Chapter 17 – Description of the Evolution of Stars Beyond the Main Sequence

1. Introduction

Stars spend most of their lives burning hydrogen into helium-4. Because of this, most stars lie on a certain locus on the Hertzsprung-Russell diagram, known as the “main sequence”. The Hertzsprung-Russell, or HR, diagram plots luminosity against colour, or surface temperature, with luminosity on a logarithmic scale. Traditionally the HR diagram is plotted with high temperatures (blue or white stars) on the left and low temperatures (red stars) on the right. Figure 1 shows the trajectory of a solar mass star on the HR diagram as it evolves over its life. Also shown is a part of the main sequence (specifically, the part relevant to stars between solar mass and five times solar mass).

The position of a star on the main sequence is determined principally by its initial mass. The greater the mass, the greater is the luminosity and the higher the surface temperature. However, stars do move along the main sequence to some degree, as the amount of hydrogen remaining in the core diminishes[1]. Thus, when it first joined the main sequence, a star with solar mass and solar metallicity would have a surface temperature of ~5,690K and a luminosity of ~65% of the Sun’s. About half way through its life, comparable to the Sun now, its surface temperature would be ~5,850K. Just before the time when all the hydrogen in the centre of the star is exhausted, the surface temperature would reach almost 6,000K and the luminosity would be ~60% greater than the Sun’s at present. However, these changes in the star’s location on the HR diagram are very modest compared with the much larger movements once the star leaves the main sequence.

The period of hydrogen burning at the star’s centre is relatively simple (with the emphasis on the word “*relatively*”). It can be understood quantitatively, to a level of accuracy adequate for pedagogic purposes, using a few simple equations. Even in this case we need to borrow our knowledge of the temperature and density conditions from a more complete stellar model. This description of the main sequence phase of a star’s life has been provided in Chapter 13, for the case of a solar mass star which is dominated by the pp reaction sequences. However, once the star leaves the main sequence the evolution becomes far more complex. At this point it becomes essential to use detailed computer codes to model the evolution. This is beyond the scope of the present work.

In lieu of this, the purpose of this Chapter is to describe the results of such models. Many stellar models are available, and inevitably can produce different predictions. However, there is a broad consensus regarding the key features of a star’s development, from the point of joining the main sequence through to its death. The evolution differs qualitatively according to the star’s initial mass. In this Chapter we describe the salient features of the evolution of stars of low mass (~1$M_☼$), intermediate mass (~5$M_☼$) and high mass (>15$M_☼$). Unless otherwise indicated, solar metallicities will be assumed. This

[1] To be more accurate, the main sequence at which stars of different mass start their life is known as the Zero Age Main Sequence, or ZAMS. As a star burns its central hydrogen it moves slightly off the ZAMS. But it remains close to it whilst there is still hydrogen at its centre. To the accuracy of our discussion here we can approximate this part of the star’s evolutionary trajectory as lying along the ZAMS.

implies initial mass fractions of ~1% oxygen, ~0.4% carbon, ~0.1% nitrogen and ~0.5% of other elements. Astrophysicists refer to all elements beyond helium in the periodic table as 'metals', so that the total metallicity of a solar type star is ~2%.

2. Low Mass Stars (~1$M_{☼}$)

The end of the main sequence stage does not mean the end of hydrogen burning. Rather it marks the end of hydrogen burning only in the centre of the star. The central temperature for a solar mass star during the early stages of the main sequence is ~14 MK. Hence, the pp reaction sequences dominate (see Chapter 13). As the central hydrogen becomes depleted, the temperature increases, approaching nearly 19 MK, at which temperature the CN/CNO reaction sequences will become dominant. The reason for the increase in temperature can be understood from the gas law, $P = \rho_N RT$. The conversion of hydrogen to helium leads to a decrease in the number density, ρ_N. But the pressure, P, must be maintained to support the star against gravitational collapse. This leads to an increase in T.

By the time the central hydrogen is exhausted, the hydrogen concentration has fallen to about half its initial value at a mass parameter of ~0.1. The 'mass parameter' is a measure of the radial position from the centre of the star. It indicates the radius which contains the given fraction of the star's mass. The hydrogen burning will have occurred out to a mass parameter of ~0.43. Beyond this the hydrogen concentration is unchanged from its initial level. When the hydrogen at the centre of the star is exhausted, the star leaves the main sequence (point B on the HR diagram of Figure 1).

Despite the central hydrogen being exhausted, plenty of hydrogen remains away from the centre. Hydrogen burning therefore continues in an annular shell. Between points B and C on the HR diagram (Figure 1) the hydrogen burning shell extends out to a mass parameter of ~0.43. The star as a whole is expanding at this time, although the core is contracting. The density contrast between the core and the mantle is therefore getting even bigger, as is the temperature contrast. The core is getting hotter because it is contracting, and hence nuclear heating rates increase. The star is becoming cooler (redder) at its surface but also more luminous due to the increased core temperatures and hence increased nuclear heating rates. A star can only become both cooler *and* more luminous by getting bigger. Thus, stars in this phase of their life become red giants.

When the surface temperature reaches ~5,000K, the luminosity has increased to 3 times solar. This is point C on the HR diagram of Figure 1. By this time there is a marked distinction between the core and the rest of the star. The temperature profile has a near step change at the edge of the core. The hydrogen burning shell lies at the interface between the core and the outer, cooler, parts of the star. The core extends to a mass parameter of ~0.17, and the temperature (~24 MK) is roughly isothermal within this region. The core is almost all helium (plus ~2% metals), essentially all the hydrogen having been used up within this region. There is a steep temperature gradient just beyond the core, the temperature dropping to ~9 MK at a mass parameter of ~0.25, this being insufficient for nuclear reactions. The temperature of ~24 MK is insufficient to ignite helium within the core, and the temperature of ~9 MK is insufficient to burn hydrogen beyond a mass parameter of ~0.25. Consequently, nuclear reactions are confined to hydrogen burning within a thin shell between mass parameters of ~0.17 and ~0.25.

The star continues to expand, whilst the core contracts, moving from point C to point D on the HR diagram, Figure 1. This is the start of the giant branch (or the *first* giant branch, since later we will se that there is a second, or *asymptotic* giant branch). By point D the surface temperature is ~4,785K and the luminosity is about 17 times solar. The hydrogen burning shell has now become very thin indeed, extending over a mass parameter range of less than 0.01. At point D the H-burning shell is at a mass parameter of ~0.25. Between D and E the H-burning shell moves outward in mass parameter as more hydrogen is used up. By point E the H-burning shell has reached a mass parameter of ~0.43. It remains very thin. Note that, because the core is contracting, the fact that the H-burning shell is moving out to larger mass parameter does not necessarily imply that it is getting physically larger. The core remains roughly isothermal over this period, and the hydrogen burning shell is almost as hot. At point D the central temperature is ~40 MK, and at point E it is ~70 MK. This is still too low to ignite helium burning. The temperature gradient beyond the hydrogen burning shell becomes ever steeper, falling to below 1 MK in a mass parameter range of order 0.01. By point E the star has become a fully fledged red giant, with a surface temperature of around 3150 K and a luminosity of perhaps 1500 times solar. A red giant of mass less than ~1.5$M_{☼}$ will be about 100 times larger than the main sequence star from which it evolved.

So far we have said nothing about the heat transfer mechanisms prevailing within the star. The rate of heat transfer is of crucial importance in stellar models. In particular, whilst a star is in a quasi-steady state, the nuclear heating rate must balance with the rate at which heat is conveyed away from the regions undergoing nuclear fusion. Consequently it is clear that the prevailing heat transfer mechanisms are very important to a star's behaviour. However, there is another, entirely different, reason why we should be interested in which heat transport mechanism is operating. The two relevant mechanisms are radiation and convection (though there are also mechanisms of intermediate character). There is a crucial difference between these mechanisms: whilst radiation only transports heat, convection transports both heat and matter. Thus convection has the capability to move the products of the nuclear fusion reactions to other parts of the star, whereas radiation cannot do so.

The importance of this cannot be overstated. We are reliant upon stars both to create the chemical elements, and also to contrive to release this product of their labours into the inter-stellar medium (ISM). It would be of no biophilic benefit if all the carbon, oxygen, etc, remained trapped in the centre of the stars which created it. And yet, why should they not remain thus trapped? The nuclear reactions occur only in the hottest parts of the star, and this is the core not the outer mantle. We shall see below that there are mechanisms by which a star can emit material into the ISM. However, except in the case of some supernovae, it is matter from the outer mantle which is ejected, whilst the core remains behind. If the fusion products remained within the core of the star, the ejection of mantle material would not enrich the ISM with newly created elements. If steady state processes (i.e. not supernovae) are to contribute to the chemical richness of the universe, it is essential that fusion products get mixed into the mantle region. Hence, it is crucial that convective processes occur within regions containing the fusion products – even if only briefly. It turns out that convection does indeed periodically penetrate the region of fusion product. This tends to be a brief foray which the convective boundary makes into regions generally radiation dominated. For obvious reasons, such events are known as “dredge-ups”.

For a star of solar mass and solar metallicity, the heat transfer within the core is initially dominated by radiation. Indeed, radiation dominates out to a mass parameter (m) of ~0.88 whilst the star remains on the main sequence, with a convection zone occurring only at large radii, for m > 0.88. Once the star leaves the main sequence and starts to expand, the convection boundary moves inwards in terms of the mass parameter, reaching m ~ 0.55 at point C. Up to this point, convection has not been significant in any region within which nuclear reactions have occurred. Consequently, reaction products will not have been conveyed away from their location of origin. However, by point D the convective boundary reaches a minimum mass parameter of ~0.25. This is within the region where nuclear reactions have taken place (recalling that, prior to point C, reactions had occurred out to m ~ 0.43). As a result, convective processes will convey reaction products to the outer parts of the star for the first time. This is known as “the First Dredge-Up”. After point D the convective boundary again moves out to a larger mass parameter.

