stops, shutting off the outward radiation pressure. Inward gravitational attraction causes the helium core to contract, converting gravitational potential energy into thermal energy. Although fusion is no longer taking place in the core, the rise in temperature heats up the shell of hydrogen surrounding the core until it is hot enough to start hydrogen fusion, producing more energy than when it was a main sequence star. This so-called shell-burning causes some interesting effects.



Hydrogen Shell Burning on the Red Giant Branch

The new, increased radiation pressure actually causes the outer layers of the star to expand to maintain the pressure gradient. As the gas expands it cools, just as a spray can feels colder after use as the gas has been released. This expansion and cooling causes the effective temperature to drop. Convection transports the energy to the outer layers of the star from the shell-burning region. The star's luminosity eventually increases by a factor of 1000 × or so. During this stage of expansion, the star will move up and to the right on the HR diagram along the Red Giant Branch (RGB). A G (V)-class star may end up as a high-K or low-M luminosity class III giant.

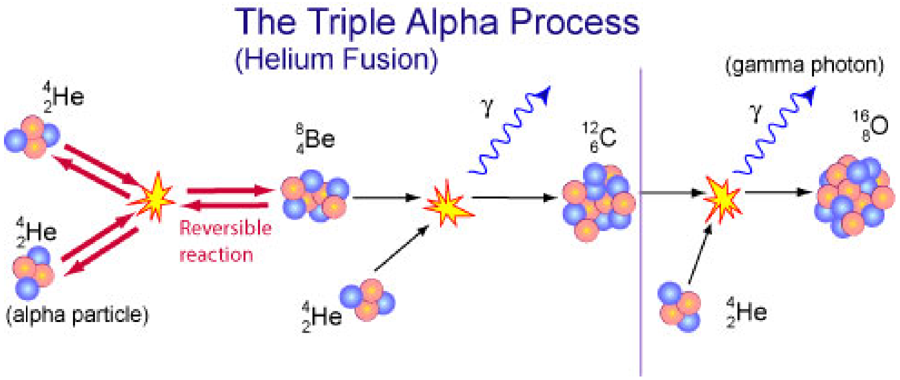
A red giant displays extremes of density. The outer envelope is grossly extended and thus at a density below that of a vacuum on Earth. It is only weakly held by gravitational force to the rest of the star and easily ejected. Mass loss from a giant is typically about 10^{-7} solar masses per year, compared with only 10^{-17} solar masses per year currently for the Sun. Whilst the envelope is tenuous and cool, the contracted helium core is incredibly dense. It is only about one-third its original size. Electrons within the core form a *degenerate electron gas*, they are packed tightly together in a volume governed only by the uncertainty principle. In this state it no longer behaves as an ideal gas.



When the Sun becomes a red giant its radius will be approximately 0.5 AU, that is about 100 × its current size.

