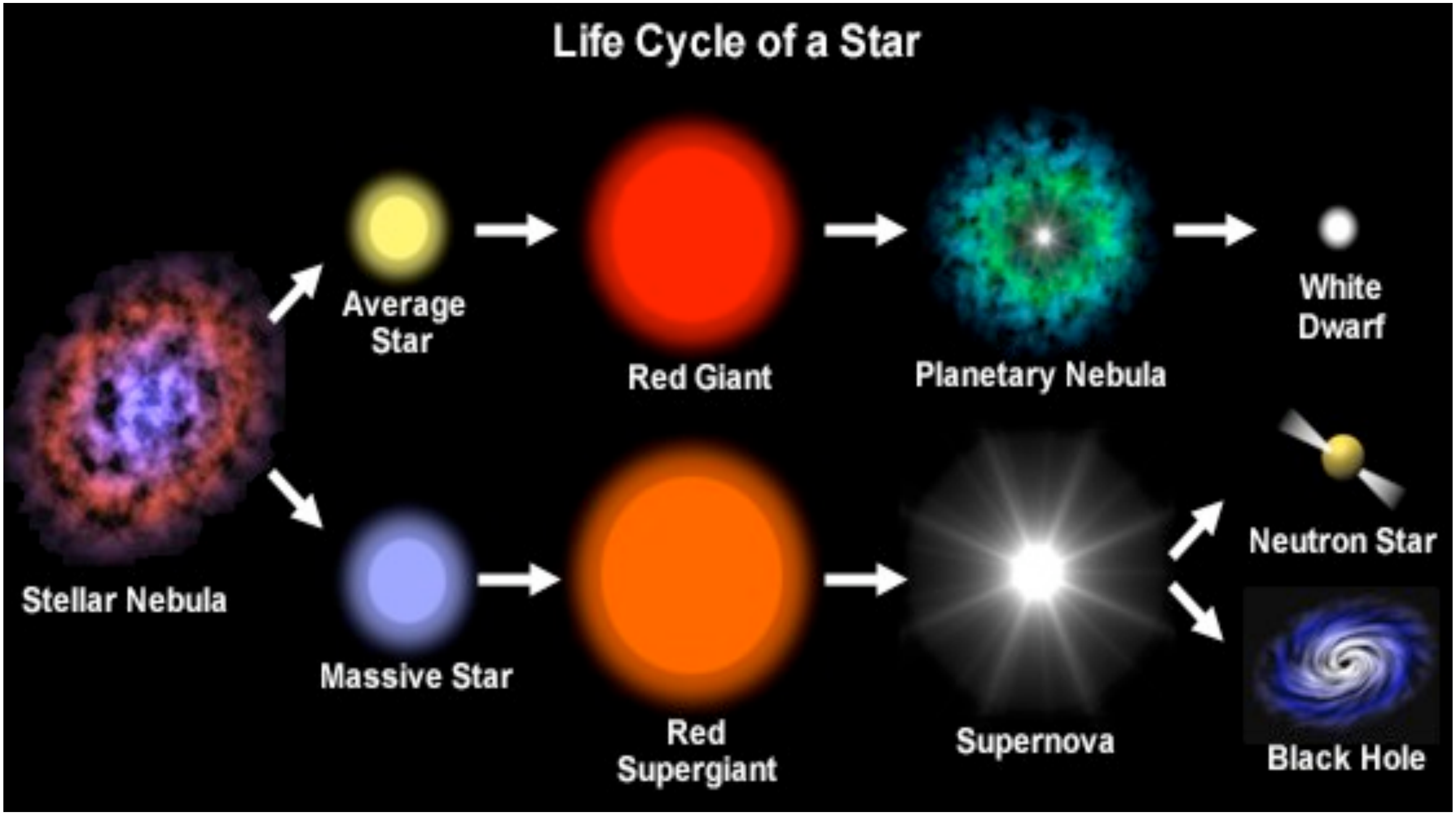
Chapter 12: Stellar Evolution

In the previous lectures we have seen how stars form from the molecular clouds in the ISM, collapse under gravitational free-fall contraction, heat up and eventually form protostars. How stars go from these infant stars to the fully fledged stars we studied in chapter 8 is the subject of the next lectures.



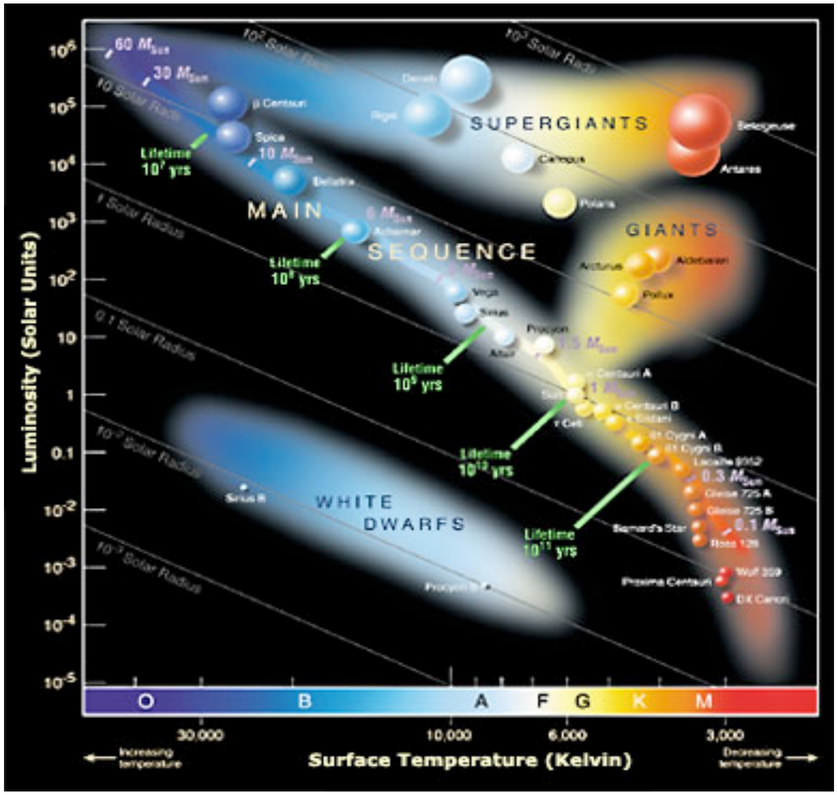
Not All Stars Are Equal.....

Not all stars evolve in the same way. Some stars will barely fizzle to life, whilst others will be powerhouses of energy for billions of years. Some stars will gradually fade from view as they get old whilst others will explode as supernova that will temporarily outshine the entire galaxy.

The single most important factor that governs a star's fate is its mass.

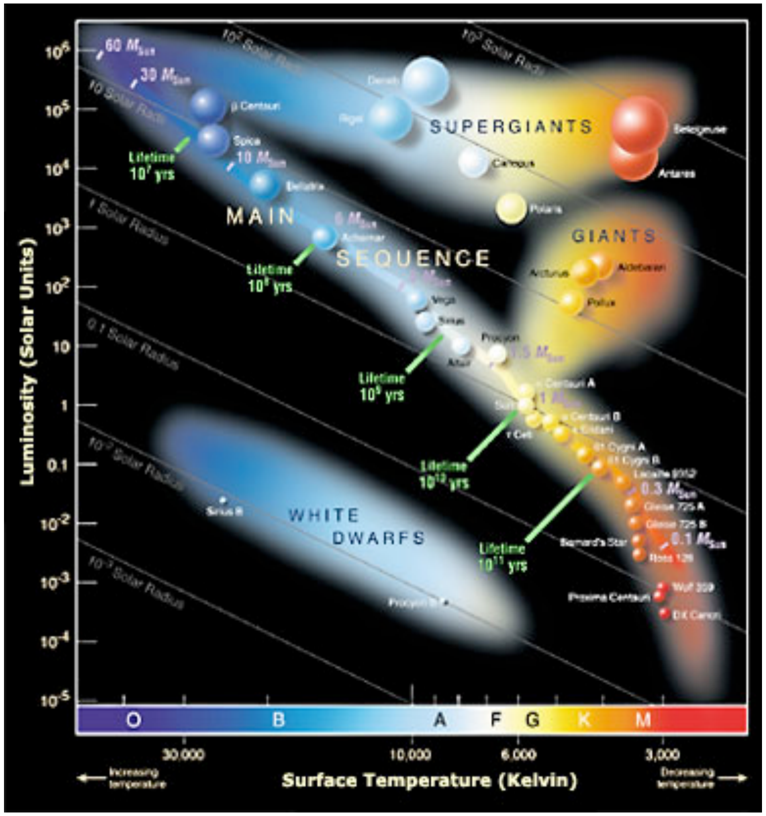
High mass stars will:

1) Burn their fuel faster....
2) ...and so have shorter lives
3) Have hotter cores....
4) ...and so fuse heavier nuclei
5) Have a bright blue-white colour on the MS
6) Appear at the top left of the MS



Remember that high mass stars are quite rare. The majority of stars have masses a few times that of the sun or less.