A star does not have a constant mass. It looses material through a stellar wind. Whilst on the main sequence, little material is lost. However, as the star climbs the giant branch, the core contracts and the mantle expands, so that the outer parts of the star become less strongly bound by gravity. Consequently, the rate of mass loss due to the stellar wind increases as the star moves up the giant branch. At point C only ~1% of the star’s mass will have been lost, despite this representing most of the star’s life. By point D the mass loss is ~3%, and by the time the star becomes a red giant at point E the total mass lost has reached ~13%. Hence, a substantial amount of stellar material is returned to the inter-stellar medium (ISM) by this mechanism.

As the helium core continues to contract beyond point E, it eventually reaches a temperature sufficient to ignite helium burning, at about 100 MK. Helium burning occurs via the so-called triple alpha reaction which converts three alpha particles (He^4 nuclei) into carbon (C^{12}). For stars of mass less than about $2M_{☼}$, a curious instability phenomenon occurs at this time, known as the helium flash. A star is generally an auto-stabilised system which responds to a potential increase in nuclear heating rate in such a way as to maintain a quasi-steady condition. Thus, a notional increase in nuclear heating will tend to raise the local temperature, which will cause an increase in the local pressure via the gas law, $P \propto \rho T$. Since the pressure is now greater than is required to support the star against gravity, the core expands. The expansion reduces the pressure, regaining hydrostatic equilibrium, and as a consequence also reduces the density and the temperature. Since nuclear reaction rates are extremely temperature sensitive, this turns down the wick on the nuclear heating rates. In this way a new equilibrium condition arises, satisfying the requirements of both hydrostatic equilibrium (i.e. the balance between gravity and pressure) and also thermal equilibrium (i.e. the balance between the nuclear heating rate and the rate of heat transport away from the core). This thermostatic mechanism relies upon a local temperature increase resulting in expansion via the gas law, $P \propto \rho T$. However, near point E the core becomes so dense that this gas law no longer holds. The gas becomes degenerate, which means that its pressure is determined by quantum effects leading to a polytropic equation of state in which $P \propto \rho^{\gamma}$. The salient point is that the pressure becomes insensitive to temperature, thus breaking the usual thermostatic mechanism. The ignition of helium burning therefore has the potential to create a run-away escalation of nuclear heating rate. Increased heat production leads to higher temperatures leads to greater heat production, without the benefit of expansion cooling to tame the escalation. The result is a helium flash.

The nuclear power density in the region of helium burning does indeed become prodigious during a helium flash. The power produced by the helium burning region can be as much as 10^{10} times solar luminosity, albeit for extremely short periods (hours). However, the luminosity falls steeply at the edge of the helium burning region and the helium flash has no observable effect on the luminosity of the star at the surface. The reason is that the energy released in the helium flash is used in lifting the degeneracy of the core. Lifting the degeneracy completely would convert the core once again into a gas with the familiar equation of state, $P \propto \rho T$. If this happened the star’s thermostatic mechanism could reassert itself, thus turning off the helium flash. In practice an intermediate gas condition is sufficient to temporarily switch off the first helium flash. But the run-away conditions then return, resulting in a second helium flash. This is again switched off by further relief of the degeneracy. It typically requires several helium flash cycles, with a periodicity in the order of tens of thousands of years, to fully lift the degeneracy and re-establish stable thermostasis.

Degenerate, or near degenerate, conditions in the core imply very high densities. Sufficiently high, in fact, that neutrino reactions, normally negligible, become significant. So neutrinos provide an additional mechanism for cooling the central region, but this does not apply at larger radii where the densities are lower. This causes the location of maximum temperature to move away from the centre of the star, perhaps to around a mass parameter of 0.1 to 0.2. Consequently the helium flashes initiate in a shell at around this radius.

Another effect of the large power densities during a helium flash is that sufficient energy is available within the helium burning regions to change the dominant heat transport mechanism from radiation to convection. Previously in the life of this solar mass star the nuclear reactions have taken place within radiation dominated zones. For the first time convection is dominant in the nuclear heating region, though only the helium burning part. Hydrogen burning is still occurring within a shell of larger radius, and radiation is dominant within an annulus containing the H-burning shell. Moreover, the helium flash occurs in a shell, not at the centre which remains radiation dominated. Consequently, during a helium flash, the transient condition has four heat transfer zones: (a)up to $m \sim 0.1$ radiation remains dominant; (b)within the helium burning shell, just beyond $m \sim 0.1$, and out to perhaps $m \sim 0.45$, convection is dominant ; (c)an annulus around the hydrogen burning shell remains radiation dominated, its radial extent varying rapidly in time depending upon the progress of the helium flash; (d)the outer mantle, beyond m ~ 0.8, remains convection dominated throughout. The convective zone, (b), is particularly noteworthy since it has the effect of moving reaction products from the helium burning shell into the region between the helium and hydrogen shells (the inter-shell region). These products are, of course, the biologically important carbon and oxygen.

This pattern of heat transport mechanism zones is a transient condition applying only during the helium flash. Between flashes the star reverts to radiation dominance throughout the core and out to m ~ 0.8, with convection at m > 0.8 as usual. But by the time the core degeneracy has been lifted by a sufficient number of helium flashes, stable helium burning in the core has become established under convection dominated conditions. In effect, the final helium flash does not 'switch off' but instead becomes a steady, long-lived, helium burning process. The process of achieving steady helium burning via a series of helium flashes can be likened to trying to start a recalcitrant car engine. The engine may fire briefly, but keep spluttering out. Eventually the periods of firing become longer, and the spluttering shorter, until the firing becomes continuous and stable.

We are now at point F on the HR diagram (Figure 1). The star is now a yellow giant. Convection is now dominant within the core (to m ~0.1) and in the mantle (m > 0.8), with radiation dominant between the two. Because helium burning produces carbon, the concentration of carbon in the helium burning region increases (reaching ~3%) during the descent from red giant to yellow giant (i.e. from point E to point F).

The re-adjustments brought about by the helium flashes lead to the core expanding again, and the star overall shrinks between E and F. Thus, although a yellow giant has a higher surface temperature than a red giant, it has a much lower luminosity. The surface luminosity is ~50 times solar and the surface temperature is ~4730 K. Depending upon composition, the star may now make an excursion along the "horizontal branch" (see Figure 1) during which period the surface temperature can increase significantly, though the luminosity remains approximately constant. It is worth noting just how rapidly the star's rate of evolution is accelerating. Our solar mass star will spend ~9 billion years on the main sequence, happily burning hydrogen in its core. But it spends only about one billion years as a red giant, and a mere 100 million years as a yellow giant. Blink and you miss it! The subsequent rate of evolution will be faster still.

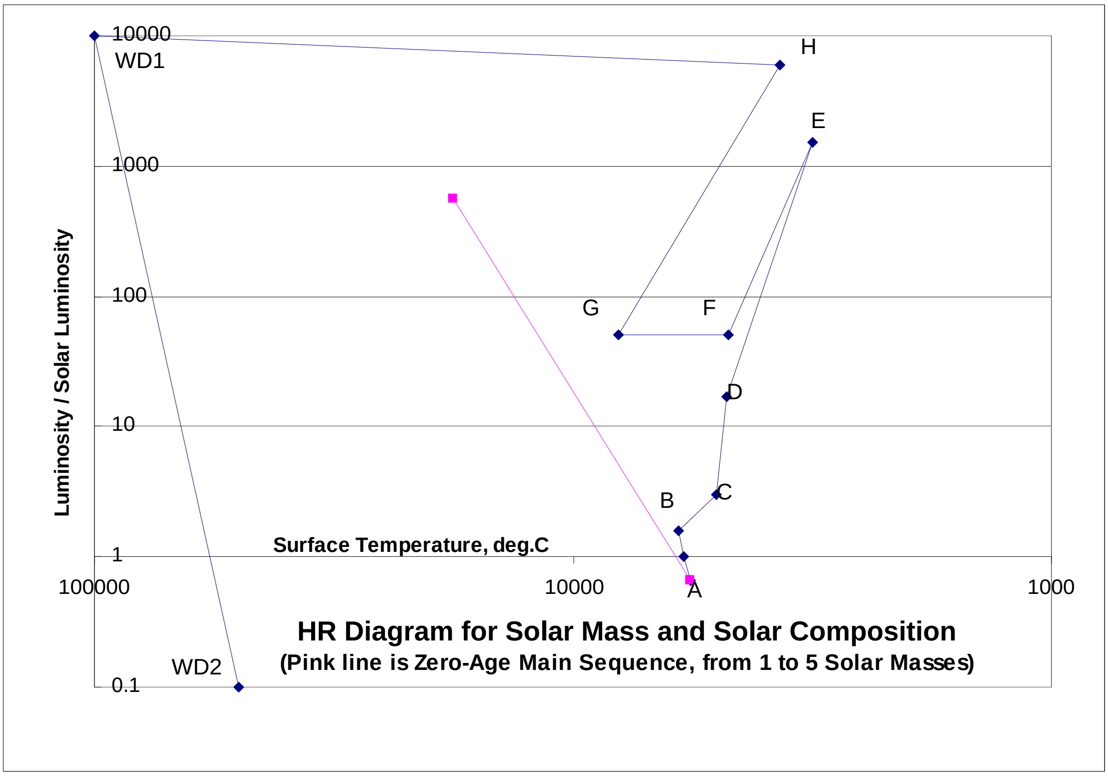
The star remains on the horizontal branch, FG, as a yellow giant whilst helium remains at the centre of the star. When the central helium is exhausted, about 60% has been converted to carbon (C^{12}) and 40% to oxygen (O^{16}). When the helium is all burnt out to a mass parameter of ~0.2, the star starts to ascend the second giant branch (from G to H). The second giant branch is generally called the "asymptotic giant branch", (AGB), because it becomes roughly asymptotic with the first giant branch. Just as the first giant branch (CDE) involves the shell burning of hydrogen, so the AGB involves the shell burning of helium. Note, though, that hydrogen also continues to burn in a shell at greater radius. In order of increasing radius, the star now consists of: (a)the central core of carbon-oxygen 'ash' left by completed helium combustion, and which is not itself burning; (b)a helium burning shell; (c)a helium rich inter-shell; (d)a hydrogen burning shell; (e)a thin radiative zone; and, (f)the outer convective envelope.

