ASTR367 - Stellar Evolution
C+O Chapter 13

As we saw when discussing the Sun, stars are fairly stable over their main sequence lifetimes in terms of their luminosities, radii, and temperatures. Their structures and energy outputs change dramatically as they evolve off the main sequence.

Stars spend 80-90% of their lifetimes on the main sequence where they happily convert hydrogen into helium. The main sequence in the H-R diagram is not infinitely thin. What could cause the width of the line? For starters, the fact that stars do change their energy output slightly throughout their lives (their temperatures change less). Thus, they move upward throughout their lives. The physical mechanism is that as stars deplete their H in favor of He, the mean particle mass μ increases. Thus gravity becomes stronger, the core contracts, fusion increases, and the overall radius (which is set by the balance between thermal pressure and gravitational) increases.

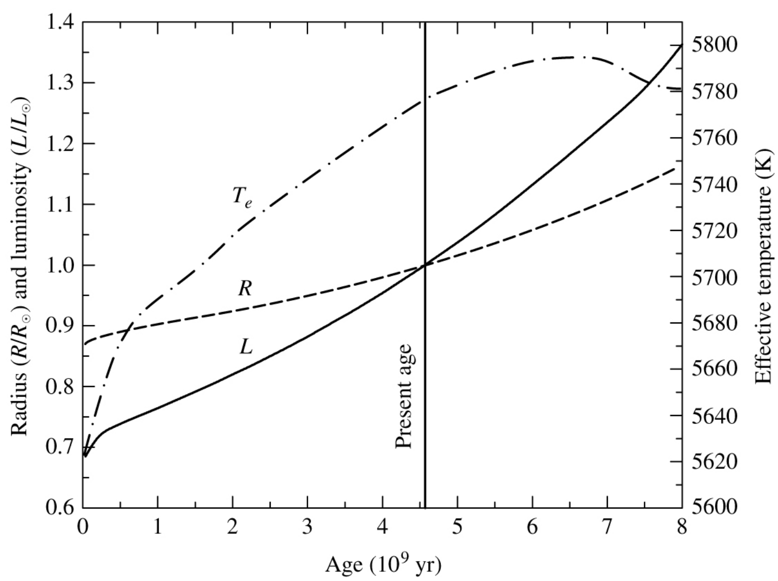


Figure 1: Evolution of the Sun on the Main Sequence.

Also, there is variation in the metallicity of stars. We have only just touched on metals so far. Astronomers call the fraction of hydrogen by mass "X", helium "Y", and everything else a "metal", "Z" such that $X + Y + Z = 1$.

The first stars in the Universe were born with essentially zero metallicity. The overall metallicity of the Universe has increased as the Universe has evolved. The metallicity of an individual star depends on the metallicity of the gas cloud from which it formed, and thus depends on the enrichment of that cloud. The Sun, for example, is high in metals, because there was a supernova that went off relatively near to the time when the Sun formed. For the Sun, $X_\odot = 0.738$, $Y_\odot = 0.249$, and $Z_\odot = 0.013$. Most stars have similar values, differing only by small percentages. If the Big Bang made 93.4% H, 7.6% He by number, with no metals, we would have $X = 93.4/(93.4 + 7.6 * 4) = 0.754$ and $Y = 0.246$. As metallicity increases, we would expect X to decrease.

Despite being a tiny fraction of the mass of a star, metals have a dramatic impact. Compared to H or He, metals have way more options for absorbing photons - way more photon energies can be absorbed because they correspond to energy differences between levels. This characteristic means that metals add significantly to the opacity of stars. High metallicity stars will be lower temperature and redder than their low metallicity counterparts because this opacity has a wavelength dependence. High metallicity stars therefore move to the right on the H-R diagram. Fully convective stars $M \lesssim 0.5\ M_\odot$ change in metallicity throughout their lifetimes.