The majority of stars lie along the main sequence. Stars along this sequence are in hydrostatic equilibrium, having started to fuse hydrogen in their cores, once they are hot enough.



In addition to the relationship between T and L, there is also a correlation between mass and luminosity.

This is because of hydrostatic equilibrium. A more massive star most create a great internal thermal pressure in order support itself.

This is a one to one relation such that a given mass star must produce a certain energy to remain in equilibrium

A Thought Experiment: What would happen if we turn off the nuclear reactions in a star?

The normal situation in a star's core is that nuclear fusion reactions (such as the p-p chain or the CNO cycle) produce energy in the form of photons. This energy is transported to the surface via (mostly) convection and radiation because of the existence of a temperature gradient.

The flow of energy creates a pressure that exactly balances gravity: hydrostatic equilibrium.

Let us now artificially cool the centre of the star, so that the temperature drops below that required for nuclear fusion. The internal pressure source is now removed. So....

The star starts to shrink because there is nothing to oppose the force of grav

However, the process of shrinking heats the core up again (just like when the protostar first formed) so the nuclear reactions are re-ignited.

As nuclear reactions are re-ignited, the thermal pressure is re-acquired and the star will regain its original size.

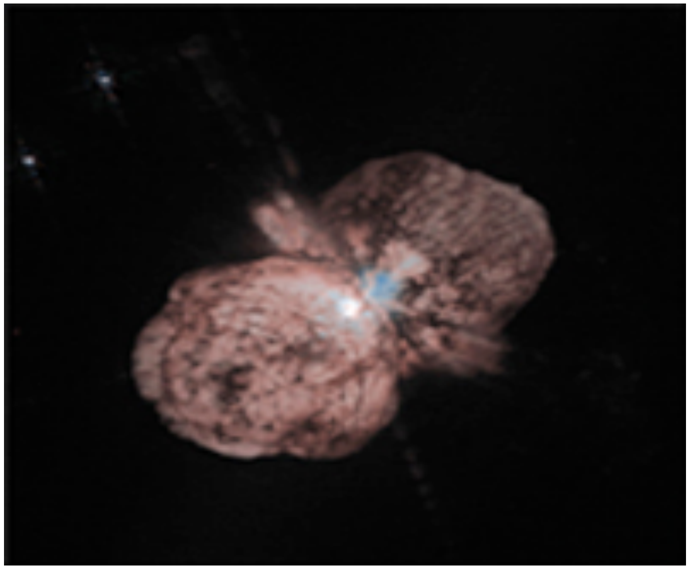
The Extremes of Stellar Mass

Our theory of stellar structure and our understanding of the balance between physical forces allows us to make predictions about the masses of stars.

Stellar Heavyweights

A very high mass star must produce a lot of energy in order to remain in hydrostatic equilibrium. Note that this is why massive stars are short lived – they exhaust their nuclear fuel quickly in order to maintain the internal pressure balance.

Stellar models predict an upper limit of about 100 solar masses. At higher masses the energy output from the core is so high that it would blast surface layers of the star away in powerful stellar winds.



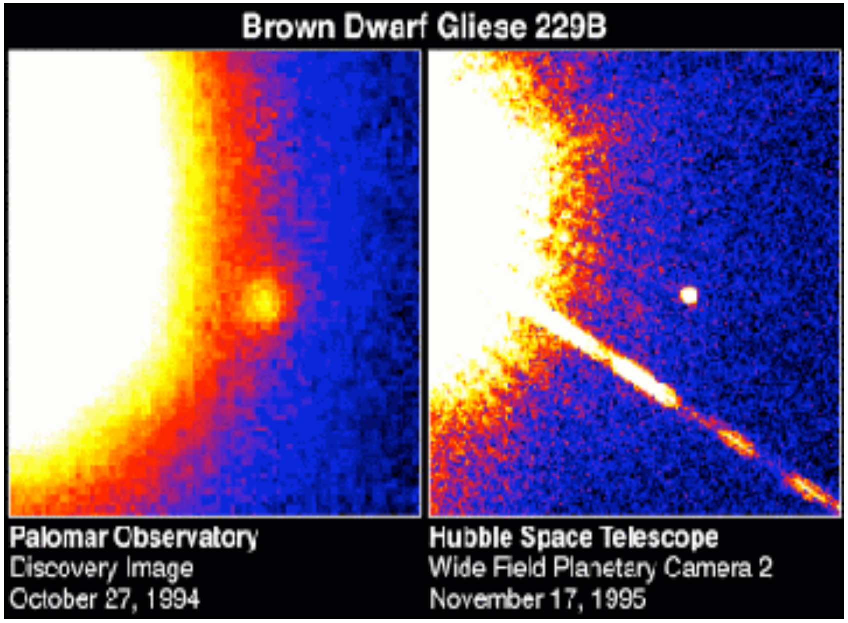
For the few very high mass stars that have been observed, they do indeed have Doppler blue-shifted spectral lines indicative of material outflowing towards us.

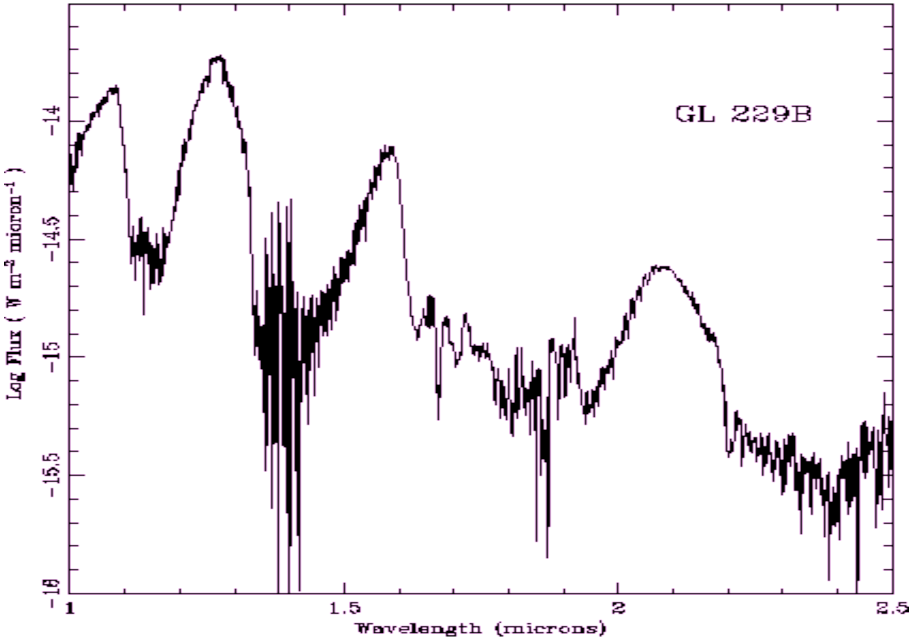
Note that a second reason we don't find very massive stars is that large molecular clouds will fragment to form several lower mass stars.

Stellar Lightweights

There is a minimum mass for stars, because below about 0.08 solar masses there is not enough thermal energy produced to start fusing hydrogen. These “failed stars” are called brown dwarfs and they should be very common.

Even though brown dwarfs don't create nuclear energy, they still glow, but very dimly, because they must radiate the heat they gained as they collapsed and formed. Because brown dwarfs are cool, they are best detected in IR observations, or via reflected light of nearby companion (binary) stars.





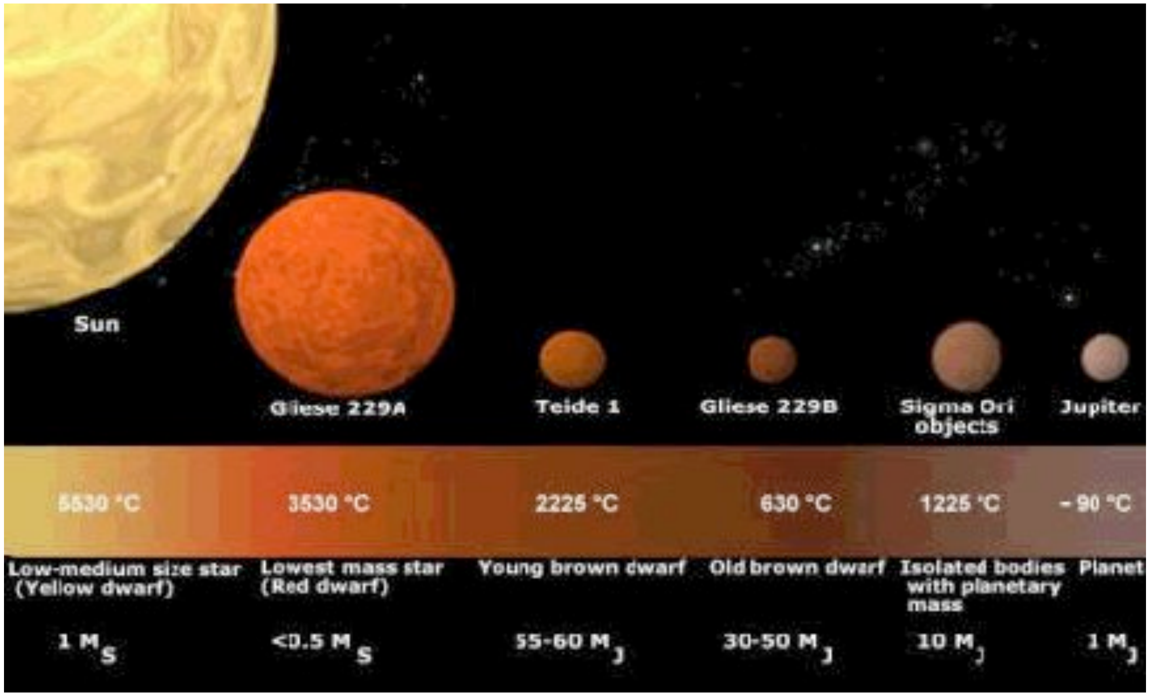
Further evidence that brown dwarfs are cool comes from the detection of methane (CH_4) which would be destroyed by high temperatures.

When is a star not a star? When it's a Planet!

Normally, astronomers think of a star as an object that produces its own energy via nuclear fusion and a planet as an inert body that orbits a star

So how do brown dwarfs fit this picture? They neither produce energy nor (necessarily) orbit other stars. So, are they failed stars or starless planets???

Some astronomers draw the dividing line between stars and planets at 0.08 solar masses (or 80 Jupiter masses, since at small masses this becomes a more convenient unit). Others, however, think that 13 Jupiter masses is an appropriate cut-off between stars and planets. This is because brown dwarfs above 13 Jupiter masses can fuse deuterium ("heavy hydrogen", i.e. hydrogen with an extra neutron) which does emit a very little amount of energy.



We could also consider planets as only objects that form out of a disk around a sta in which case brown dwarfs more easily fit the template of "failed star".

At what wavelengths can we observe different stars?

We can use Wien's law to calculate the wavelength at which stars of differen masses (temperatures) will emit most of their energy.

Recall Wien's law: $\lambda_{max}(nm) = 3 \times 10^6 / T(K)$

Example

An IR survey centred at 3000 nm finds a large number of brown dwarfs. What can we infer about their temperature?

Using Wien's law, T=3000000/3000 = 1000 K

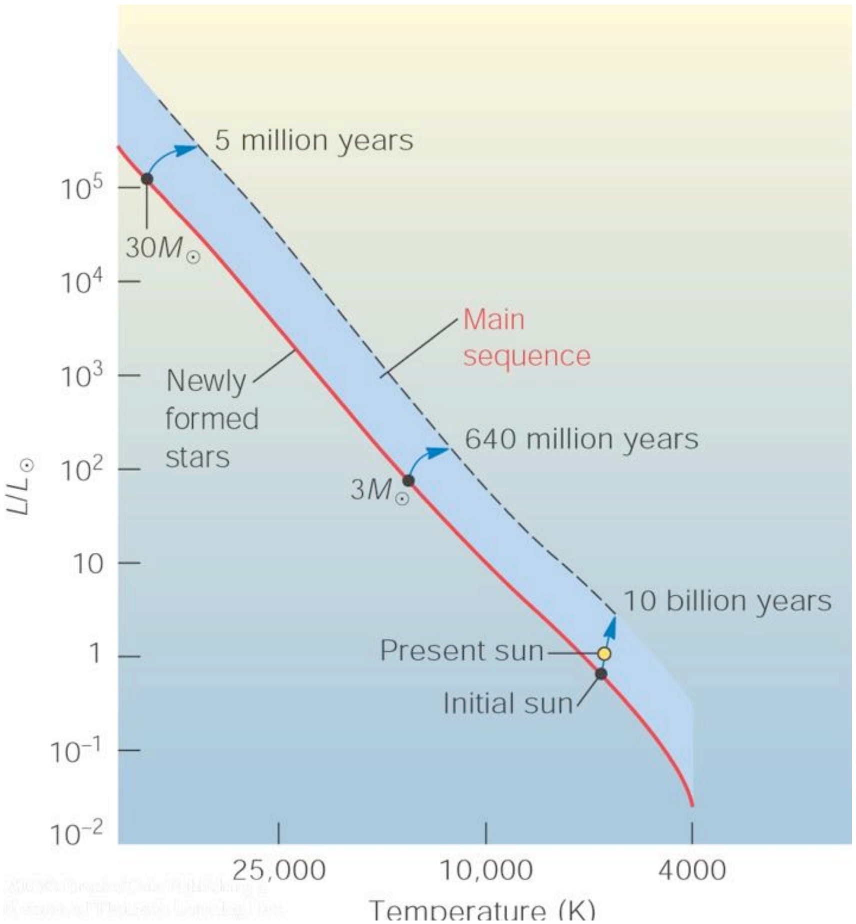
Methane molecules are destroyed at temperatures above about 1500 K. What is the minimum wavelength at which we should preselect objects that might contain methane?

wavelength = 3000000/1500 = 2000nm. This is in the near infrared.

The Zero Age Main Sequence – A Star's Early Years

We have already stated that most stars spend most of their time on the main sequence (MS). Indeed, this is where things are nice and stable, nuclear reactions burn happily and the star is in hydrostatic equilibrium.

However, the MS is not an sharp line, but a band on the HR diagram. When a star turns on its nuclear reactions it does so at the bottom of this band, the so-called zero age main sequence (ZAMS).



As hydrogen fuses to helium, the internal pressure in the star goes down (because now there are 4 times fewer nuclei). This causes an inbalance between pressure and gravity so that the core gets squeezed.

This in turn causes the core to contract, hea up and burn more efficiently.So now fusion goes on at a higher rate causing the star to puff up and cool.

The net result of this is that a star gets larger, brighter and cooler as it gets older. So it migrates up and right on the MS.

A Star's Life on The Main Sequence

The migration of a star on the MS is quite slow for most of its life. However, ir its later phases, evolution is rapid and the changes in the star's properties cause it to leave the tight relation of the MS.

The amount of time a star spends on the MS depends on its mass.

Hot stars (e.g. O types which have ~40 solar masses) only spend about 1 million years on the MS, whereas the sun will spend 10 *billion* (current age o sun ~5 billion years, or 5 gigayears).

This is because massive stars use their nuclear fuel much more quickly due to high internal temperatures. This is one of the reasons why very massive stars are so rare – they just don't hang around long enough for us to count many of them!

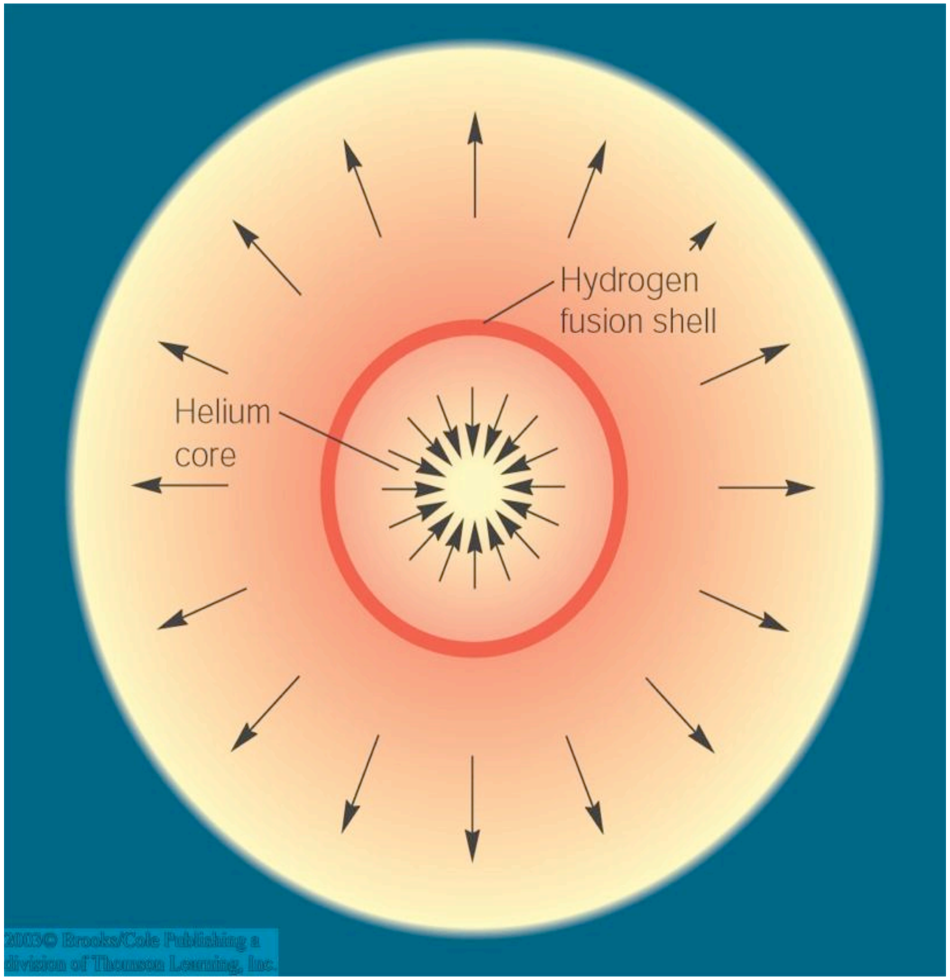
So, the Sun has about 5 billion years left on the main sequence. In this time, the temperature on Earth will rise by about 20 C because the sun will get much larger. This doesn't sound like much, but it will be enough to melt the ice caps, evaporate the oceans and cause much of the atmosphere to be lost into space.

Post Main Sequence Evolution: The Formation of a Red Giant

We have already mentioned that even on the main sequence the pressure in a star's interior decreases somewhat with age as it fuses hydrogen to helium

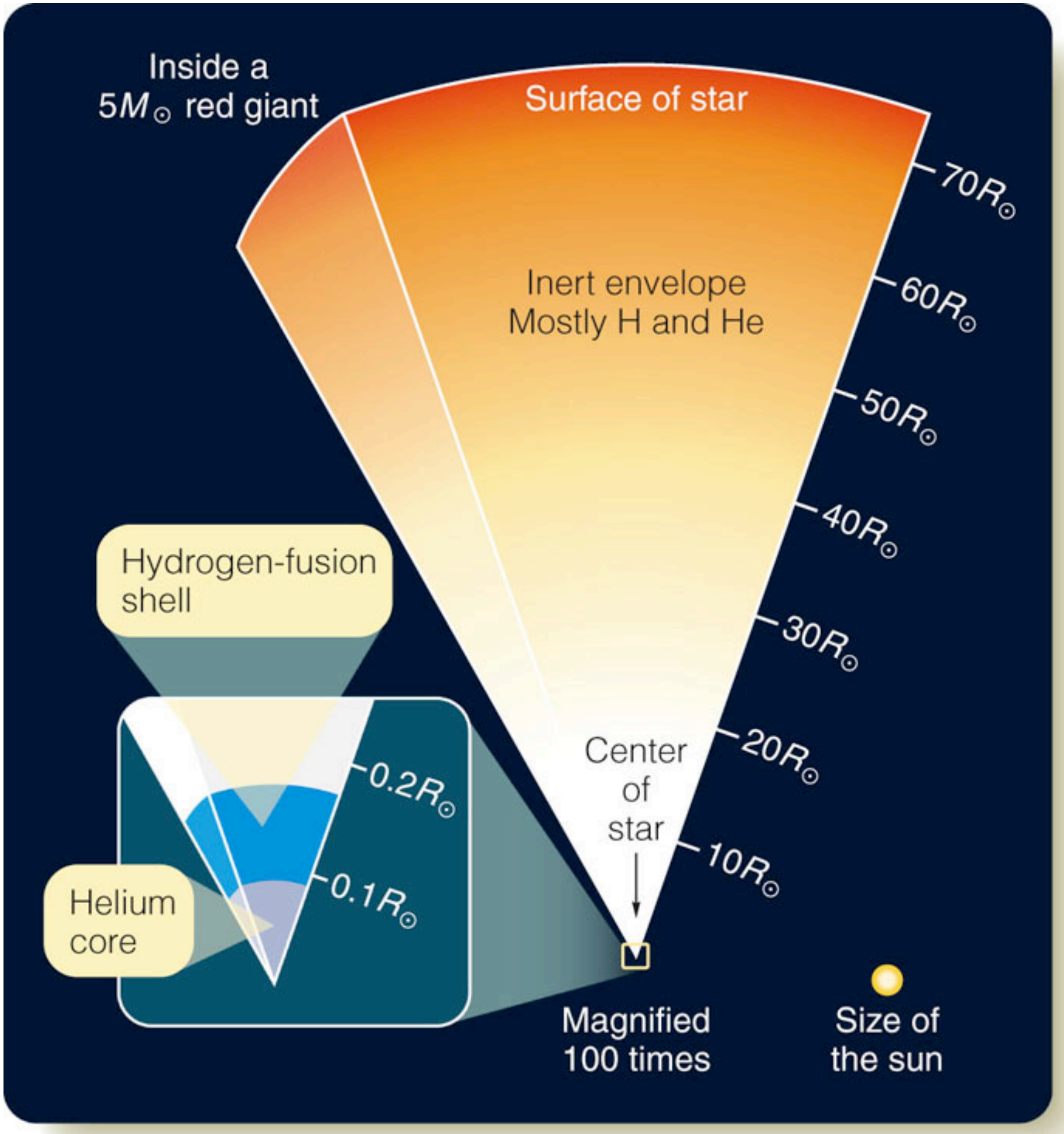
This helium “ash” (so called because it is the end product of the burning reaction) builds up in the centre of the star and can not be used in fusion reactions because the temperature is not high enough.

Eventually, the hydrogen in the core is exhausted and all that remains is a ball of inert helium. At this point the energy production in the star stalls. The weight of the star's outer layers causes it to contract and increases the temperature.

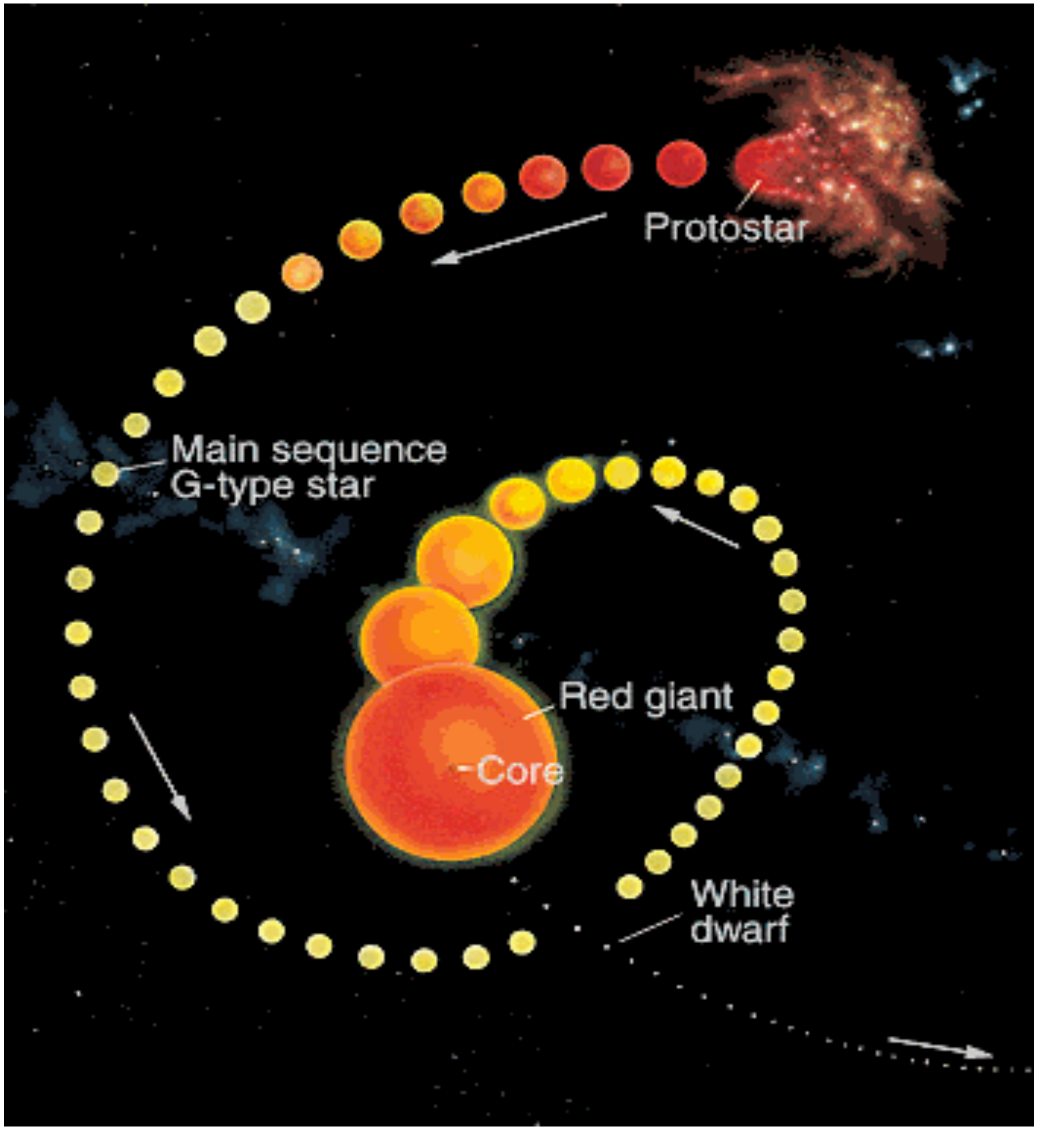


This increase in temperature is just enough to start hydrogen fuse in the shell around the core of helium ash. The hydrogen core burns outwards and the helium ash continues to all to the centre

As helium ash continues to fall onto the core, it starts to contract under its own gravity, and consequently heats up. Although there are no nuclear reactions in the helium core at this point, thermal energy is produced through the contraction which must be transported away.



We now have energy from both the hydrogen burning shell and the compressed helium core. This inbalance in energy production causes high pressures which forces the star to expand rapidly, forming a giant.

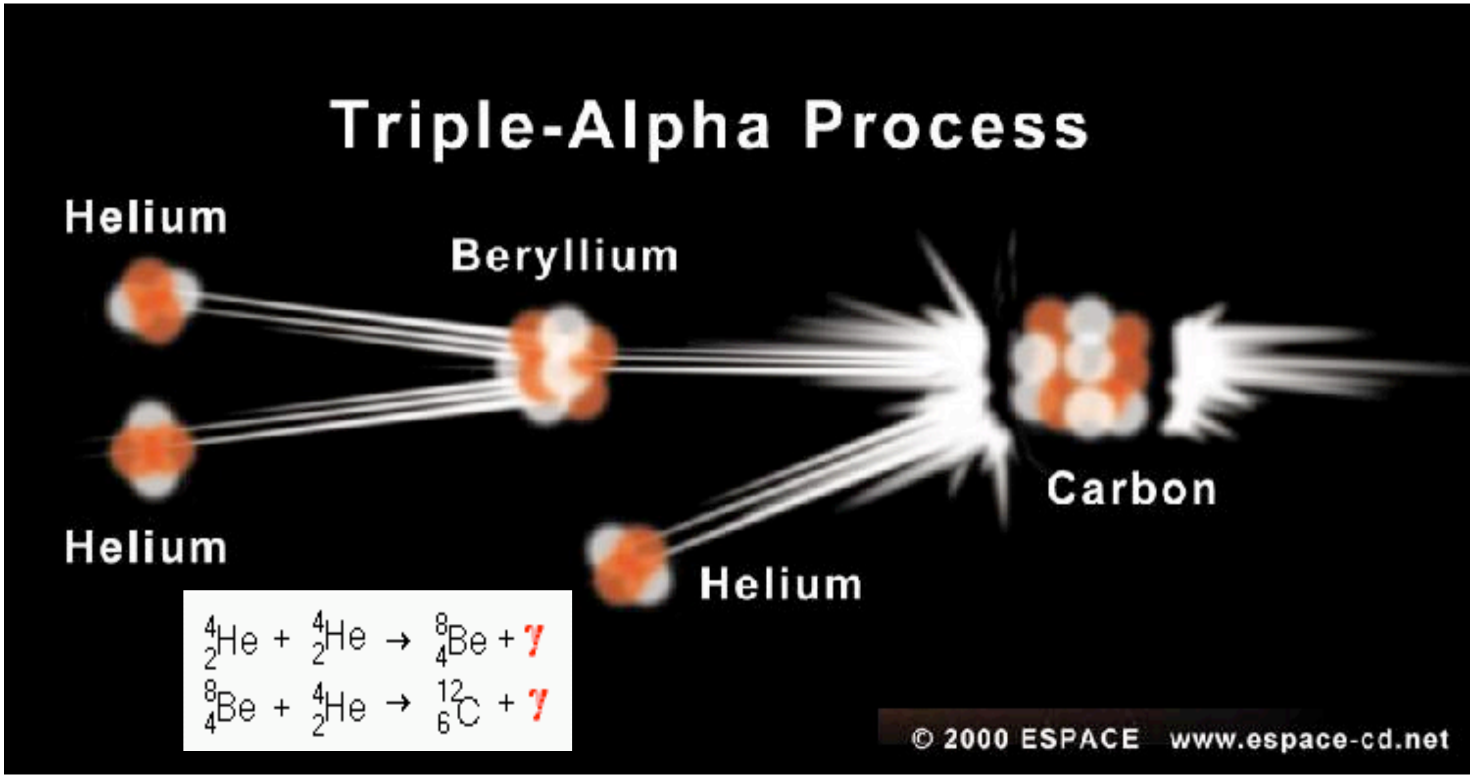


This rapid expansion also cools the outer layers of the star. So the star is now both physically larger and cooler. Since cooler stars look redder (remember spectral types), we call these red giants.

Helium Fusion and The Triple Alpha Process

The contraction of the helium core continues, as does the rise in temperature. Eventually, when the core reaches ~ 100 million K, helium starts to fuse.

The reaction by which helium fuses is called the triple alpha process, because 3 alpha particles (helium nuclei) are required.



$$ {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{8}_{4}\mathrm{Be} + \gamma $$

$$ {}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + \gamma $$

Stars more massive than 3 solar masses ignite helium in a gradual process, whereas stars less than 0.4 solar masses never achieve the required temperature.

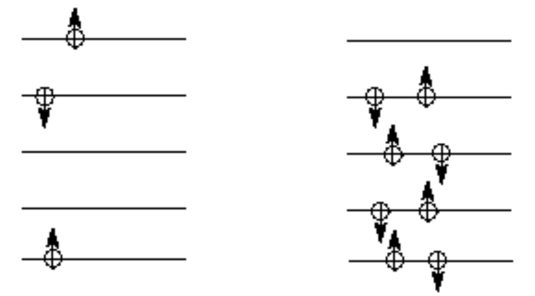
Stars between this range start their triple alpha process with a violent helium flash.

Before we can understand the helium flash we have to understand how matter behaves at very high densities.

A Brief Diversion: Degenerate Matter

The gas inside a star is made of nuclei and free electrons and the pressure within this gas is usually (as we've seen up until now) governed by temperature. However, different laws star to apply at very high densities whe matter becomes degenerate and these laws break down.

Just as electrons within an atom have fixed energy levels (orbits), so do free electrons have fixed energies. Only two electrons (with opposite spins) can occupy a given energy level. This is called Pauli's exclusion principle.



Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.

Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

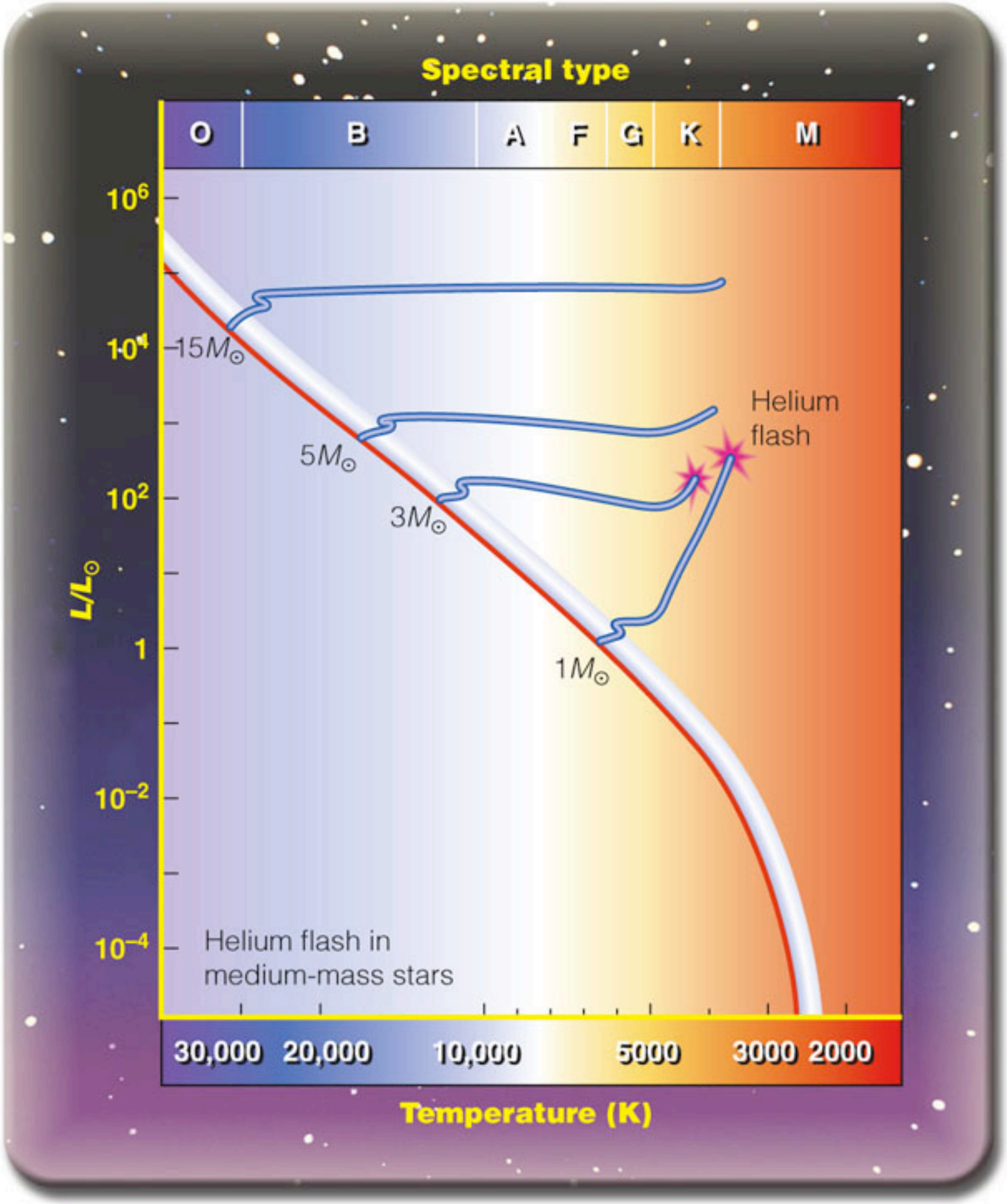
At very high densities (far in excess of anything that can be produced on Earth), all the lower levels get filled, we call this degenerate matter. Degenerate matter can not be compressed any further, even though it is still gas.

The other strange property of degenerate matter is that its pressure barely changes with temperature. This is because most electrons are not free to move about (which is what normally causes the pressure to increase), only those few in the higher energy levels are mobile.

The Helium Flash

Stars of between 0.4 and 3 solar masses commence their triple alpha process with a helium flash. This flash occurs only in stars where the core becomes very dense and at least partially degenerate.

The density of a star's core when it becomes a giant is 1 million g/cubic cm. At these densities the gas is degenerate so that pressure and temperature are no longer regulating each other.



The Helium Flash

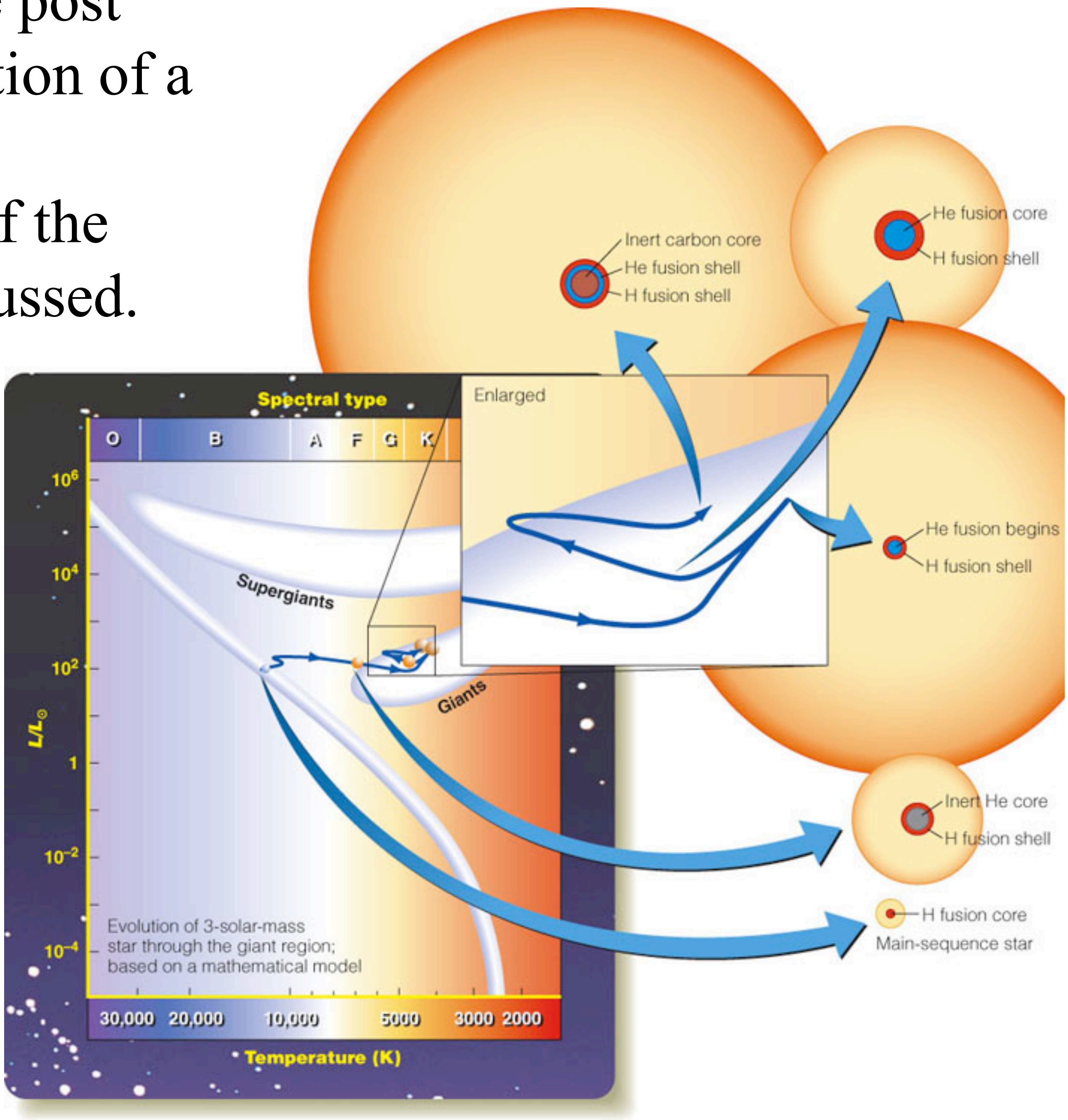
Therefore, when the He core of the giant ignites and produces energy, the temperature increases, but the pressure does not respond by expanding the core size. Instead, there is a runaway reaction whereby the temperature increases and the reactions keep going faster. For a few minutes the core generates a trillion times the energy of the sun

However, this runaway reaction is short-lived; within a few minutes the temperature increases so much that electrons break free of their degeneracy, and now He burning continues normally

Note that “helium flash” is a bit of a misnomer, because the He core is so hidden inside the star that most of the energy is absorbed and there is no visible evidence of an eruption.

This figure shows the post main sequence evolution of a 3 solar mass star and summarises several of the processes we've discussed.

Note the wiggles on the HR diagram as the balance between energy output and gravity cause the star's temperature and luminosity to change slightly.