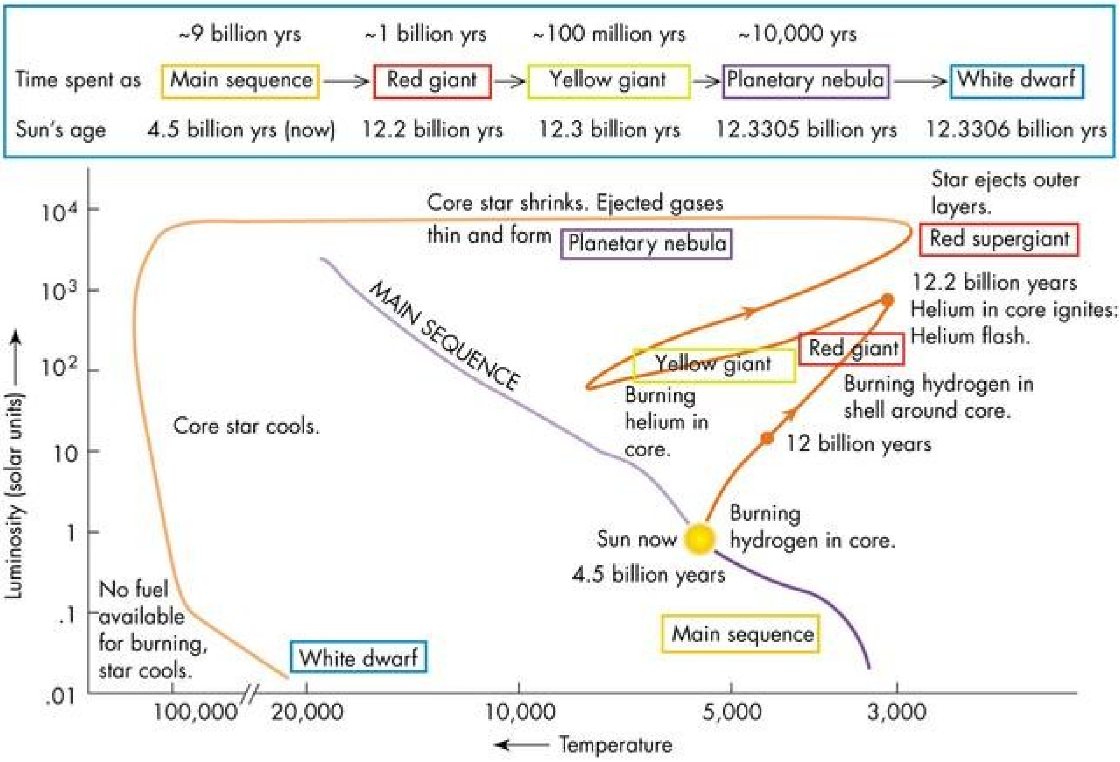
In Section 4 we continue the description of the ascent up the AGB. But first, in Section 3, we make a digression to describe the early evolution of a star of mass ~5$M_☼$.

Table 1: Salient Points on HR Diagram (1$M_☼$ Star)

Point(s)	Features	$L/L_☼$	T (K)
A	New star joins main sequence	0.65	5690
AB	Main sequence (central hydrogen burning)		
B	Hydrogen depleted at centre; star leaves main sequence	1.6	6000
BC	First phase of hydrogen shell burning		
C	Star builds a nearly isothermal core of almost pure helium	3	5000
CDE	The giant branch; star expands greatly, though core contracts; Star becomes redder (cooler) but more luminous; mass loss due to stellar wind becomes significant. Hydrogen shell burning continues throughout CDE.		
D	First dredge-up; convection zone reaches down to m ~ 0.25 temporarily. The hydrogen burning shell becomes extremely thin.	17	4785
E	Red giant; hydrogen burning in a very thin shell, which moves out to greater mass parameter.	1500	3150
EF	Helium flashes – the start of helium burning, initially unstable; Star shrinks but remains far larger than the Sun.		
F	Yellow giant; stable helium burning in the core	50	4730
FG	Horizontal branch. Star evolves to higher surface temperature, sensitive to composition and envelope mass. Stable helium burning in the core.	50	4730 to 8000
GH	The Asymptotic Giant Branch (AGB); helium burning in a shell, and hydrogen burning in a shell at larger radius. Thermal pulses arise due to thermal instabilities between the two shells.		
H	Red supergiant at tip of AGB. Large mass loss rates exacerbated by pulsation, ending with emission of a planetary nebula.	6000	3700
WD1	A white dwarf is left as remnant following the emission of the planetary nebula	10,000	100,000
WD2	The white dwarf cools over a billion year timescale.	0.1	50,000

Figure1


10000
WD1
H
E
1000
100
G
F
D
10
B
C
1
Surface Temperature, deg.C
100000
10000
A
1000
Luminosity / Solar Luminosity
HR Diagram for Solar Mass and Solar Composition
(Pink line is Zero-Age Main Sequence, from 1 to 5 Solar Masses)
WD2
0.1


~9 billion yrs
~1 billion yrs
~100 million yrs
~10,000 yrs
Time spent as
Main sequence
Red giant
Yellow giant
Planetary nebula
White dwarf
Sun's age
4.5 billion yrs (now)
12.2 billion yrs
12.3 billion yrs
12.3305 billion yrs
12.3306 billion yrs
Star ejects outer layers.
Red supergiant
Core star shrinks. Ejected gases thin and form
Planetary nebula
MAIN SEQUENCE
12.2 billion years
Helium in core ignites: Helium flash.
Red giant
Yellow giant
Burning helium in core.
Burning hydrogen in shell around core.
12 billion years
Core star cools.
Burning hydrogen in core.
Sun now
4.5 billion years
No fuel available for burning, star cools.
White dwarf
Main sequence
Luminosity (solar units)
10⁴
10³
10²
10
1
.1
.01
100,000
20,000
10,000
5,000
3,000
Temperature

3. Intermediate Mass Stars (~5M☼)

In many ways the evolution of a 5M☼ star follows a similar course to that of a 1M☼ star. However, there are important differences. Most importantly, the 5M☼ star lies at much higher luminosities on the HR diagram than a 1M☼ star. On the main sequence its luminosity is ~500 times solar, whereas on the giant branches its luminosity is up to an order of magnitude higher than a 1M☼ star at the same stage of evolution. Consequently, despite its greater mass, its lifetime is much shorter, around 1% of that of a 1M☼ star.

Like a 1M☼ star, the 5M☼ star evolves off the main sequence when it runs out of hydrogen at its centre. Unlike a 1M☼ star, though, convective conditions dominate in the core at the start. Also, whereas the hydrogen burning fusion reactions of a 1M☼ star proceeded via the pp sequences (for most of its life), the 5M☼ star has a hotter core and hence the CNO sequence dominates. This has the effect of increasing the abundance of nitrogen in the core at the expense of oxygen and carbon. The conversion of hydrogen to helium causes the number density of particles to decrease, and hence causes the temperature of the core to rise according to the gas law, $P \propto \rho_N T$, noting that pressure support must be maintained. By the time the central hydrogen is exhausted, the central temperature has risen from ~28 MK to ~40 MK. At this time the central convective region has shrunk and vanished, so the whole of the inner region is radiation dominated and convection is confined to the outer mantle. Like the 1M☼ star, hydrogen burning continues in a shell as the star ascends the first giant branch.

As the star ascends the first giant branch it expands and the outer parts cool, progressing towards becoming a red giant. As with the 1M☼ star, this drives the convective boundary inwards and results in the first dredge-up. In the case of the 5M☼ star, the CNO sequence has resulted in nitrogen production in the core. Consequently the first dredge-up conveys this new nitrogen to the mantle whose nitrogen content increases (but with a reduction in carbon and oxygen).

The ignition of helium marks a major qualitative difference between the evolution of a 5M☼ star and a 1M☼ star. The more massive star has a hotter and less dense core. The lower density means that degenerate conditions are avoided and hence the star's thermostatic mechanism functions throughout. Thus, helium ignition can occur in a stable manner without the intervening helium flashes. The reversal of the HR trajectory corresponding to the locus EF in the 1M☼ star HR diagram (Figure 1) is therefore less marked. Our 5M☼ star evolves smoothly through central helium burning and then shell burning of helium. Avoidance of degenerate conditions, and hence avoidance of helium flashes, applies to stars of mass greater than ~2.2M☼. When the central helium is exhausted it reaches a red giant state with a surface temperature of around 4170 K and a luminosity of 2500 times solar. With the start of helium shell burning, the star ascends the AGB which is virtually a continuation of the first giant branch for this mass. For stars of mass >2.2M☼.the red giant stage is about 25 times larger than the progenitor main sequence star.

In the early phase of helium shell burning, the energy produced by the helium is sufficient to push the hydrogen burning shell out to a larger radius and hence to cool it down sufficiently to temporarily switch off the hydrogen burning. This causes the temperature to fall and hence the opacity to rise in this region, reducing the effectiveness of heat transport by radiation, and thus causing convection to become dominant. The convective boundary therefore moves inwards to smaller mass parameters (perhaps to as low as m ~ 0.17 with respect to the total mass of the star) resulting in a second dredge-up. This second dredge-up occurs only for stars of initial mass greater than about $4M_☼$[2]. Once again this results in an increase in the near-surface levels of nitrogen, but a decrease in the oxygen and carbon levels.