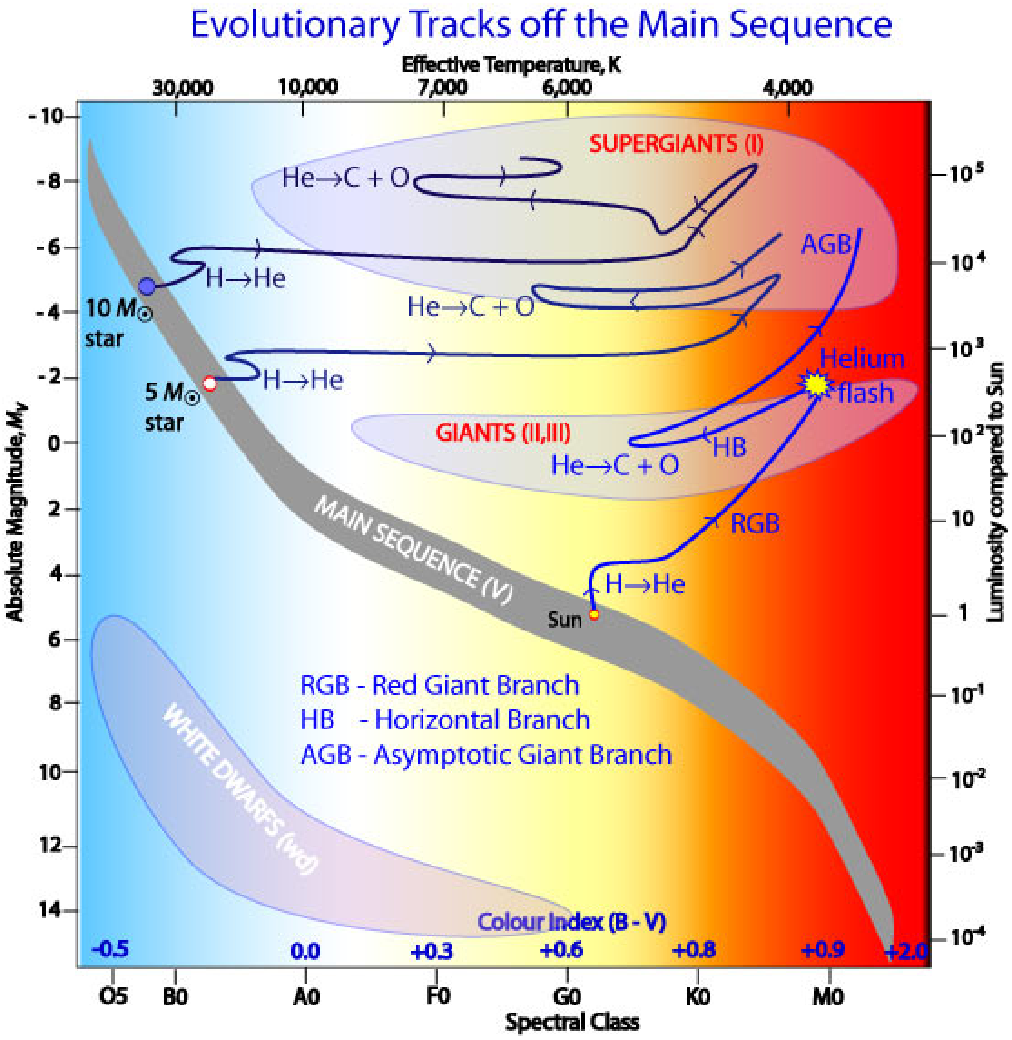
Helium "Burning" and the Helium Flash

Hydrogen fusion in the shell produces more helium. This gets dumped onto the core, adding to its mass, causing it to heat up even more. When the core temperature reaches 100 million K, the helium nuclei now have sufficient kinetic energy to overcome the strong coulombic repulsion and fuse together, forming carbon-12 in a two-stage process. As three helium nuclei, also known as alpha particles, are used it is called the triple alpha process. Subsequent fusion with another helium nucleus produces oxygen-16 nuclei. This process is the main source of the carbon and oxygen found in the Universe, including that in our bodies.



The triple alpha process for post-main sequence stars. Two helium nuclei (alpha-particles) fuse to form a beryllium-8 nucleus. This is unstable and normally decays back into two H-4e nuclei within a fraction of a second but given the high number of He-4 nuclei in the core will sometimes collide with one before it has had a chance to decay. This produces a carbon-12 nucleus and releases a gamma photon. The C-12 nucleus in turn may fuse with another He-4 nucleus to produce oxygen-16 and a gamma photon. Neon-20 may also be formed by oxygen nuclei fusing with helium but only negligible amounts are produced.

In stars with mass less than about 2-3 solar masses the triple alpha process initiates in a matter of minutes or hours. Once the temperature is hot enough for helium fusion in one part of the core, the reaction quickly spreads throughout it due to the behaviour of the electron degenerate gas. This sudden onset of helium core fusion (or "burning") is called the *helium flash*.



