Evolution of High Mass Stars

Astronomy 101
High Mass Stars

• **O & B Stars** \((M > 4 \, M_{\text{sun}})\):
  – Burn Hot
  – Live Fast
  – Die Young

• **Main Sequence Phase**:
  – Burn H to He in core via CNO cycle
  – Build up a He core, like low-mass stars
  – Lasts for only ~ 10 Myr
Maximum Mass: $60-100 \, M_{\text{sun}}$

- If a star is too massive, the core gets so hot that:
  - Radiation pressure overcomes gravity
  - Star becomes unstable & disrupts.
- Ultimate limit is not precisely known
- Such stars should be very rare.
- Massive stars live on the edge...
Red Supergiant Phase

• After H core exhaustion:
  – Inert He core contracts & heats up
  – H burning in a shell around the He core
  – Huge, puffy envelope ~ size of orbit of Jupiter

• Moves horizontally across the H-R diagram:
  – Takes ~ 1 Myr to cross H-R diagram
Crossing the Supergiant Branch

Temperature (K) vs. Luminosity ($L_{\odot}$) graph:
- The graph shows a line labeled "Main Sequence" descending from high temperature and high luminosity to lower temperature and lower luminosity.
- Another line labeled "Red Supergiant" is shown crossing the "Main Sequence."
Helium Flash

• Core Temperature reaches 170 Million K
• Ignites Helium burning to C & O:
  – Rapid Phase: ~ 1 Myr
  – He burning in the core
  – H burning in a shell
  – Start building a C-O core
• Star becomes a *Blue Supergiant*. 
Blue Supergiant

Temperature (K)

Luminosity ($L_{\text{sun}}$)

Main Sequence

Blue Supergiant

Helium Flash
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:
  – $T_{\text{core}} > 600$ Million K
  – density $> 150,000$ g/cc

• Ignites Carbon Burning in the Core.
End of Helium Burning
Carbon Burning:

- **Nuclear reaction network**: $^{12}\text{C} + ^{12}\text{C}$ fuses to:
  - $^{24}\text{Mg}$
  - $^{20}\text{Ne} + ^4\text{He}$
  - $^{16}\text{O} + 2 \times ^4\text{He}$

- Build up an inert O-Ne-Mg core

- Very inefficient:
  - Makes many neutrinos
  - Lasts only $\sim1000$ years before C runs out.
End of Carbon Burning Phase:

- Inert O-Ne-Mg Core
- C Burning Shell
- He Burning Shell
- H Burning Shell
- Red Supergiant Envelope
Intermediate Mass Stars

• Stars with $4 < M < 8 \, M_{\text{sun}}$
• After 1000 years:
  – Inert O-Ne-Mg core contracts & heats up
  – C, He, & H burning shells
• Thermal pulses destabilize the envelope:
  – Eject the envelope in a massive stellar wind.
  – Leave O-Ne-Mg white dwarf core behind.
High Mass Stars: $M > 8 \, M_{\text{sun}}$

• At the onset of Carbon Burning:
  – Evolution is so fast that the envelope can no longer respond.
  – Should see little outward sign of the inward turmoil to come.

• Exception:
  Strong stellar winds can erode the envelope, changing the outward appearance of the star.
Neon Burning

- O-Ne-Mg core contracts & heats up until:
  - $T_{\text{core}} \sim 1.5$ Billion K
  - density $\sim 10^7$ g/cc

- Ignite Neon burning:
  - reaction network makes O, Mg, & others
  - Huge neutrino losses: $> L_*$
  - Builds a heavy O-Mg core

- Lasts for a few years before Ne runs out.
Oxygen Burning

• Ne runs out, core contracts & heats up until:
  – $T_{\text{core}} \sim 2.1 \text{ Billion K}$
  – density $\sim \text{ few x } 10^7 \text{ g/cc}$
• Ignite Oxygen burning:
  – reaction network making Si, S, P, & others
  – Huge neutrino losses: $> 100,000 \ L_*$
  – Builds a heavy Si core.
• Lasts for $\sim 1 \text{ year}$ before O runs out.
Silicon Burning

• O runs out, Si core contracts & heats up until:
  – $T_{\text{core}} \sim 3.5 \text{ Billion K}$
  – density $\sim 10^8 \text{ g/cc}$

• Ignite Silicon burning:
  – Si melts into a sea of $^4\text{He}$, p, & n
  – Fuses with rest into Nickel (Ni) & Iron (Fe)
  – Builds a heavy Ni/Fe core.

• Lasts for $\sim 1$ day...
The Nuclear Impasse

• Fusion of light elements releases *nuclear binding energy*.

• Iron (Fe) is the most tightly bound nucleus:
  – Fusion of nuclei lighter than Fe *release* energy.
  – Fusion of nuclei heavier than Fe *absorb* energy.

• Once an Fe core forms, there are no new fusion reactions left for the star to tap.
End of Silicon Burning Phase:

- Si Burning Shell
- O Burning Shell
- Ne Burning Shell
- C Burning Shell
- He Burning Shell
- H Burning Shell

Envelope: ~ 5 AU

Core Radius: ~1 \( R_{\text{earth}} \)
End of the Road

• At the end of the Silicon Burning Day:
  – Star builds up an inert Fe core
  – Series of nested nuclear burning shells

• