Lecture 17: The Evolution of High-Mass Stars

Readings: 22-5

Key Ideas:

Intermediate Mass Stars ($4M_{sun} < M < 8M_{sun}$)
High Mass = O & B stars ($M > 8M_{sun}$)
Main Sequence Phase
Red Supergiant Phase
- He burning
- Carbon burning $M>4M_{Sun}$
- Neon, Oxygen & Silicon Burning $M>M_{Sun}$
- Ends with Iron Core Formation

Intermediate-Mass Stars

Stars with M = 4-8 M_{Sun}
- He fusion starts under non-degenerate conditions, so no He flash
- After asymptotic giant branch phase, core gets hot enough to fuse C. Results in an O-Ne-Mg core
- Inert O-Ne-Mg core contracts & heats up
- C, He, & H burning shells

Thermal pulses destabilize envelope:
- Eject envelope in a massive stellar wind
- Leave O-Ne-Mg white dwarf core behind

High-Mass Stars

<u>O&B Stars</u> ($M>8M_{Sun}$)
- Burn Hot
- Live Fast
- Die Young

<u>Main Sequence Phase</u>:
- Burn H to He in core via CNO cycle
- Build up a He core, like low-mass stars
- Lasts only for ~10 Myr

Red Supergiant Phase

After H core exhaustion

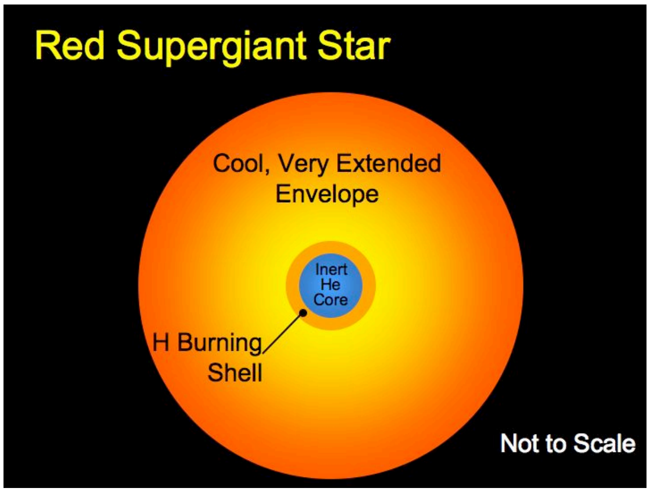
He core contracts & heats up

H burning in a shell around the He core

Huge, puffy envelope ~ size of the orbit of Jupiter!

Moves horizontally across the H-R diagram:

Takes ~ 1 Myr to cross H-R diagram. This is not very long, so we see very few stars in the crossing phase



Helium Ignition

Core Temperature reaches 170 Million K

Ignites Helium burning to Carbon & Oxygen

Not Degenerate=No Flash

Rapid Phase: ~ 1 Myr

He burning in the core

H burning in a shell

Start building a C-O core

Star becomes a <u>Blue Supergiant</u>

He Core Exhaustion

When He runs out in the core:

Inert C-O core collapses & heats up

H & He burning moves into shells

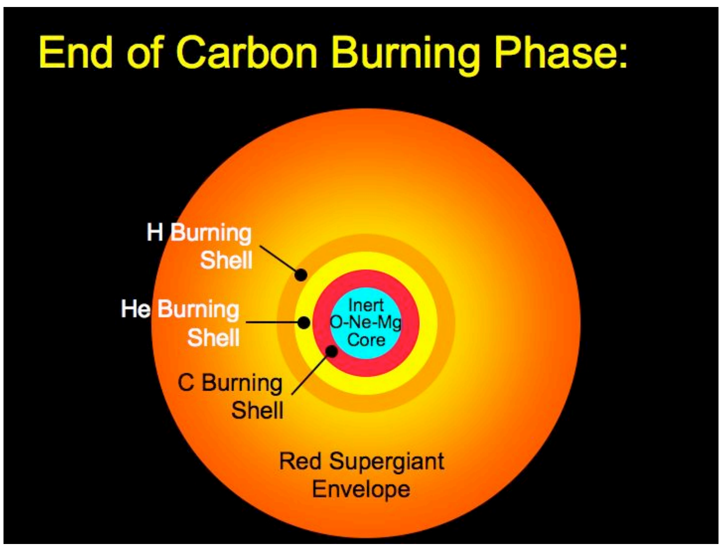
Becomes a Red Supergiant again

C-O core collapses until

T_{Core}> 600 million K
Density > 150,000 g/cc
Ignites Carbon Burning in the Core
Needs to be this hot to overcome 6proton-6proton electric repulsion

Carbon Burning

$^{12}C+^{12}C$ fuses to
^{24}Mg
$^{20}Ne + ^{4}He$
$^{16}O+^{4}He+^{4}He$
+ many side processes
Very inefficient
Makes many neutrinos
Lasts ~1000 years before C runs out.