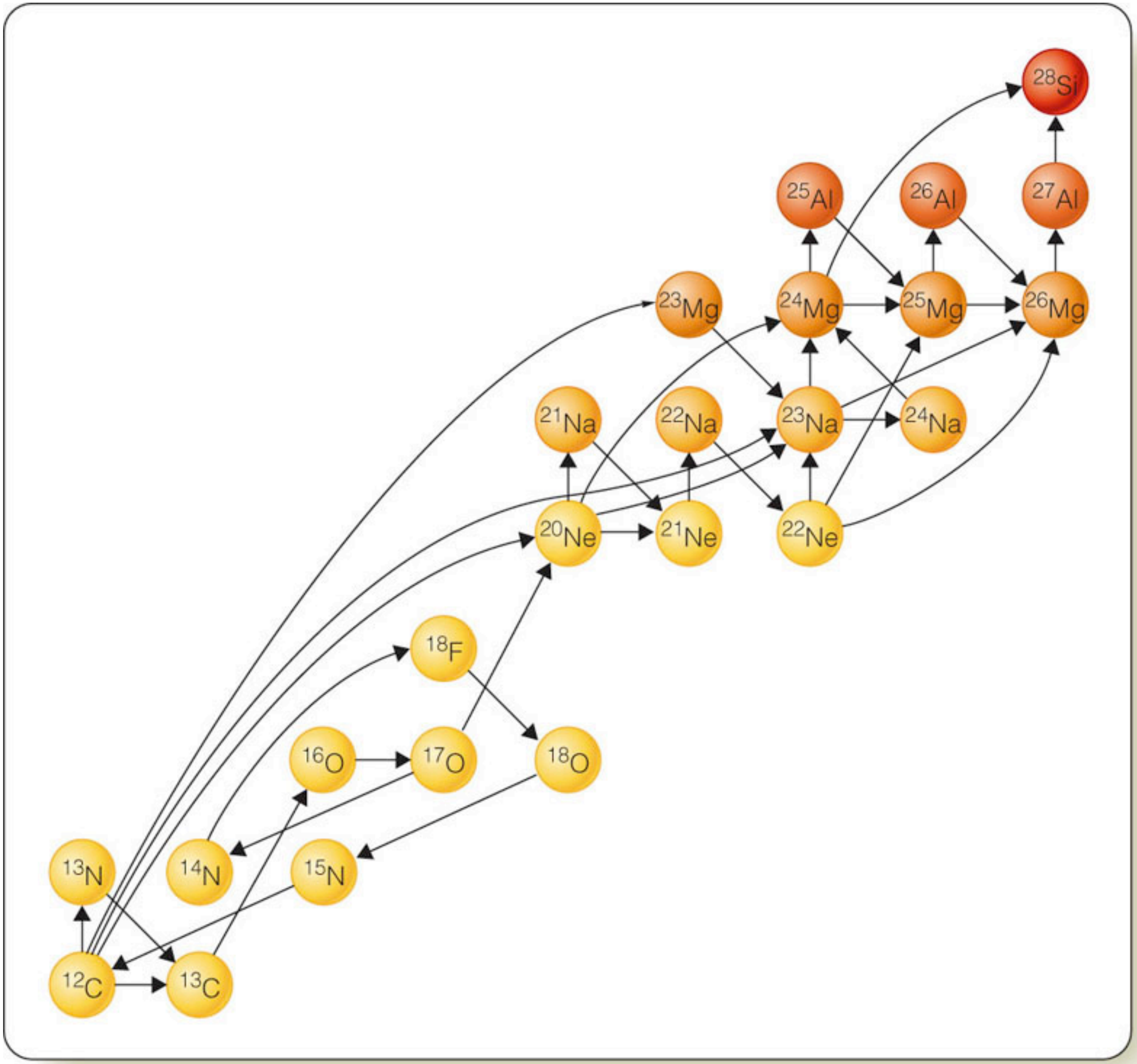
Evolution of 3-solar-mass star through the giant region; based on a mathematical model

Making Elements Heavier Than He

We have seen that stars more massive that 0.4 solar masses can fuse He int
C, in addition to the basic H into He reaction. Indeed, the more massive a sta
is, the heavier nuclei it can fuse.

Only high mass stars can fuse heavy nuclei. This is because high temperatures are required to overcome the coulomb potential and support th core with fewer nuclei.

Fuel	Product	Temp. needed	Minimum mass
H	He	$4x10^6$ K	0.1 solar mass
He	C, O	$12x10^7$ K	0.4 solar masse
C	Ne, Na, Mg, O	$60x10^7$ K	4 solar masses
		↓	
Si	Ni to Fe	$3x10^9$ K	8 solar masses


^{28}Si
^{25}Al
^{26}Al
^{27}Al
^{23}Mg
^{24}Mg
^{25}Mg
^{26}Mg
^{21}Na
^{22}Na
^{23}Na
^{24}Na
^{20}Ne
^{21}Ne
^{22}Ne
^{18}F
^{16}O
^{17}O
^{18}O
^{13}N
^{14}N
^{15}N
^{12}C
^{13}C

Variable Stars

A variable star is any star that changes its magnitude in a regular periodic way.

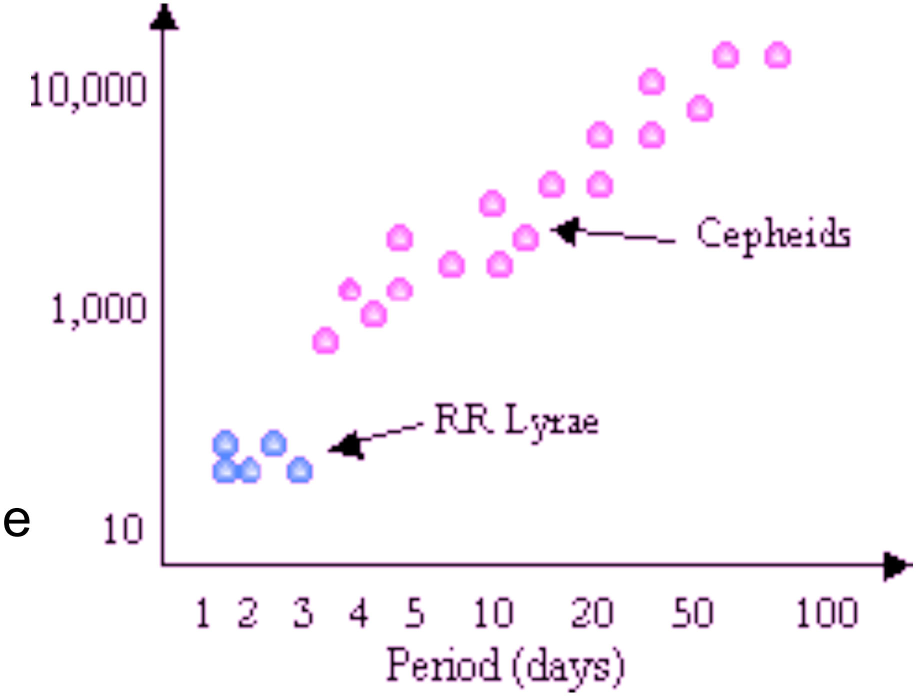
A star could be a variable for several reasons, only some of which are due to changes within the star itself (i.e. intrinsic variables). For example, an eclipsing binary would be classified as a variable star.

Cepheid variables: This type of variable is named after the first of its kind to be discovered – δ Cephei. Cepheid variables are giants or supergiants of type F or G and have cycles with periods of 2 – 60 days and amplitudes of about 0.5 mags.

Type I Cepheids have a chemical composition like the sun, but Type IIs have fewer heavy elements.

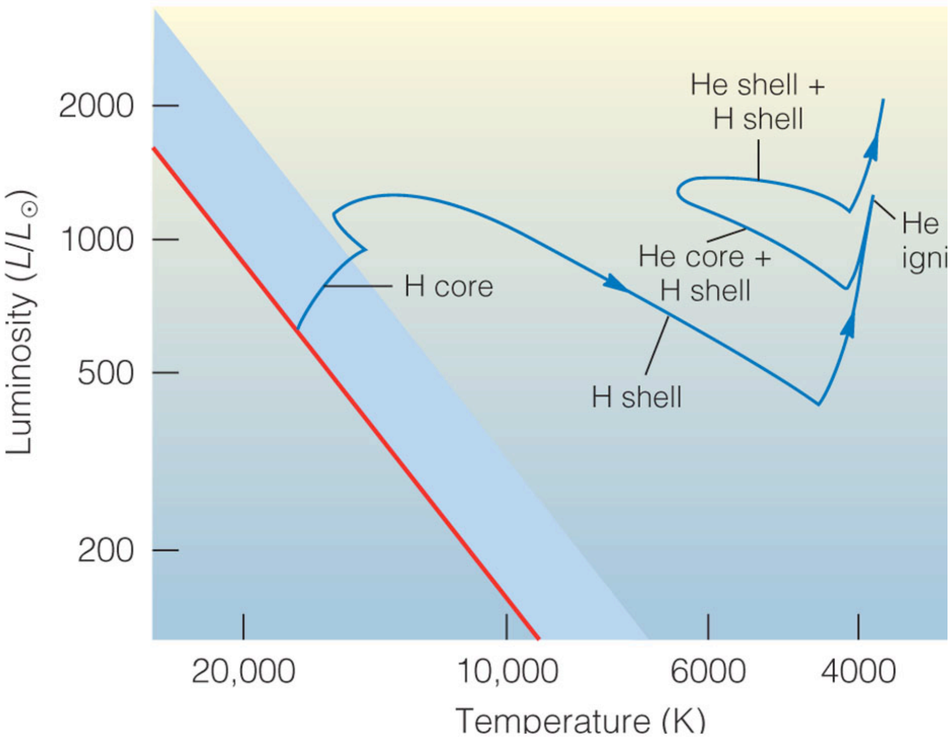
The most important feature of both of these types is their period luminosity relation. This was first discovered by Henrietta Leavitt in the early 1900s. This property makes them very reliable distance indicators.