Stars convert hydrogen into helium in their cores. This process increases the mean particle mass. From the ideal gas law,

$$P = \frac{\rho k T}{\mu m_H}, \tag{1}$$

we see that increases in mass per particle must be compensated by the temperature or the density going up. Both of these will necessarily increase the reaction rates, leading to an increase in luminosity. The strong dependence of the P-P chain on the energy output increases the luminosity for small changes in temperature.

Since main sequence evolution is relatively slight, we will focus here mainly on stellar evolution post-main sequence. This evolution has some basic principles that we already know well:

- Stars lose mass, and therefore fuel, via fusion
- This loss of fuel reduces the central pressure
- reduced pressure causes the star to contract
- A contracted star may have other fusion processes available.
- These other fusion processes may lead to more central pressure, increasing the luminosity and size of the star.

Additionally, more massive elements tend to "sink" toward the center, increasing the metallicity there.

The evolution of stars differs dramatically for stars of different masses. The dividing mass between two different evolutionary sequences is about 8 $M_\odot$. All post-main-sequence evolution begins when stars run out of hydrogen *in their cores.* A star can have hydorgen outside the core that is not available for fusion (because the temperature is too low) and this sam evolutionary sequence will begin.

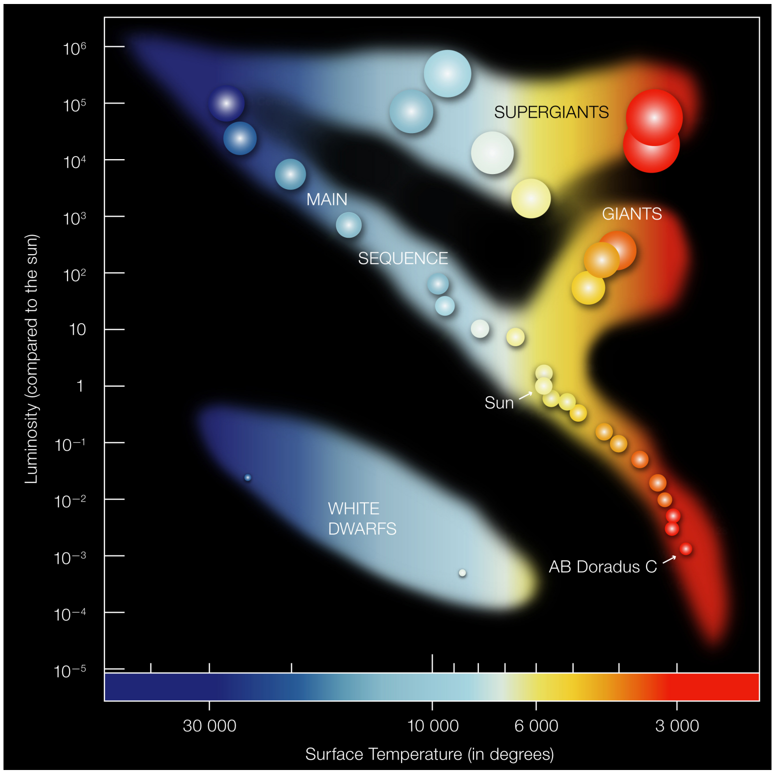


Figure 2: H-R diagram

Low-mass ($M < 8\ M_\odot$) Main Sequence Evolution

Eventually, stars run out of hydrogen in their cores. Stars still are plenty hot enough for fusion, but without hydrogen, they have trouble doing fusion in their cores. For instance, the triple-alpha process requires temperatures unreachable by stars on the main sequence, and without hydrogen, both P-P and CNO are not possible. Thus the core shrinks, giving off energy transformed from gravitational potential. The luminosity increases.

This situation has a problem: the core is no longer producing radiation and therefore a significant source of pressure is removed. There is still thermal pressure, but no radiation pressure. If we are prevent the collapse of the core, we need an additional source of pressure.

Electron Degeneracy Pressure

Luckily, we have a source of pressure! When the density of a gas is sufficiently high, the electrons are forced to occupy the lowest available energy levels. Electrons obey the Pauli exclusion principle, which means that they cannot all occupy the same quantum state. The electrons are therefore found in progressively higher energy states.