Post-main sequence evolutionary tracks for 1, 5 and 10 solar mass stars.

The Horizontal Branch

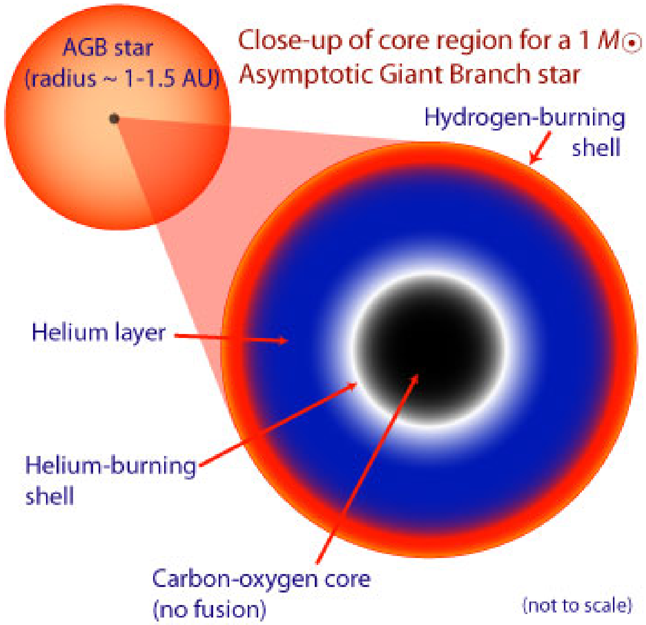
The energy released by the helium flash raises the core temperature to the point where it is no longer degenerate. It thus starts to behave again as an ideal gas so can expand and cool. Energy transfers result in a hotter outer layer of the star but a smaller overall size. The rise in effective temperature and decrease in surface area are such that the luminosity remains roughly constant. Such a star tracks across to the left along the *horizontal branch* on the HR diagram. HB stars have helium core-burning and hydrogen shell-burning.

A solar-mass star has sufficient helium fuel for core-burning to last for about 100 million years.

The Asymptotic Giant Branch

Eventually all the helium in the core has fused into carbon and oxygen and so the core contracts again. Carbon and oxygen nuclei have more protons in them than helium does so the coulombic repulsion is greater. The temperature needed to fuse these into heavier nuclei must be even greater than the 100 million K needed for He fusion. In stars of 8 solar masses or less there is insufficient gravitational energy to generate the temperatures required. No more core fusion can thus take place. The core contraction does however generate sufficient heat for the surrounding layer of helium to start fusing, that is helium shell burning starts. Energy from the helium-burning in turn heats up surrounding unused hydrogen which also starts shell burning.

The giant star expands again, possibly up to 1.5 AU, equivalent to the orbit of Mars. It is now an asymptotic giant branch star (AGB), occupying the upper-right portion of the HR diagram. A one-solar mass AGB may have a luminosity 10,000 × that of our current Sun. *Mira* (*o* Ceti) is an example of an AGB star.



Outer layers of AGB stars are only weakly held by gravity. The helium-burning shell is not dense enough to be degenerate so helium flashes occur with a runaway temperature rise. The resulting increased reaction rate generates a large energy release or thermal pulse for a couple of hundred years. During this phase nuclei within the helium-burning shell can be synthesised into heavier nuclei through the capture of neutrons and radioactive beta decay. This so-called *s-process* (*s* for *slow*, in comparison with the rapid, *r-process* that occurs in more massive stars) produces elements as heavy as bismuth with 83 protons. AGB stars may produce a thermal pulse every 10,000 - 100,000 years.

Large convection currents in AGB stars carry material produced in the thin helium-burning shell up to the surface. These heavier nuclei are detected in the star's spectrum which thus provides an insight on what is happening deep within the star. As with RGB stars, the radiation pressure tends to blow away much of the tenuously-held outer layer. The rate of mass loss is an order of magnitude higher though starting at about 10^{-6} solar masses per year. As the star evolves up the AGB branch, pulsations increase the rate of mass loss up to about 10^{-4} solar masses per year.