4. Evolution On The Asymptotic Giant Branch (AGB)

We now consider both our $1M_☼$ star and our $5M_☼$ star as they evolve up the AGB. Their evolution is qualitatively similar, though the more massive star continues to lie at higher luminosities. The stars are progressing towards the red supergiant status when they will have a surface temperature of ~3,300-3,700 K and a luminosity several thousands of times greater than solar.

The nuclear heating in this phase is being provided both by a helium burning shell and a hydrogen burning shell at larger radius. The hydrogen burning is briefly extinguished during the second dredge-up phase in the case of the $5M_☼$ star (but not the $1M_☼$ star) and then re-ignites. Unlike earlier helium burning, which has produced a core containing large quantities of both carbon and oxygen, helium burning in a shell now produces mostly carbon and much less oxygen. This is because the helium in the thin shell is quickly exhausted, and the shell moves out to a larger radius with fresh helium, providing little time for the subsequent burning of carbon to oxygen. This has a bearing on the relative contributions to carbon and oxygen abundance by intermediate mass stars compared with massive stars.

The helium and hydrogen shells become very thin and move very close together as the star ascends the AGB. They can be separated in mass parameter by a mere 0.001. The proximity of the two shells, and the great temperature sensitivity of the nuclear reactions, leads to a thermal instability. The resulting thermal pulses can lead to helium luminosities reaching 10^8 times solar, though these tend to be accompanied by hydrogen luminosity becoming virtually zero. The effect on the surface luminosity is relatively modest. The duration of the spike in the helium power during a thermal pulse is very short on stellar timescales, typically of the order of tens of years. The interval between successive thermal pulses is in the order of tens of thousands of years.

Thanks to these thermal pulses on the AGB a sequence of "third[3] dredge-ups" occurs. The heat released during a helium power pulse creates an inter-shell convection zone. This initially has the effect of mixing the carbon produced in the helium shell into the inter-shell zone. Following this, the expansion caused by the helium power pulse causes a reduction in temperature in the region of the hydrogen shell. The higher opacities at

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[2] Though lower mass stars do undergo the third dredge-up discussed in Section 4.

[3] This is the usual terminology, though it is only the third dredge-up for stars of mass > $4M_☼$. For lower mass stars it is actually the second time that dredge-up has occurred, though the term "third dredge-up" is retained. There is no second dredge-up for lower mass stars.

reduced temperatures causes the convection zone to move inwards, enveloping what was the hydrogen shell and part of the inter-shell region. This is the third dredge-up. Thanks to the earlier conveyance of carbon from the helium shell into the inter-shell region, the third dredge-up is able to transport the carbon to the outermost parts of the star. Note that this transportation is effectively a two-stage conveyer, though both are the result of the helium power pulses. Hence, the violent events deep within the star’s interior lead to the conveyance of fusion product, particularly carbon, to the surface of the star. This enables stellar winds and other mechanisms to eject this product into the ISM.

5. Nucleosynthesis On The Asymptotic Giant Branch

Stars on the AGB synthesise all the elements between carbon and silicon. This is accomplished by combining nuclei with protons, alphas or neutrons. The latter have to be produced by preceding reactions. There are two mechanisms predominantly responsible for this nucleosynthesis. The first is associated with the thermal pulses described above.

The thermal pulses provide conditions of sufficiently high temperature to drive reactions that would otherwise not occur at significant rates. They also provide the dredge-up mechanisms for transferring the products to the envelope, as discussed above. Stars usually have a greater abundance of oxygen than carbon in their observable spectra. However, AGB stars which have been subject to a great many thermal pulses can have had so much carbon dredged to the surface that the carbon becomes more abundant than oxygen. Such stars are called “carbon stars”.

Recall that the CN/CNO sequences will already have produced certain species. For example, N^{14} is the major residue of the CNO cycles, although this is a secondary product which relies on a pre-existing metallicity from earlier generations of stars. Similarly, some C^{13} and N^{15}, produced in the CN/CNO sequences, will be available for subsequent reactions. A selection of reactions occurring during the late AGB stage is,

a) $N^{14} + \alpha \to F^{18} + \gamma$

b) $N^{15} + \alpha \to F^{19} + \gamma$

c) $F^{18} \to O^{18} + e^{+} + \nu_e$

d) $F^{19} + \alpha \to Ne^{22} + p$

e) $O^{18} + \alpha \to Ne^{22} + \gamma$

f) $O^{18} + \alpha \to Ne^{21} + n$

g) $C^{13} + \alpha \to O^{16} + n$

h) $Ne^{22} + \alpha \to Mg^{25} + n$

i) $Ne^{22} + \alpha \to Mg^{26} + \gamma$

j) $Ne^{21} + \alpha \to Mg^{24} + n$

k) $Ne^{22} + p \to Na^{23} + \gamma$

l) $Mg^{25} + \alpha \to Si^{28} + n$

m) $Mg^{25} + n \to Mg^{26} + \gamma$ *I guess this happens??*

n) $Mg^{25} + p \rightarrow Al^{26} + \gamma$

o) $Mg^{26} + p \rightarrow Al^{27} + \gamma$

For example, reaction (b) occurs efficiently at ~250 MK, which might be attained within the thermal pulses. The subsequent reaction (d) will occur efficiently within the inter-shell region. Having thus produced Ne^{22}, reactions (h) and (i) will then produce magnesium provided the inter-shell region is hot enough. The (repeated) third dredge-ups will then convey the magnesium produced to the envelope.

Any surviving Ne^{22} can be conveyed by the dredging to the H-shell. Here reaction (k) will produce sodium. The next dredge-up will convey it to the envelope. In a similar manner, magnesium can be deposited in the H-shell and hence produce aluminium via reactions (n) and (o), although only Al^{27} is stable.

Note the reactions which produce neutrons and hence enable the so-called “s-process” and “r-process” neutron capture reactions. This terminology was originated by Burbidge, Burbidge, Fowler and Hoyle in their seminal 1957 paper on stellar nucleosynthesis. The “s” and “r” refer to neutron capture reactions which are slow or rapid with respect to the competing beta decay of the product nucleus. By successive neutron captures, heavier and heavier isotopes of a given element can be produced. Eventually an isotope unstable to beta decay must be formed. The element with atomic number one greater is thus created. This can then also undergo neutron capture, ultimately producing the next element in sequence by beta decay. In this way all the elements could be formed given enough neutrons and enough time. But neutrons are in short supply. Nevertheless, the s-process and r-process result in a rich variety of elements and isotopes.

The second main process involved in AGB nucleosynthesis is the delightfully named “Hot Bottom Burning” (HBB). This occurs when the convective envelope penetrates the H-shell so that nucleosynthesis is taking place directly within a convecting zone. This makes possible mechanisms such as the Cameron-Fowler process which rely on nuclei being rapidly conveyed to cooler regions to avoid being consumed in subsequent reactions. The Cameron-Fowler mechanism produces lithium: $He^3 + \alpha \rightarrow Be^7 + \gamma$, $Be^7 + e \rightarrow Li^7 + \gamma$. Convection whisks away the beryllium and the lithium to cooler regions before subsequent reactions lead to the usual ppII and ppIII sequences.

HBB is also responsible for producing more N^{14}. This occurs via the CN cycles. The difference here is that the carbon being consumed is that produced by the star itself via the triple alpha reaction, rather than from the initial metallicity of the star. Consequently the N^{14} produced is primary nitrogen.

Finally, HBB produces silicon by burning aluminium in hydrogen via these reactions:-

p) $Al^{26} + p \rightarrow Si^{27} + \gamma$

q) $Si^{27} \rightarrow Al^{27} + e^{+} + \nu_e$

r) $Al^{27} + p \rightarrow Si^{28} + \gamma$

As a reminder, the stable isotopes up to silicon are:-

Element	Z	Stable A
H	1	1,2
He	2	3,4
Li	3	6,7
Be	4	9
B	5	10,11
C	6	12,13
N	7	14,15
O	8	16,17,18
F	9	19
Ne	10	20,21,22
Na	11	23
Mg	12	24,25,26
Al	13	27
Si	14	28,29

6. Stellar Winds and Mass Loss from Stars

The most dramatic means by which stars loose mass is in explosive events: novae and supernovae. However, novae and supernovae are not the only ways in which stars can transfer material to the ISM. Very large quantities of matter are shed from stars in the AGB and later stages in the form of a stellar wind. The mass loss rate can sometimes be high enough so that a star at the tip of the giant branch will become surrounded by a circumstellar shell of ejected gas and dust, which can redden and potentially extinct the star. The term “stellar wind” is generally reserved for a fairly steady, continuous process, although there are also more episodic outbursts of ejecta. Examples are the emissions from stars in the planetary nebula (PN) or pre-PN phases.

The steady stellar winds are driven by two broad classes of mechanism: gas pressure gradients and radiation pressure. In the case of relatively cool stars, of roughly solar surface temperature or less (<6000K), the wind is driven by the pressure gradient from the photosphere through the corona. The very low density corona extends out to several stellar radii. In low mass stars, the corona is at very high temperature, around a million degrees. The energy to maintain such high corona temperatures is provided by at least two mechanisms. Sound waves propagate from beneath the photosphere, becoming shock waves as they travel into the increasingly tenuous corona, and thus deposit energy mechanically. The other mechanism of energy transfer into the corona is essentially electromagnetic, specifically in the form of magnetohydrodynamic (MHD) waves. Elevated gas temperature implies elevated gas pressure (although the absolute pressure is low due to the very tenuous nature of the corona). The corona therefore continually expands outward into the extremely low pressure of interstellar space. The lost corona material is replaced from the stellar surface, which is at higher pressure (being at lower temperature but far more dense than the corona). Hence, the energy transfer mechanisms also drive the mass transfer.