If the gas is completely degenerate, its pressure is independent of the temperature. In this

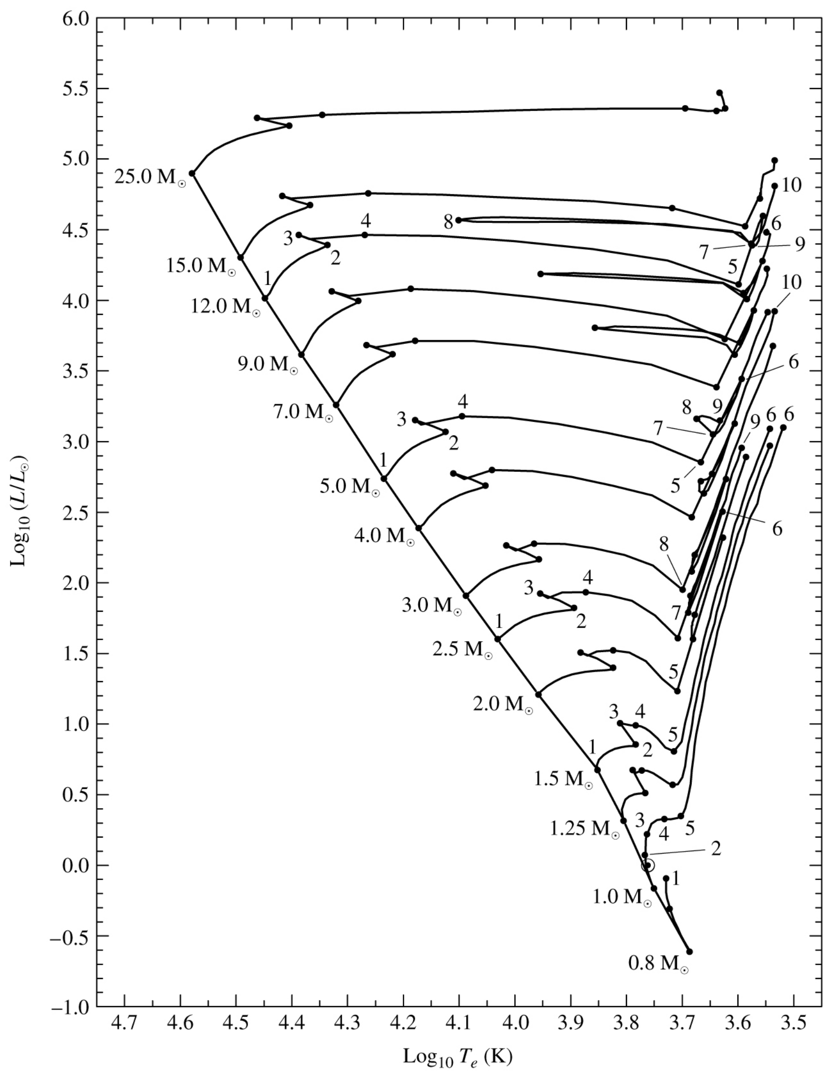


Figure 3: Main sequence and post-main sequence evolution of stars.