The ejected material comprises a mixture of elements including carbon and oxygen dredged up from within the star. Carbon-rich molecules form dust and soot particles that tend to shroud the actual star. As the cloud expands it cools but the dust absorbs and re-emits the radiation from the star at longer wavelengths. AGBs are thus often more luminous in the infrared than visible wavebands. The expanding cloud can also be observed at radio wavebands.

AGBs such as Mira are intrinsic variable stars with periods of months or a few years. They can vary by up to 10 magnitudes. Mira's radius differs by a factor of two during its oscillations.

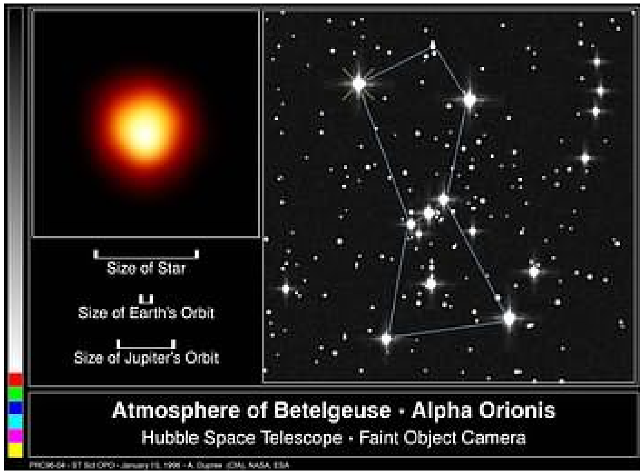
What happens to solar-mass stars once fusion is completed is discussed on the next page.

High-Mass Post-Main Sequence Evolution.

Evolution of high-mass stars off the main sequence is an involved process and one still not fully understood. Such stars are rare and have very short lifespans relative to lower-mass stars. Supergiants such as Betelgeuse, Deneb, Rigel and Antares are some of the most prominent stars in our sky and visible over vast distances due to their extreme luminosities. This section provides a basic outline of the stages.

High-mass stars consume their core hydrogen at prodigious rates so may only survive on the main sequence for millions rather than billions of years. Once this fuel is used up, the core contracts due to gravity and heats up. This triggers helium-burning in the core. Unlike lower-mass stars, this helium fusion (triple-alpha process) starts gradually rather than in a helium flash. In moving off the main sequence, the effective temperature of the star drops as its outer layers expand. The decrease in temperature balances the increased radius so that the overall luminosity remains essentially constant. Evolutionary tracks for these massive stars thus move horizontally across the supergiant region of the HR diagram as shown on the diagram above. The energy liberated by helium fusion in the core raises the temperature of the surrounding hydrogen shell so that it too begins fusing.

The size of these supergiants is enormous. Betelgeuse, thought to be between 13 and 17 solar masses, is so large that its envelope would extend beyond the orbit of Jupiter if it replaced our Sun. Its angular size is so large that it can be directly imaged by the HST.



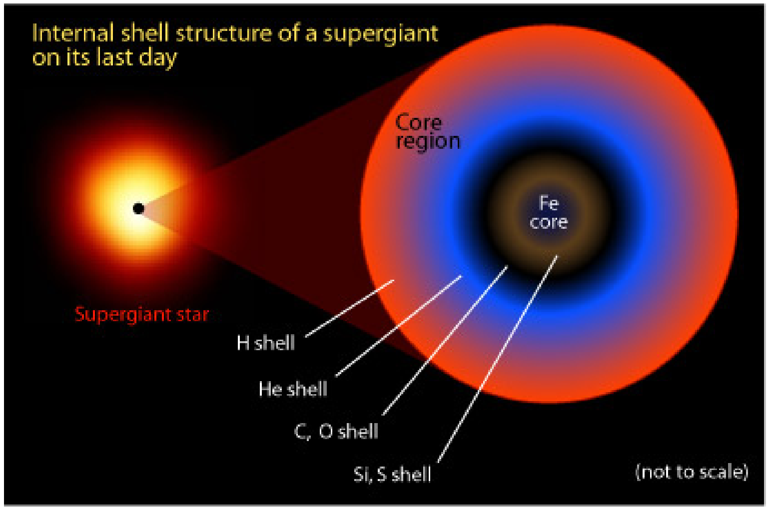
Credit: *Andrea Dupree (Harvard-Smithsonian CfA), Ronald Gilliland (STScI), NASA and ESA*