The corona pressure gradient mechanism applies to low mass main sequence stars and also to AGB stars. However, the mass loss rates in these two cases are very different. Low mass main sequence stars loose only very little mass, the rate being roughly of order 10^{-14} solar masses per year, i.e. accounting for only ~0.01% in a 10 billion year lifetime. In contrast, cool AGB red stars may loose mass at a rate 10^{-6} $M_\odot$ per year, give or take an order of magnitude or two. This faster mass loss rate is largely due to the far greater size of red giants, around 25-100 times their main sequence size. Their mass loss rate may be expected to be crudely proportional to their surface area, which thus accounts for a factor of up to ~10,000. In addition, the photosphere in a red giant is far less strongly bound gravitationally, and therefore more readily 'boils off'. The main sequence and AGM cases also differ significantly as regards the speed of the stellar wind particles. Main sequence winds, though of very low flux, are at higher speeds, typically in excess of 200 km/sec. Red giant winds typically move at less than 50 km/sec.

In massive stars with high photosphere temperatures (say, ~10,000K), the corona heating mechanisms which apply to low mass stars do not operate. The corona is therefore at a temperature comparable with the photosphere and no gas pressure gradient is available to drive a wind. The other main class of mechanism generating stellar winds arises from radiation pressure. Radiation carries momentum. It is only necessary to transfer this momentum to the plasma by some absorption process in order to drive a stellar wind. Again there are two main sub-mechanisms. The first is absorption of radiation by transitions between electron states in atoms, known as "line scattering" (referring to transitions between spectral lines). The second is absorption by dust particles. Line scattering is the dominant mechanism in hot, massive stars. The efficiency of this mechanism is increased by the Doppler broadening of the transition energy band by virtue of the wind acceleration itself. In the case of luminous blue variable (LBV) stars, line scattering can give way to continuum scattering. The winds from hot stars achieve speeds in excess of 2000 km/sec and typical mass loss rates between 10^{-8} and 10^{-4} solar masses per year. Even greater 'superwind' rates can occur from LBVs.

The maximum momentum transfer rate available from the radiation is L/c, where L is the luminosity. In terms of the mass loss rate, $\dot{M}$, and the velocity of the wind, v, the momentum transferred to the wind is $\dot{M}v$. Hence a parameter, η, can be defined which measures the efficiency of the momentum transfer, where $\eta = \frac{\dot{M}vc}{L}$. In fact the wind mechanisms can be very efficient, with η approaching unity. Doesn't this imply a very high level of dimming of the star's apparent luminosity (even extinction)?

The other means of transferring radiation momentum to the gas is via absorption by dust particles. This applies particularly to cool AGB stars. The dust in question is generated by the AGB star itself and consists mostly of carbon. Recall that the thermal pulses of AGB stars result in carbon, produced in the core, being transported to the surface. Cool conditions produce particles of amorphous carbon which are ejected from the star. These particles are efficient at absorbing radiation and hence capture the momentum of the radiation, from whence it is communicated also to the plasma by collisions. The resulting wind velocities are modest (<50 km/sec) but the mass loss rates are large (typically between 10^{-4} and 10^{-8} solar masses per year). Note that at the upper bound loss rate, the star may loose (say) 7 solar masses in just 70,000 years as an AGB star. For stars of initial mass $<8.4M_{☼}$, this is sufficient to reduce their mass to below the Chandrasekhar limit, consistent with their fate to become white dwarfs. For such stars, the majority of their mass could potentially be lost via the stellar wind (Though the upper bound loss rates will apply only in a minority of cases). Hence, the stellar wind can be an important mechanism for enriching the ISM, potentially returning more mass to the ISM than any subsequent supernova explosion. However, the ejected envelope material is more dilute in fusion product than the core, so supernovae can provide a more concentrated contribution to the chemical abundance within the ISM.

The mechanism of radiation absorption by dust particles is enhanced during the pulsations of late AGB stars. The whole star may be involved in the pulsation, making the ejection process more effective by 'levitating' material into a 'dustosphere' (see Stan Owocki's web site). These physical pulses of the star, which are accompanied by large variations of luminosity, are not to be confused with the thermal pulses discussed in Section 4 (and which are not directly visible at the surface). An example is the so-called Mira variable stars (named after the original Mira in the constellation Cetus, The Whale). These typically have periods of 100-1000 days and are believed to be stars with less than two solar masses.

The life of a LIM star ends with the emission of a misleadingly named "planetary nebula"[4]. This is essentially the last and largest pulsation of the star at the end of its AGB stage. The final pulse is large enough for most of the star's envelope to achieve the escape velocity. Hence the core of the star is left exposed as a remnant white dwarf, whilst the envelope is ejected as a planetary nebula (PN). The PN is actually a plasma cloud expanding outwards from the parent star. They are very rarefied, with a density of perhaps 10^9 particles per m^3, though this varies with age and hence size, of course. When observed, they are typically of the order of a light year in size and at a temperature around 10,000 K. Temperatures tend to be greater further from the parent star, since the more energetic photons penetrate deeper into the nebula cloud. This gives the nebulae their ring-like appearance, with a darker centre and brighter clouds further out. They can look uncannily like eyes in space:-

[4] The name is historical. Planetary nebulae can look rather like giant planets. But they are not planets at all, of course.

The remnant white dwarf is white because the very hot core is suddenly exposed. However, its luminosity is initially comparable with that of a red giant because it is very small (in stellar terms). Its luminosity is bound to decrease since its nuclear reactions have ceased, but over a very long timescale. The white dwarf must have a mass less than the Chandrasekhar limit (~1.4 $M_{☼}$), and all stars with initial mass, M, less than about 8$M_{☼}$ will end as white dwarfs. Consequently, the stellar wind, the AGB pulsations and the planetary nebula expulsion between them must return (M-1.4 $M_{☼}$) to the ISM. Hence, the bulk of the mass of intermediate mass stars is returned to the ISM without the requirement for a supernova explosion. Thanks to the successive “third” dredge-ups, the ejected material contains a substantial amount of carbon and nitrogen, and to a lesser extent, oxygen, as well as all the other elements up to silicon formed by the reactions discussed in Section 5. Do they also contain elements beyond Si due to the s-process? But, of course, the bulk of this ejected mass is just the hydrogen and helium with which the star started its life.

7. Abundances of Elements from Pre-Supernova LIM Stars

We have seen in Section 5 that LIM stars may produce elements up to silicon. In Section 6 we have seen that there are mechanisms for ejecting the elements produced into the ISM prior to any nova or supernova events. In this Section we briefly examine the approximate abundances of elements produced in this way by LIM stars. The potential contribution by novae and supernovae of Type Ia is considered in the next Section. Note that the literature generally expresses abundances as a quantity like [C/H] defined as $\log_{10}\left(\frac{C/H}{(C/H)_{solar}}\right)$. Thus, [C/H] is a measure of the abundance of carbon relative to its solar abundance. In the form [C/Fe] it is also relative to the iron abundance.

Herwig et al (2005) model the element production by a 2 solar mass star up to the point at which it is about to eject a planetary nebula. By the time the star’s mass has fallen to one solar mass, the abundance of carbon at the surface has risen from ~0.1% to ~0.6%. Thus, such a star might contribute roughly 0.005 of a solar mass of carbon to the ISM. The earlier work of Forestini & Charbonnel (1997) calculated carbon production amounting to a few percent of a solar mass for stars of initial mass around 2 - 2.5 solar.

The emission of planetary nebulae will also contribute to the elements deposited in the ISM. The observational evidence is that ~50% of the planetary nebulae are carbon rich (i.e., with $C/O \geq 1$). The observed PN birth rate is around one per year in our Galaxy. A typical PN mass of (say) $0.3M_{☼}$, suggests that planetary nebulae contribute about $0.003M_{☼}$ of carbon per year to the ISM. Thus, planetary nebulae alone could be significant contributors to the ISM chemical abundances, particularly of carbon and nitrogen.

Whether LIM stars or massive stars contribute more to carbon production appears to be unsettled. Prantzos (2005) notes that "*In summary, in view of all current uncertainties on stellar yields, it is not yet clear whether the dominant source of C at high metallicities is massive or LIM stars. As for N, most of it at high metallicities apparently originates from AGB stars. However, its origin (as a primary element) at very low metallicities remains a mystery*". Gustafsson et al (1998) have put forward evidence that carbon originates predominantly from massive stars, rather than LIM stars. This may be because they regarded novae and supernovae of Type Ia as contributing little carbon to the ISM, quoting Nomoto et al (1997) and Gehrz et al (1998) in support of this contention. However, the majority view now appears to be that the bulk of carbon and nitrogen arises from LIM stars, but that the bulk of oxygen originates from massive stars. The enrichment of the ISM by LIM stars through the nova and Type Ia supernova mechanisms are discussed next.

8. White Dwarfs and Type Ia Supernovae

Following the ejection of the bulk of its envelope as a planetary nebula, the end point of the evolution of an isolated star with initial mass between $0.5M_{☼}$ and $\sim 8M_{☼}$ is a white dwarf composed primarily of carbon and oxygen[5]. The surface temperature of the white dwarf is initially in the order of 10^5 K because there is now only a thin covering over the extremely hot core. Despite its small size, its very high surface temperature means that the new white dwarf initially has about the same luminosity as the progenitor AGB star. Hence, on ejecting the planetary nebula the star moves suddenly horizontally to the left on the HR diagram (see Figure 1). Since all nuclear reactions have ceased, the luminosity of the white dwarf reduces steadily and it moves slowly downwards on the HR diagram. This trajectory is almost vertical, the temperature remaining high (i.e. white) because of the initial extremely high temperature of the core (hundreds of millions of degrees). Eventually the surface temperature must drop, but cooling may take the order of a billion years.