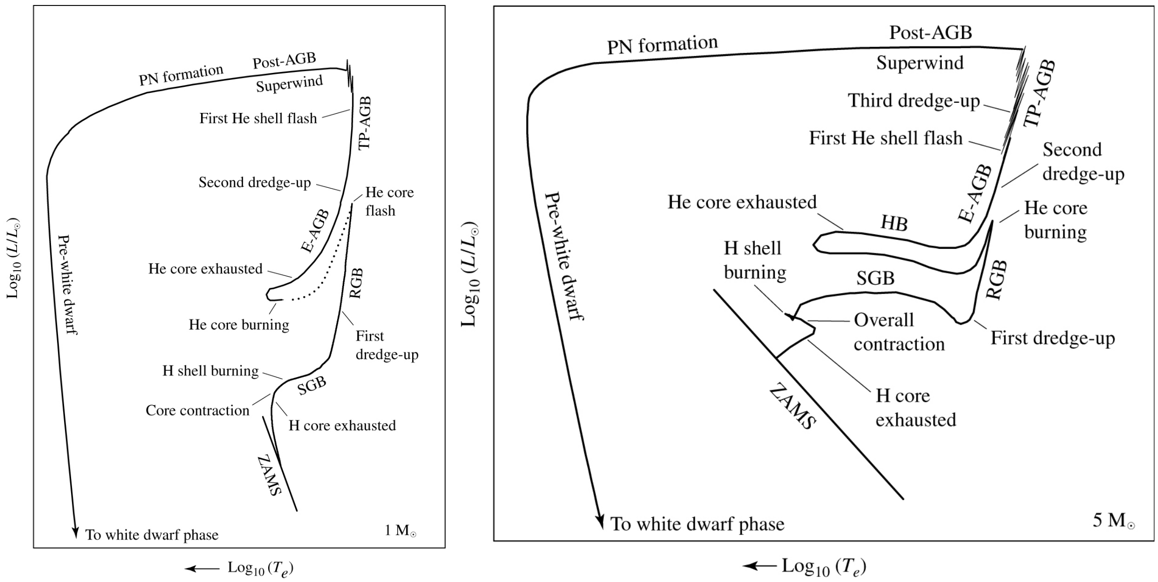


Figure 4: Evolution off the main sequence for 1 (left) and 5 $M_\odot$ (right) stars.

case, (for non-relativistic gas) the equation of state is

$$P = K\rho^{5/3}\,, \tag{2}$$

where K is a constant. Partially-degenerate gas will have some temperature dependence.

Even electron degeneracy cannot completely save a star from collapse though, as we'll see. At some point the external pressure is too great for electron degeneracy to support it.

Evolution off the Main Sequence

After core contraction, stars begin fusion in a shell around their cores. This reaction actually produces more energy than the stars did on the main sequence lives, moving them upward on the H-R diagram. Much of this energy does not make it out of the star, increasing its radius and lowering its temperature. Stars therefore move to the right in the H-R diagram. The stellar cores are made up of the byproducts of fusion, the "ash." This material sinks toward the core.

Subgiant Branch

Eventually the core contracts enough that the outer layers of the core at at a temperature high enough to sustain fusion. This phase is known as the "subgiant branch." During the subgiant branch, the luminosity is higher than it was on the main sequence. H shell burning produces more energy than H core burning. Throughout the subgiant branch, the star's temperature decreases and its radius increases. These effects nearly offset so the luminosity is stable.

Red Giant Branch

With the decrease in temperature, there are more H^- ions formed in stars' photospheres. This leads to a high opacity and a further lowering of the temperature. As a result, convection takes over as the dominant energy transport method ($d\ln P/d\ln T \lesssim 2.5$). This convective zone starts at the surface and reaches deep into the stellar interiors, down to the hydrogen burning shell. The energy transport is so efficient that the luminosity skyrockets. This is known as the "red giant branch."

The transport of materials is known as the "first dredge up."

Red Giant Tip

Eventually the central temperature and pressure are high enough to fuse helium nuclei through the triple-alpha process. Some C is fused with He to make O at this stage.

Initially, most of the energy still comes from H shell fusion, but the triple alpha process quickly expands the core due to its extreme energy output. This cools the H shell to the point where it cannot create significant energy. Removed of its main fusion source, the star decreases in luminosity.

Helium Flash

Stars with masses less than 1.8 $M_\odot$ create electron-degenerate cores. Surprisingly, their cores are at lower temperatures than the material outside at higher radius. This happens because the neutrinos from the core carry away significant energy.

Eventually, the core reaches a temperature and pressure great enough for the triple-alpha process. This releases tons of energy all at once, equivalent to the luminosity of an entire galaxy. The "helium flash" only lasts a few seconds though.

Evolution beyond the helium flash is difficult to predict, and so stellar models sometimes momentarily stop here.

Stars with masses greater than 1.8 $M_\odot$ do not have a helium flash.