High-Mass Stars: $M>8M_{sun}$

At the onset of Carbon Burning:
Evolution is so fast the envelope can no longer respond
See little outward sign of the inward turmoil to come

Exception
Strong stellar winds can erode envelope, changing the star's outward appearance.

Neon Burning

O-Ne-Mg core contracts & heats until

T_{core}~1.5 billion K

Density ~10^7 g/cc

Ignite Neon Burning

Reaction network makes O, Mg & others

Huge neutrino losses. More energy comes out in neutrinos than in electromagnetic radiation.

Builds a heavy O-Mg core

Lasts for a few years before Ne runs out

Oxygen Burning

Ne runs out, core contracts and heats until

T_{core}~2.1 billion K

Density ~ few x 10^7 g/cc

Ignite Oxygen Burning

Reaction network makes silicon, sulfur, phosphorus and other elements

Huge neutrino losses, neutrino energy > 100,000 photon energy

Builds a heavy silicon (+other stuff) core

Lasts for ~1 year before O runs out!

Silicon Burning

O runs out, core contracts & heats until:

T_{core} ~ 3.5 Billion K

Density ~10^3 g/cc

Ignite Si burning

Si melts into a sea of ^{4}He, p & n, shredded by photons

These smaller particles fuses with other particles into Nickel (Ni) and Iron (Fe)

Builds a heavy Ni/Fe core

Lasts for only ~1 day before Si runs out.

The Nuclear Impasse

Fusion of light elements releases nuclear binding energy, as the mass of the more tightly bound nucleus is lighter than the sum of the reactants.

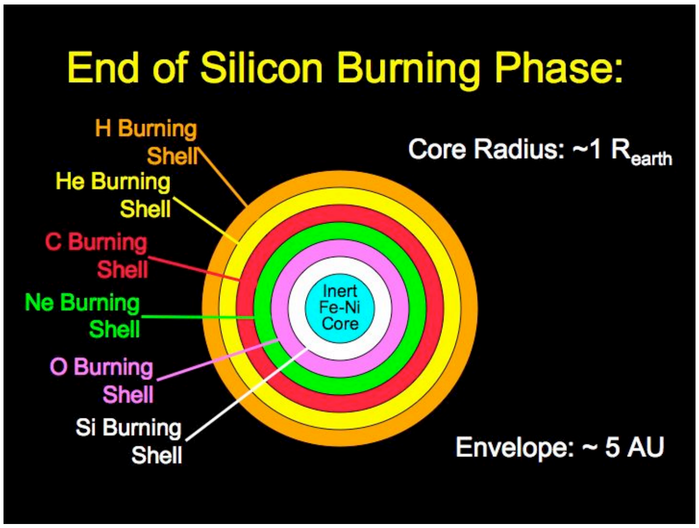
Iron (Fe) is the most bound nucleus. In general,

Fusion lighter than Fe *releases* energy
Fusion heavier than Fe *absorbs* energy

So $^{12}C + ^{12}C$ -> releases energy
But $^{56}Fe + ^{56}Fe$ -> requires energy

Once a Fe core forms, there are no fusion fuels left for the star to tap.

Fe has the lowest mass/nucleon of any nucleus. You can also see that the mass difference/nucleon is greatest between H and He, and much smaller as heavier nuclei are fused. He, C, Ne, O, etc. fusion release a lot less energy. And in many cases, a lot of it comes out in the form of neutrinos, instead of heating the gas and helping to support the star.



The Approach to the Iron Catastrophe

At the end of the Silicon Burning Day
Star builds up an inert Iron core
Series of nest nuclear burning shells continue to add Fe to the core
Finally, the Fe core exceeds 1.2-2 M_{Sun}
Fe core begins to contract & heat up
This collapse is final & catastrophic