For isolated white dwarfs, that is the end of their story. But around half of all stars may occur in binary systems. For white dwarfs in a binary system the most dramatic events may be yet to come. There are two possible dramatic events which may occur in a binary

[5] The reason for stipulating masses greater than $0.5M_{☼}$ is that below this mass the star would never burn helium and hence would not end up as a carbon-oxygen white dwarf. Such stars, if isolated, have not yet ended up as anything – they are still burning their hydrogen since their lifetime exceeds the age of the universe. However, they will eventually end up as helium white dwarfs. Actually a small percentage of observed white dwarfs are composed of helium, but these are thought to have formed through a mass loss mechanism in a binary system.

system including a white dwarf: a nova and/or a Type Ia supernova. Either, neither or both may happen. And a nova may happen repeatedly since it leaves the core of the white dwarf intact. A Type Ia supernova, on the other hand can only happen once since the progenitor star is completely destroyed. Unlike other types of supernovae, a Type Ia supernova leaves no central remnant (only the ejected gas). The total kinetic energy of the ejecta from a nova is typically of order ?? J, whereas for a Type Ia supernova it is ~10^{44} J. In our Galaxy there are ~40 novae per year, but only one or two supernovae per century.

Both novae and Type Ia supernovae occur due to the accretion of material onto the white dwarf from the companion star. In both cases, therefore, the companion star must be near enough for material to become transferred to the white dwarf gravitationally. In practice this means that the companion star must have reached the red giant or supergiant stage in its evolution, and for the white dwarf to be close to its surface. This suggests that they are separated by a distance of roughly an astronomical unit.

If the white dwarf acquires hydrogen by accretion at more than a critical rate, then the hydrogen may undergo stable burning on the surface of the white dwarf. However, slower rates of accretion can lead to an accumulation of hydrogen prior to ignition, and hence to explosive burning. This is the nova. The mechanism is thought to be predominantly via CNO type reaction sequences. If the conditions for a nova are met, the likelihood is that novae will occur repeatedly, the interval being determined by the accretion rate but typically in the order of thousands or tens of thousands of years.

The mechanism for a Type Ia supernova, though not uncontroversial, is most likely to involve thermonuclear ignition in the core. For a review of the possible explosion mechanisms see Hillebrandt and Niemeyer (2000). In theory, as sufficient material is accreted for the mass to approach the Chandrasekhar mass limit (~$1.4M_\odot$), the white dwarf could collapse into a neutron star. However, it is thought that as this limit is approached, the temperature of the core is raised so as to ignite carbon fusion (i.e. $C^{12} + C^{12} \to Mg^{24} + \gamma$ or $C^{12} + C^{12} \to Ne^{20} + He^4$) creating a deflagration[6] wave which propagates rapidly through the star. Because the core is degenerate, the usual stellar thermostatic mechanism is not available. Increased heating rates do not cause an expansion which cools the plasma. Instead the temperature is permitted to increase unchecked, thus pushing up the reaction rates further. The resulting thermonuclear flame tears through the whole star in a few seconds, blowing it apart completely. Alternatively, a Type Ia supernova may occur due to the merging of two white dwarfs.

Observationally, Type I supernovae are distinguished from Type II by the absence of hydrogen lines in their spectra. This is due to the absence of extended H-envelopes in white dwarfs. Type Ia is characterized by the presence of a deep Si II absorption line and the absence of helium lines. Types Ib and Ic do not show a Si II line. Type Ia supernovae have had a high profile over the last decade as a result of their use in determining the

[6] Deflagration is the propagation of a flame front at sub-sonic speeds, as opposed to detonation in which the speed is supersonic. Some Type Ia supernova models have the speed becoming supersonic.

deceleration of the universal expansion. Their utility in this respect arises because all Type Ia supernovae have almost the same absolute luminosity (when suitably recalibrated by their light curve), and hence function as standard candles. The reasons for this are not fully understood but will be related to the fact that they all occur from a progenitor white dwarf of the same mass, namely the Chandrasekhar limit.

Brown et al (2005) have simulated the Type Ia explosion and the resulting nucleosynthesis. Their model suggests that approximately 70% of the original oxygen and carbon core is ejected unburnt into the ISM. This proportion of unburnt O and C is sensitive to the details of the flame propagation model. 3D models tend to predict a smaller percentage of remaining C and O [e.g. ~40%, see Travaglio et al (2004)]. When added to the carbon released in a LIM star’s evolutionary history prior to going supernova, this reinforces the claim that LIM stars are the main producers of carbon. However, ~30% or more of the white dwarf’s mass (which is ~1.4$M_{☼}$ at the time of the explosion) is converted to heavier elements, from neon through nickel. The elements formed with mass fractions greater than 0.1% are listed below, showing the dominant isotope only [using Brown et al’s results for illustration]:-

Type Ia Supernova Element Abundances [from Brown et al (2005)]

Ne^{20}	Mg^{24}	Si^{28}	S^{32}	Ar^{36}	Ca^{40}	Fe^{54}	Co^{55}	Ni^{56}
s	s	s	s	s	s	s	u	u
1%	2%	10%	3%	0.3%	0.2%	1%	0.4%	10%

s = stable; u = unstable. *theoretically unstable but with an enormous half-life (~10^{21} yrs).

The final row indicates the yield in percent of the original mass of the white dwarf. Thus, the main products (other than C and O) are silicon and nickel-56. The details of the predicted abundances are again sensitive to the model. For example, Travaglio et al (2004) suggest less silicon. However, large quantities of nickel-56 are predicted by all models. The nuclear reaction networks entering such models are complex, involving hundreds of reactions. In some regimes the networks can be simplified by appeal to nuclear statistical equilibrium (NSE). Despite the rapidity of the combustion, NSE will hold provided that the temperature is high enough that the nuclear reactions are faster still. When NSE holds, the relative proportions of product depend only upon temperature, pressure and the neutron:proton ratio, obviating the need to solve the many simultaneous reaction rate equations. For example, Travaglio et al assume NSE holds above 6 x 10^9 K. The temperature varies extremely rapidly as the thermonuclear flame sweeps through the star. The final abundances are obtained by integrating over the history of a range of physical ‘particles’. For sufficiently low temperatures the reaction rates are not fast enough to produce a significant amount of product in the very short time available and may be approximated as ‘unburnt’. Travaglio et al (2004) take this temperature to be 1.5 x 10^9 K.

The dominant product, nickel-56, decays by positron emission, first into cobalt-56 and then into iron-56, over a period of a few weeks. The cobalt-55 also decays by positron emission to iron-55 in a few days. Hence, as regards elements beyond oxygen, iron is ultimately the dominant product of the Type Ia supernova explosion. In fact, Type Ia supernovae are the main producers of Fe-peak elements. Although thermonuclear fusion reactions power the SN explosion, the luminosity of the expanding gas is provided by the radioactive decays starting with nickel-56, i.e. $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$. Hence, the characteristic timescale of Type Ia SN light curves is defined by this decay, and is thus the order of a few weeks.

Finally, if our binary LIM stars avoid going supernova, another possible outcome of their evolution is a pair of neutron stars. The orbit of such a pair of neutron stars will decay by gravitational wave emission. The famous binary pulsar discovered by Hulse and Taylor is expected to lead to a merged system in about 10^8y. Such neutron star mergers are candidates for explaining gamma ray bursts in events which might be 1000 times more energetic than a supernova. *Some sources say ~10^{44} J, which is about the same as a SN. Which is it?* A merger of two neutron stars may also lead to the ejection of neutron-rich material and hence the production of r-process elements. Thus, even a pair of neutron stars can contribute to the elemental abundance of the ISM in a sensible timescale.

9. Evolution Of High Mass Stars (>15M☼)

Stars with initial masses above ~8M☼ evolve in a similar manner to intermediate mass stars up to the point where the C-O core becomes sufficiently large to ignite carbon burning. The mass of the star is significant here, because too low a mass will fail to create the conditions of temperature and pressure required for carbon ignition. The carbon ignition temperature is ~600 million K. The star’s mass must also be sufficiently large to allow carbon to ignite in a core which is not degenerate, i.e. initial masses above ~8M☼. So long as the core is not degenerate the carbon burning can proceed under the thermostatic control provided by approximately perfect-gas law conditions in the core. The carbon-carbon reactions are principally,

$$\begin{aligned}
C^{12} + C^{12} &\rightarrow Mg^{24} + \gamma \\
C^{12} + C^{12} &\rightarrow Mg^{23} + n \\
C^{12} + C^{12} &\rightarrow Na^{23} + p \\
C^{12} + C^{12} &\rightarrow Ne^{20} + \alpha \\
C^{12} + C^{12} &\rightarrow O^{16} + 2\alpha
\end{aligned}$$

In a similar manner to the formation of hydrogen and helium burning shells, when the carbon in the centre is exhausted, carbon burning continues in a shell which gradually progresses outward in mass parameter. These massive stars will then contract further until oxygen ignites in the core at about a billion K. Ultimately the oxygen also becomes depleted at the centre and starts to burn in a shell. The principle oxygen reactions are,

$$\begin{aligned}
O^{16} + O^{16} &\rightarrow S^{32} + \gamma \\
O^{16} + O^{16} &\rightarrow S^{31} + n \\
O^{16} + O^{16} &\rightarrow P^{31} + p \\
O^{16} + O^{16} &\rightarrow Si^{28} + \alpha \\
O^{16} + O^{16} &\rightarrow Mg^{24} + 2\alpha
\end{aligned}$$