The Horizontal Branch

The core at this point contracts, increasing the energy output. The temperature also increases, leading to evolution blue-ward. This is called the "horizontal branch."

Eventually, all the He in the core has been converted into C and O. The star at this point contracts and reddens.

The contracting core leads to a dual-shell burning phase on the horizontal branch, with nested shells of hydrogen and helium burning.

Early Asymptotic Giant Branch

The "Early Asymptotic Branch" is the dual shell burning phase, although the He shell is doing all the energy output. At this point the luminosity rises and the temperature decreases, analogous to what happens in the H shell burning phase.

Once again, convection takes over in the outer layers, leading to a "second dredge up."

Thermal-Pulse Asymptotic Giant Branch

Now the hydrogen burning shell has reignited. Yay! But the helium shell is running out of fuel. The hydrogen shell is dumping its helium ash onto the helium shell. This results in intermittent explosions of He fusion, leading to pulsations. The He runs out again and the process repeats, leading to pulsations.

Due to the fact that their atmospheres are tenuously bound, AGB stars lose significant fractions of their mass, up to $10^{-4}\ M_{\odot}$ per year. AGB stars are a significant source of dust production in the Universe.

One class of such AGB stars are known as long-period variables (LPVs). LPVs have pulsation periods of 100 to 700 days.

Post-AGB Evolution

The evolution of stars post-AGB is heavily dependent on the initial mass. Stars with $M < 8\ M_{\odot}$ will go on to form planetary nebulae and white dwarfs. Stars with $M >\ M_{\odot}$ will go supernova (more on this later).

The extreme mass loss exposes the stellar core, moving the stars leftward on the H-R diagram. Pulsations contribute to the mass loss as more mass is lost at each pulsation.

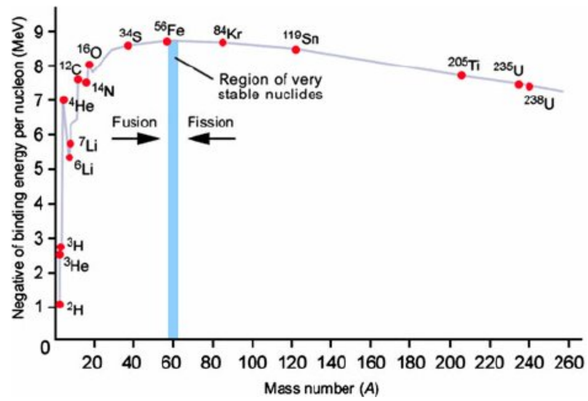


Figure 5: The binding energy curve.

Eventually, the core is completely exposed. This core is composed of carbon and oxygen, and is known as a "white dwarf."

Planetary Nebulae

The term "planetary nebula" is a misnomer, because they have nothing to do with planets. Instead, they are the layers of material expelled during AGB pulsations that remain around white dwarfs.

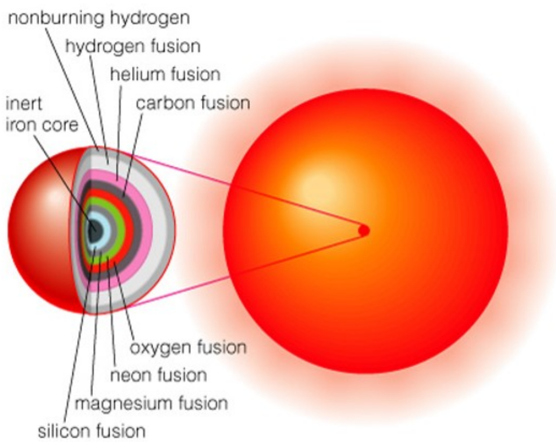
Expansion speeds of planetary nebulae are typically 10-30 $\mathrm{km\,s^{-1}}$. Sizes are $\sim 0.3\,\mathrm{pc}$. Lifetimes are just 10^4 years before a planetary nebula fades back into the interstellar medium.