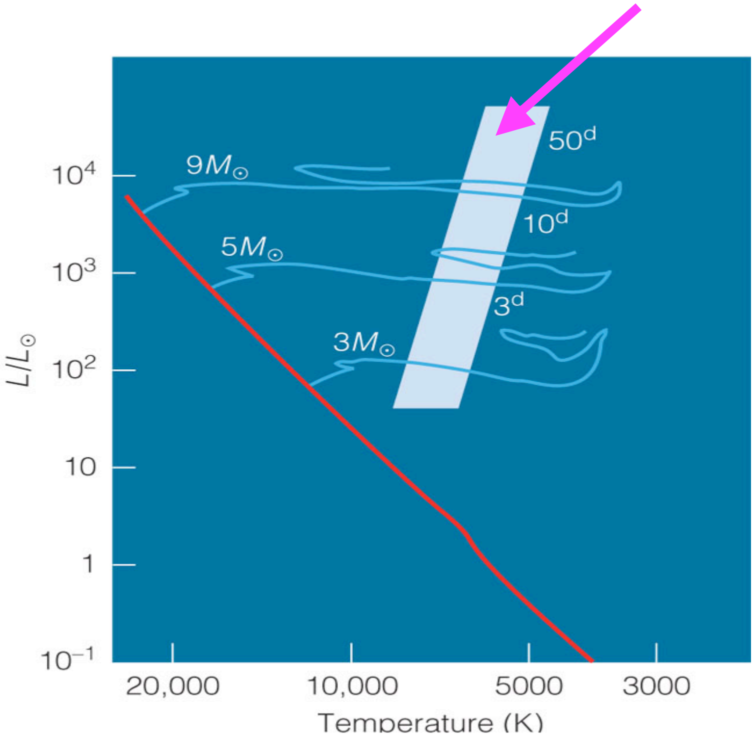
RR Lyrae variables: Related to the Cepheids, RR Lyrae stars are fainter than Cepheids and have periods of a few days.



Why do stars pulsate?

When a star leaves the main sequence, it undergoes a series of changes in its temperature and luminosity. Certain combinations of temperature and luminosity make the star unstable, this region is called the instability strip.



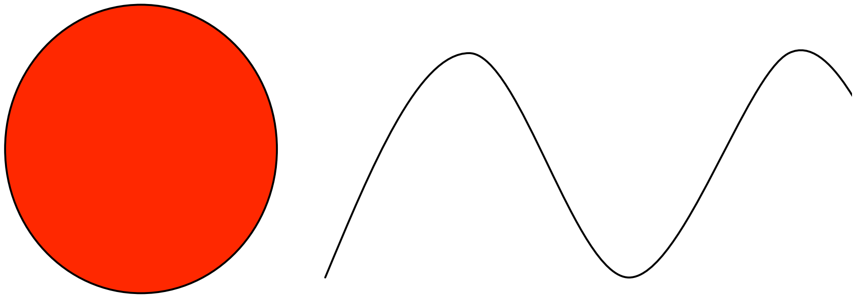


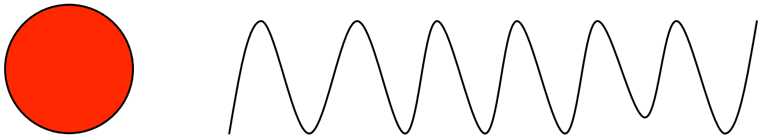
A star in the instability strip can pulsate because it has a layer of ionized helium in its outer layers which is good at absorbing energy. This layer expands as it absorbs energy, but then cools and sinks back down, releasing the energy again.

Only stars in the instability strip show this behaviour. Outside of this region, the ionized helium layer is either too deep in the star to be able to push out all the mass in the outer layers, or it is too near the surface to have much to push against.

We can also understand the origin of the period luminosity relation. For high mass stars, which are more luminosity, they pulsate with a lower frequency, just like a large bell has a lower frequency (pitch) to a small bell. The low mass star resonates (pulses) more rapidly than the high mass star.

Bright, high mass, long pulsatio

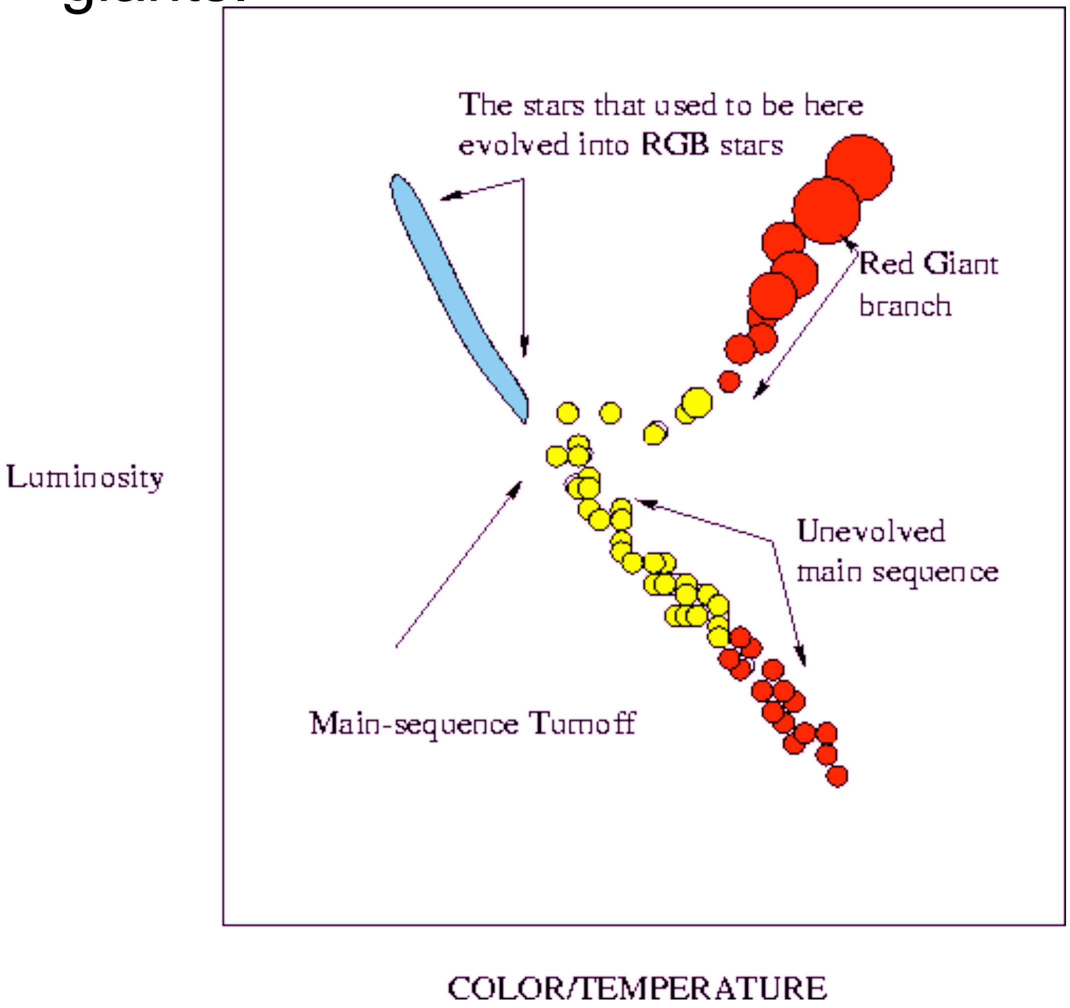




Fainter, low mass, short pulsation

The Age of Star Clusters

Studying the HR diagrams of star clusters is a powerful way of determining their ages. We need to measure the turn off point. This i the location on the main sequence where stars start to evolve towards giants.



Old clusters have turn-off points that are towards the lower right of the HR diagram.

This technique is only useful in clusters because all the stars were formed more or less at the same time.