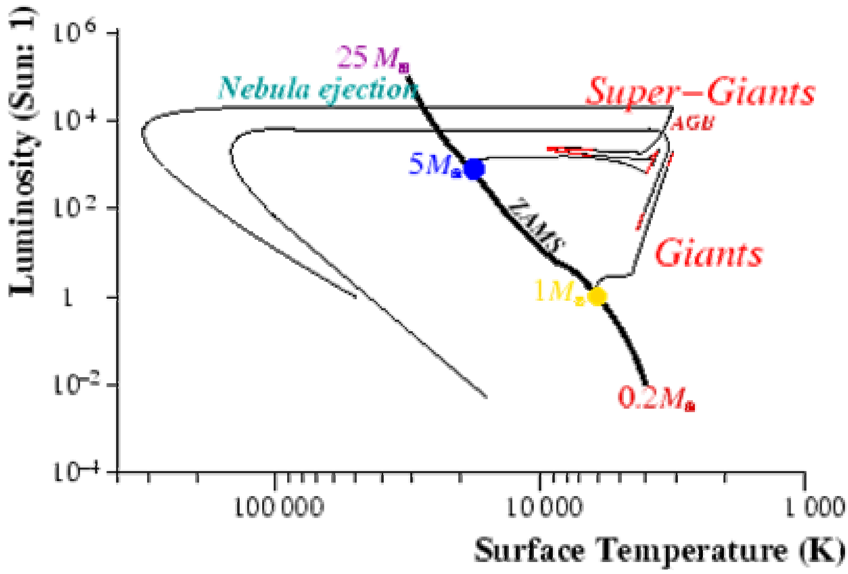
When the oxygen burning shell is formed, there will still be carbon, helium and hydrogen burning shells at successively larger mass parameter. The final stage of quiescent evolution is the ignition of silicon burning. Strictly this is a misnomer. The temperature required to overcome the Si/Si Coulomb barrier is so prodigiously high that photodisintegration of silicon nuclei occurs earlier, at ~3 billion K. The result is a potage of nuclear species approximating to nuclear statistical equilibrium (NSE). Since the iron-group nuclei (Fe, Co, Ni) have the largest binding energies per nucleon, NSE conditions tend to drive their production. This is the final stage of steady fusion in a stably evolving star because, after iron, the formation of heavier nuclei would be endothermic. The iron group elements form in the central core of the star, whilst concentric shells of oxygen, carbon, helium and hydrogen continue to burn. The conditions required in the various burning stages are summarised as follows:-

Thermonuclear Burning and Electron Degeneracy

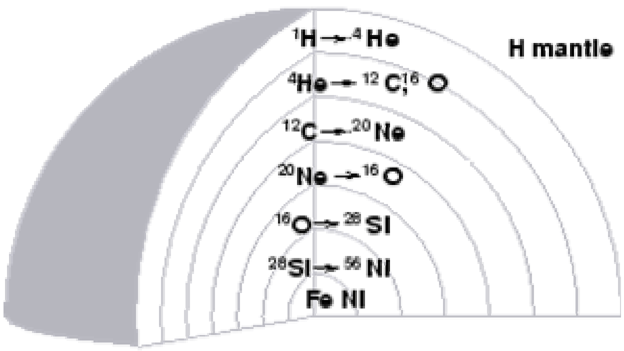
Thermonuclear Process	Initial Mass Required (M_{Sun})	Ignition Temp. (K)	Approx Density (g/cm^3)	Electron Degeneracy Density	Energy per nucleon (MeV)
Hydrogen burning H → He (pp)	0.1	4×10^6	10^1-10^2	$\sim 10^3$	6.55
Hydrogen burning H → He (CNO)		15×10^6	10^1-10^2	$\sim 10^3$	6.25
Helium burning He → C, O	0.5	100×10^6	10^3-10^6	$\sim 10^5$	0.61
Carbon burning C → Ne, Na, Mg, O	8.0*	600×10^6	10^5-10^8	$\sim 10^7$	0.54
Oxygen & neon O, Ne → S, Si, P, Mg	8.0	10^9	$>10^7$	$\sim 10^9$	0.3
silicon burning Si → Ni → Fe	8.0	3×10^9	$>10^7$	$\sim 10^9$	<0.18

**Lower mass stars may ignite carbon burning explosively, especially in binary systems (Type Ia supernovae)*

Note the diminishing heat output per unit mass in each successive stage. Each successive stage is of shorter duration. For example, a $25M_{Sun}$ star spends about 5 to 10 million years in hydrogen burning, 0.5 to 1.0 million years in helium burning, 500 to 1000 years in carbon burning, 6 to 12 months in oxygen burning, and a mere day or so in silicon burning. Even when on the main sequence, a $25M_{Sun}$ star is extremely luminous, at least 10,000 times solar brightness, and with a surface temperature of around 30,000 K.



In the final stages of quiescent fusion the structure of a massive star's core is,



Very massive stars present the greatest challenge to stellar modellers. However, a combination of modelling and observations suggests that there may be a qualitative difference between the evolution of stars above ~$40M_{\odot}$ compared with those between $8M_{\odot}$ and $40M_{\odot}$. The mass loss from stars >$40M_{\odot}$.is so great that they may never become red giants but instead spend their whole life on the left of the HR diagram as luminous blue stars. Many (perhaps all?) stars >$40M_{\odot}$.will pass through a stage as a Wolf-Rayet star.

The Wolf-Rayet Stage

Wolf-Rayet (W-R) stars are a particular stage in the evolution of very massive stars, probably stars with initial mass above ~$40M_{\odot}$, though the dividing line is very uncertain. They are certainly massive stars, having very high luminosities (10^5 to 10^6 $L_{\odot}$) and are extremely hot (blue), ~50,000 K. However, they are generally substantially less massive (when observed) than conventional 'O' stars of similar luminosity. Typical as-observed masses are around 16-18 $M_{\odot}$, but can be substantially greater or smaller. Their defining observational features are a surface composition dominated by helium, rather than hydrogen, and wind emission lines showing oxygen, carbon, nitrogen and other products of core nucleosynthesis. Some sub-types show virtually no hydrogen at all. W-R stars are therefore massive stars which have shed most or all their hydrogen mantle. W-R stars are rare, reflecting the short duration of this stage in a star's evolution.

The stellar winds from W-R stars are unusually dense and usually obscure the underlying stellar atmosphere. Mass loss rates are at the top end of the range for a star in continuous evolution, i.e. 10^{-5} to 10^{-4} $M_{\odot}$ per year with velocities of 2000 km/sec or greater. The density of the ejected matter has been likened to a nova, except that in the case of a W-R star the emission is ongoing rather than a one-off explosion. The wind momenta are much higher than for an 'O' star of similar luminosity. In fact the 'efficiency' parameter $\eta = \frac{\dot{M}vc}{L}$ is generally well above unity, in the range 10 to 50 (see Stan Owocki's web site). This means, of course, that the wind cannot be driven only by radiation pressure. Is this true? It is believed that instabilities in the wind lead to large amounts of matter being ejected in random directions. With impressive scientific precision they are referred to as 'blobs'. It may be that most of the mass loss is ejected as blobs. W-R stars lie near to the Humphreys-Davidson limit on the HR diagram, i.e. the upper limit for luminosity for a given temperature. Near this limit it is to be expected that the star might be susceptible to radiation pressure driven instabilities, and this may be implicated in the blob emission phenomenon.

10. Type II Supernovae: Mechanisms and Elemental Abundances

Type II supernovae are the end point of the evolution of stars with initial masses in the range ~$8M_{\odot}$ to ~$40M_{\odot}$. When the mass of the iron core reaches the Chandrasekhar limit (~1.4 $M_{\odot}$) electron degeneracy pressure is no longer sufficient to support it against its own gravity. It collapses in free-fall, reaching velocities of around a quarter the speed of light. This prodigious kinetic energy originates from the gravitational potential, and amounts to ~10^{46} J, a staggering 10% of the star's rest mass energy. During this collapse, the intense gamma ray production photodisintegrates the iron into alphas, neutrons and protons. The latter combine with electrons to form more neutrons and electron neutrinos ($p + e^- \rightarrow n + \nu_e$) which escape, carrying away around 1% of the energy. There is nothing to stop the collapse until the density reaches nuclear density, when the core is 20-30 km in diameter. The in-fall is finally halted by the 'billiard ball' repulsive hard-core of the neutrons, i.e. the strong nuclear force, together with neutron degeneracy pressure.

This hard impact causes the collapse to rebound, the material now travelling outward at 10%-20% light speed. However, the expanding shock wave is not the direct cause of the supernova. The shock wave is believed to stall within milliseconds at a radius of ~100-200 km due to its energy being absorbed by nuclear material which is still falling inwards. The temperature behind the shock wave reaches ~10^{11} K, generating thermal neutrinos of all flavours via electroweak processes (e.g., $\gamma + \gamma \leftrightarrow e^+ + e^- \rightarrow \nu + \bar{\nu}$, $e^+ + e^- \rightarrow \nu + \bar{\nu}$, $\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}$, $e^- + A \rightarrow A + e^- + \nu + \bar{\nu}$, where A is any nucleus). There are many more of these thermal neutrinos than the earlier electron-capture neutrinos. Virtually all of the 10^{46} J of energy is converted to neutrinos in an intense burst. It is thought that a small fraction of the neutrinos are then absorbed by the nuclear material. This re-energises the shock wave and causes the supernova explosion. However, the mechanism by which the neutrinos are absorbed is not understood. The neutrinos carry away 99% (~10^{46} J) of the energy, with a mere 1% (~10^{44} J) or so being transferred to the nuclear material and resulting in the explosion.