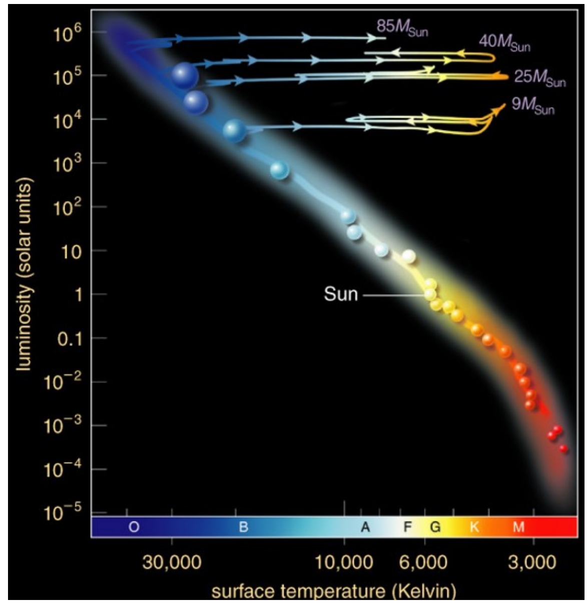
We now have a good understanding of what happens to stars of stellar mass $< 8\,M_\odot$. Stars with masses $> 8\,M_\odot$ initially follow a similar evolutionary sequence, but then they quickly diverge.

Massive Star Evolution

Lower mass stars end their lives with double-shell burning, building up a core composed of carbon and oxygen. If you remember the binding energy curve, elements up to iron can fuse to release energy. Why don't low mass stars continue to fuse heavier elements? They do not have the requisite temperatures in their cores.

Massive stars, however, can continue fusing heavier and heavier elements until they reach iron. During this advanced fusion, the stars evolve off the main sequence, as do lower mass stars, although high-mass stars do so at about the same luminosity through all their later phases. They form successive layers of non-burning H, fusing H, fusing He, fusing C, fusing O, fusing Ne, fusing Mg, fusing Si, and inert iron. You will notice that the atomic mass of





the fusion elements in the inner shells differ from one another by atomic number 2. This is because the most efficient fusion reaction with these elements involves alpha particles.

This successive fusion produces less and less energy (look at binding energy curve). As a result, stars go through these evolutionary sequences really fast. Your book notes that if the MS lifetime is 10^7) years, He burning is 10^6 years, carbon burning is 300 years, oxygen burning is 200 days, and Si burning is only two days.

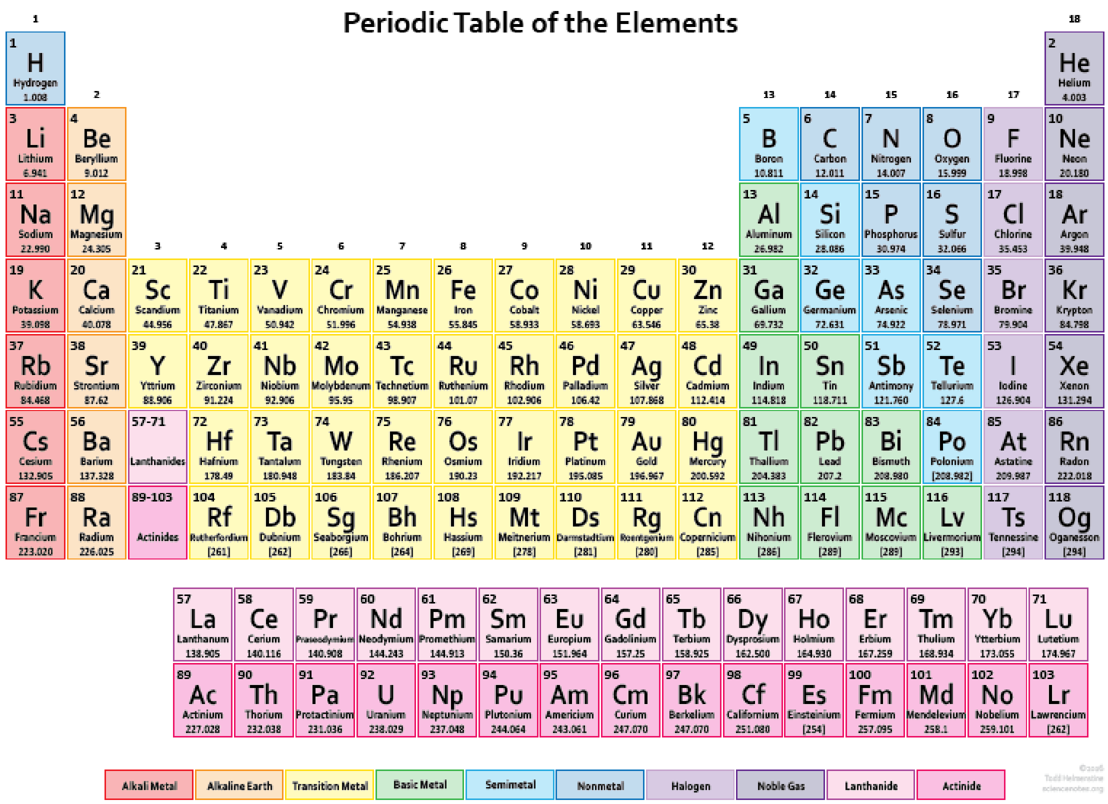
During this multiple-shell burning phase, the iron ash accumulates in the core. Ash accumulates in the other layers to but is burned off. Iron doesn't produce energy via fusion, and eventually the star goes supernova. More on supernovae later.