Betelgeuse is a red supergiant. The bright yellow spot at the bottom of the star is thought to be a hotspot due to a massive convection cell.

In stars of 5 solar masses or higher, radiation pressure rather than gas pressure is the dominant force in withstanding collapse. The mass is large enough that the gravity acting on the core after helium-burning is sufficient to produce temperatures of 3×10^8 K where fusion of carbon with helium to produce oxygen dominates. A star of 8 solar masses or more can go on to synthesise even heavier elements in the core.

Gravitational core contraction after all the core helium is used up generates a temperature of about 5×10^8 K at which point carbon nuclei fuse together to produce sodium, neon and magnesium. Production of magnesium releases a gamma photon, that of sodium releases a proton and neon produces a helium nucleus. Once all the core carbon is consumed, further collapse pushes temperatures to about 10^9 K. At this temperature, reactions that release gamma photons, such as $^{16}O + ^{4}He \rightarrow ^{20}Ne + \gamma$, may be reversed by a process called *photodisintegration*. Helium nuclei released via this process can fuse with other neon nuclei to produce magnesium.

Once the neon is used up, core contraction increases the temperature to 2×10^9 K where two oxygen nuclei fuse to form silicon. This in turn may undergo photodisintegration to form magnesium and helium nuclei that then fuse with other silicon nuclei to produce sulfur. Similar stages of reactions see sulfur produce argon and argon synthesise calcium. Eventually elements such as chromium, manganese, iron, cobalt and nickel may be produced. Ultimately the silicon in the core is converted, as *silicon-burning*, into iron with final core temperature reaching about 7×10^9 K. The core region of a supergiant thus resembles the layers of an onion with a dense iron core surrounding by shells of silicon and sulfur, oxygen and carbon, helium and an outer shell of hydrogen as shown in the diagram below.



The onion-like layers inside a supergiant in the final stages of its life. Successive layers correspond to the different elements produced by fusion, with a dense core of iron at the centre.

Nucleosynthesis of elements above helium is less efficient so that each successive reaction produces less energy per unit mass of fuel. This means that the reactions occur at greater rates so that radiation pressure balances gravity. Whilst a massive star may spend a few million years on the main sequence, its helium core-burning phase may be a few hundred thousand years. The carbon burning phase lasts a few hundred years, neon-burning phase a year, oxygen-burning half a year and the silicon-burning only a day.

These massive stars evolve extremely rapidly once they move off the main sequence. Statistically they are very low in numbers as they are less likely to form than lower-mass stars and their lifetimes are so short anyway. As we shall see in a later section, they also make dramatic exits.

Low-Mass Post-Main Sequence Evolution

As discussed previously, low mass stars consume their core hydrogen at much lower rates than stars such as our Sun. Their main sequence lifespans are tens to hundreds of billions of years. Once they have consumed their core hydrogen, gravitational core collapse causes the core to heat up. For stars with less than 0.5 solar masses however, their is insufficient mass to generate the temperatures need for the helium in the core to start fusing. A brief period of hydrogen-shell burning sees its luminosity rise as with higher-mass stars. Unable to release energy from helium fusion, H-shell burning does not last long. The star's luminosity quickly decreases and the star cools down. Its evolutionary track crosses back across the main sequence and down.

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