Neutrino production happens within a second of the core collapse. But the re-energised shock wave takes several hours to reach the surface of the star. Only then does the supernova become visible. Because of this time-delay, the neutrinos get a head start on the photons generated near the surface of the star which make the supernova visible. This prediction of supernova models has been confirmed in one instance. The neutrinos produced by supernova 1987a were directly observed by two different solar neutrino experiments, Kamiokande in Japan and IMB in Utah, USA. The neutrino signal lasted for about 12 seconds and preceded the optical signal by some hours, as expected.

Type II (and Ib/c) supernovae are the only source of elements beyond nickel. Is this true? The very high temperatures and neutron densities during the explosion lead to prodigious production of heavier elements by the r-process, i.e. neutron capture. In this way the radioactive isotopes are also formed. If it were not for Type II/Ib/c supernovae, the world would have no radioactive isotopes. The elements produced during the supernova explosion are released into the ISM in the form of a nebula. This also includes the lighter elements, up to nickel, produced during the earlier steady nuclear fusion. The isotopic composition of these lighter nuclei is also altered by the conditions during the explosion. However, it is believed that the supernova explosion does not greatly change the relative quantities of the various lighter elements. The total contribution of massive stars to enriching the ISM with elements is the sum of the SN and pre-SN contributions. Massive stars loose most of their mass prior to the SN stage. Of the many solar masses of material lost from a massive star via its stellar wind, what proportion are elements beyond helium? The answer to this may be sensitive to metallicity but it is likely that substantial amounts of the elements up to silicon are ejected prior to the SN stage. Is this true?

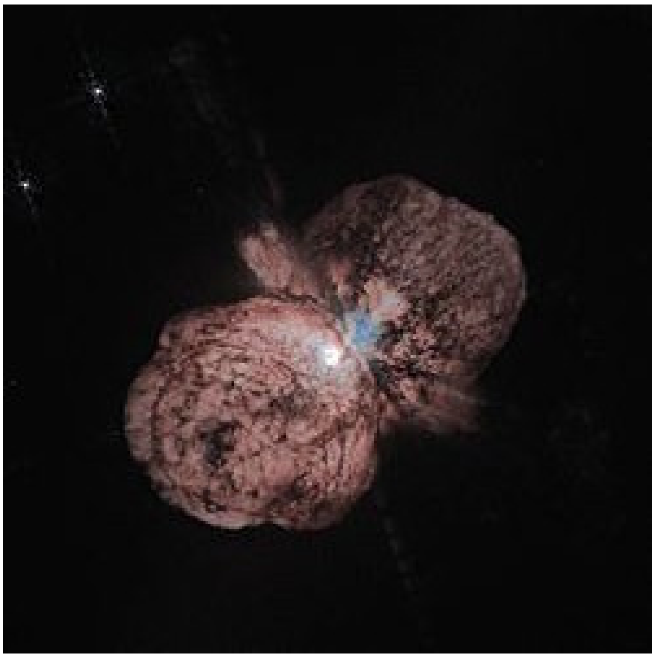
Type II supernovae leave a central remnant which is either a neutron star or a black hole. Neutron stars most likely result from stars of initial mass <20$M_☼$, and black holes from more massive progenitors.

<u>The Electron Capture Sub-Class</u>
The Type II SN mechanism described above probably only applies to initial masses greater than about 12$M_☼$. Between masses of ~8$M_☼$.and ~12$M_☼$ the nuclear burning may not proceed all the way to an iron core. Instead, fusion may stop after carbon burning, leaving a degenerate O-Ne-Mg core. Nevertheless, the basic core-collapse Type II supernova model still applies. It is triggered, however, by electron captures on the Ne and Mg nuclei. This sub-class of Type II SNe are referred to as "electron capture" SNe.

11. Type 1b/c Supernovae, Hypernovae and Gamma Ray Bursts
Type Ib/c supernovae are the end point of the evolution of very massive stars, probably >40$M_☼$. These stars are expected to have shed virtually all their hydrogen mantle prior to

going supernova, i.e. to have passed through the Wolf-Rayet stage. Hence the defining characteristic of Type Ib/c SNe is the absence of hydrogen lines in their spectra. However, the mechanism of Type Ib/c SNe are believed to be essentially the same as that of Type II SNe, noting that it is the core which generates the explosion. Type Ib/c SNe are far less common than Type II, reflecting the smaller numbers of massive stars.

The term ‘hypernova’ is used ambiguously in the literature. At one time it referred to events with energies ~100 times greater than supernovae. Currently, both ‘hypernova’ and ‘collapsar’ are used for models in which a very massive core collapses directly to a black hole (sometimes referred to as a failed Type Ib supernova). The collapsar model forms the best candidate at present for explaining gamma ray bursts (GRB). Jets of gamma rays are powered by the several solar masses of iron and other material which spirals into the newly formed black hole. However, the exact mechanism by which the gamma rays are generated is poorly understood. There seems to be disagreement as to just how much energy is needed in the event generating a GRB. This is partly because the GRB bursts are emitted as collimated rays, and partly due to uncertainty about how distant the events might be. Some sources imply that energies typical of supernovae ($\sim 10^{44}$ J) are sufficient, whereas other sources state that energies hundreds of times greater are required. Is this true?



Summary of Supernova Types

Type	Signature	Energy	Mechanism	Remnant
Ia	No H lines	~10^{44} J	Carbon deflagration	None
II	Has H lines	~10^{46} J (neutrinos) ~10^{44} J (gas & light)	Core collapse	Neutron star ($M<20M_☼$) Black hole ($M>20M_☼$)
Ib/c	No H lines; No Si lines	~10^{46} J (neutrinos) ~10^{44} J (gas & light)	Core collapse	Black hole
PopIII	SN 2006gy	~10^{45} J (gas & light)	Pair creation	None

12. Summary of Main Sources of the Common Elements

Some of the most significant features of element production are summarised as follows;

[1] C^{12} and N^{14} are mainly produced by low and intermediate mass stars ($0.5 \le M/M_☼ \le 8$), being released into the ISM by winds, pulses and planetary nebulae during the AGB stage, and also later as novae and Type Ia supernovae.

[2] O^{16} and the α-elements originate mostly from massive stars ($M > 8M_☼$).

[3] However, Ne^{20}, Mg^{24}, Si^{28}, S^{32}, Ar^{36}, $Ca^{40}$and $Fe^{54,55,56}$ are all produced by Type Ia supernovae, i.e. from LIM stars.

[4] In particular, most iron originates from Type Ia supernovae.

[5] Elements heavier than nickel are produced during Type II/Ib/c supernovae.

[6] A range of isotopes, including radioactive isotopes, are produced by neutron capture reactions during supernova explosions.

13. Summary of Salient Features of Stars Versus Mass Range

The key features of stars in various initial mass ranges are summarized below:-

<u>$M < 0.09M_☼$ (Brown Dwarfs)</u>: These stars never ignite nuclear fusion.

<u>$0.09M_☼ < M < 0.5M_☼$ (Very low mass stars)</u>: If isolated, they will end their lives as helium white dwarfs. But their lifetime exceeds the age of the universe, so this has not happened yet.

<u>$0.5M_☼ < M < 2M_☼$ (Low mass stars)</u>: After exhausting their central hydrogen, these stars ignite He burning explosively but without destroying themselves. If isolated, they end their lives as C-O white dwarfs. Their lifetimes range from a few billion years to a few times the age of the universe.

<u>$2M_☼ < M < 8M_☼$ (Intermediate mass stars)</u>: After exhausting their central hydrogen, these stars ignite He burning quiescently. If isolated, they end their lives as C-O white dwarfs, the upper mass limit of ~$8M_☼$ corresponding to the upper limit for a C-O degenerate core (~$1.4M_☼$). Their lifetimes range from 10 million years to about a billion years. If in binary systems they can give rise to cataclysmic variables such as novae and Type Ia supernovae.

<u>$8M_☼ < M < 12M_☼$ (Moderately massive stars)</u>: Stars with Main Sequence masses in this range end up as electron-capture SNe leaving neutron stars as remnants. These SNe will appear as Type II SNe which show H in their spectra.

<u>$12M_☼ < M < 20M_☼$ (Massive stars - 1)</u>: Stars in this mass range end their life as core-collapse SNe (Type II, showing H in their spectra). They will probably leave a neutron star as a remnant.

$20M_☼ < M < 40M_☼$ (Massive stars - 2): Stars in this mass range also end their life as core-collapse SNe (Type II, showing H in their spectra). They will probably leave a black hole as a remnant.
$40M_☼ < M < 100M_☼$ (Very massive stars): Stars in this mass range probably pass through the Wolf-Rayet stage. Their lifetimes are of the order of a million years. They probably explode as Type Ib/c SNe which do not show H in their spectra. These events may be the cause of gamma ray bursts, but this is uncertain. Do they leave black holes as remnants?
$M > 100M_☼$ (Extremely massive stars): Such extremely massive stars could probably not form in the current universe but are thought to have formed in the first population of stars (Population III) when metallicity was almost zero. A large proportion of the gravitational energy goes into the creation of electron-positron pairs and the star becomes unstable and explodes as a "pair creation" supernova. They leave no remnants and their lifetime is less than a million years.

Most Common Spectral Types Versus Mass

star mass (solar masses)	Time to contract to main sequence (years)	Lifetime (years)	Lifetime after main sequence (years)	Spectral type
60	20,000	2-3 million		O3
30		6-11 million	0.9 million	O5-O7
15	60,000	15 million	2 million	B0
10	200,000	32 million	5 million	B3-B4
5	600,000	68 million	22 million	B5
3	3 million	330-370 million	90 million	A0-A5
1.5	20 million	3 billion	280 million	F2-F5
1	50 million	10 billion	680 million	G2 (Sun)
0.5	200 million	30-40 billion		M0
0.1	500 million	1000's billions		M7

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