Types of Evolved Massive Stars

Before a star goes supernova, it goes through distinct evolutionary phases, many of which are named.

Luminous Blue Variables (LBVs)

LBVs are extremely massive, nearly 100 $M_\odot$. The most famous example is η Carinae. LBVs have tremendous mass loss of 10^{-3} $M_\odot$ per year (the Sun's is 10^{-14} $M_\odot$ per year). Some of this mass loss is explosive, as was the "Great Eruption" of η Car, which temporarily made it the second brightest star in the sky. η Car's mass loss has created the "homonculous," a massive cloud of gas and dust that is expanding outward at 650 $\mathrm{km\,s^{-1}}$. https://www.youtube.com/watch?v=u5mZuCD-gSY


Periodic Table of the Elements
1
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1 H Hydrogen 1.008
2 He Helium 4.003
3 Li Lithium 6.941
4 Be Beryllium 9.012
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.007
8 O Oxygen 15.999
9 F Fluorine 18.998
10 Ne Neon 20.180
11 Na Sodium 22.990
12 Mg Magnesium 24.305
13 Al Aluminum 26.982
14 Si Silicon 28.086
15 P Phosphorus 30.974
16 S Sulfur 32.066
17 Cl Chlorine 35.453
18 Ar Argon 39.948
19 K Potassium 39.098
20 Ca Calcium 40.078
21 Sc Scandium 44.956
22 Ti Titanium 47.867
23 V Vanadium 50.942
24 Cr Chromium 51.996
25 Mn Manganese 54.938
26 Fe Iron 55.845
27 Co Cobalt 58.933
28 Ni Nickel 58.693
29 Cu Copper 63.546
30 Zn Zinc 65.38
31 Ga Gallium 69.732
32 Ge Germanium 72.631
33 As Arsenic 74.922
34 Se Selenium 78.971
35 Br Bromine 79.904
36 Kr Krypton 84.798
37 Rb Rubidium 84.468
38 Sr Strontium 87.62
39 Y Yttrium 88.906
40 Zr Zirconium 91.224
41 Nb Niobium 92.906
42 Mo Molybdenum 95.95
43 Tc Technetium 98.907
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.906
46 Pd Palladium 106.42
47 Ag Silver 107.868
48 Cd Cadmium 112.414
49 In Indium 114.818
50 Sn Tin 118.711
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.904
54 Xe Xenon 131.294
55 Cs Cesium 132.905
56 Ba Barium 137.328
57-71 Lanthanides
72 Hf Hafnium 178.49
73 Ta Tantalum 180.948
74 W Tungsten 183.84
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.217
78 Pt Platinum 195.085
79 Au Gold 196.967
80 Hg Mercury 200.592
81 Tl Thallium 204.383
82 Pb Lead 207.2
83 Bi Bismuth 208.980
84 Po Polonium [208.982]
85 At Astatine 209.987
86 Rn Radon 222.018
87 Fr Francium 223.020
88 Ra Radium 226.025
89-103 Actinides
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [278]
110 Ds Darmstadtium [281]
111 Rg Roentgenium [280]
112 Cn Copernicium [285]
113 Nh Nihonium [286]
114 Fl Flerovium [289]
115 Mc Moscovium [289]
116 Lv Livermorium [293]
117 Ts Tennessine [294]
118 Og Oganesson [294]
57 La Lanthanum 138.905
58 Ce Cerium 140.116
59 Pr Praseodymium 140.908
60 Nd Neodymium 144.243
61 Pm Promethium 144.913
62 Sm Samarium 150.36
63 Eu Europium 151.964
64 Gd Gadolinium 157.25
65 Tb Terbium 158.925
66 Dy Dysprosium 162.500
67 Ho Holmium 164.930
68 Er Erbium 167.259
69 Tm Thulium 168.934
70 Yb Ytterbium 173.055
71 Lu Lutetium 174.967
89 Ac Actinium 227.028
90 Th Thorium 232.038
91 Pa Protactinium 231.036
92 U Uranium 238.029
93 Np Neptunium 237.048
94 Pu Plutonium 244.064
95 Am Americium 243.061
96 Cm Curium 247.070
97 Bk Berkelium 247.070
98 Cf Californium 251.080
99 Es Einsteinium [254]
100 Fm Fermium 257.095
101 Md Mendelevium 258.1
102 No Nobelium 259.101
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide

$$M > 85\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

$$40\,\mathrm{M}_\odot < M < 85\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

$$25\,\mathrm{M}_\odot < M < 40\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

$$20\,\mathrm{M}_\odot < M < 25\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{SN}$$

$$10\,\mathrm{M}_\odot < M < 20\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{BSG} \rightarrow \mathrm{SN}$$

https://www.youtube.com/watch?v=07hqULmszC8

Wolf-Rayet (WR) Stars

WR stars are less massive that LBVs, maybe only 20 $M_\odot$. They are rapidly rotating and are losing mass at a rate of $> 10^{-5}$ $M_\odot$ per year.

Unlike most stars, WR stars have strong (and broad) emission line spectra. Where could the broadness come from? The emission line spectra have lines of He, C, N, and O. Where could these come from? The H atmosphere of WR stars is completely absent, having been stripped off. It is the processed layers that are revealed, and they are enriched. We can separate WR stars into the WN class, which has N and He emission lines, the WC class, which has C and He, and the WO class, which has O (and is quite rare).

Other Evolved High-Mass Star Types

$10 - 40$ $M_\odot$ stars will first evolve into Red SuperGiants (RSGs) immediately off the main sequence. These are luminous, but red.

$10 - 20$ $M_\odot$ stars will evolve through a Blue SuperGiant (BSG) phase that is characterized by high luminosities and (relatively) blue colors.

> 40 $M_\odot$ stars will evolve into Of stars, which are like O stars but have emission lines.

Supernovae (SN)

All good things must come to an end, and so too must a massive star's life end. In keeping with their "live fast, die young" mantra, they go out with a bang, as a SN.

There are type main types of supernova, designated (confusingly) as Type 1a and "Other"

(other Type 1s and Type IIs). We will here be dealing with the Other category. These arise from core-collapse.

Eventually, fusion of Fe ceases, removing a source of pressure in the cores. Then the gravitational pressure becomes too great to be opposed by electron degeneracy pressure in the core, and the core will collapse in on itself. The layers just above the core are then drawn into a high temperature region and fusion takes place in these layers violently, leading to a SN explosion. These leave behind a supernova remnant, SNR. The SNR is the entirety of the star, minus the iron core which can turn into a neutron star or black hole. SNRs therefore enrich the interstellar medium. We are all made of stars!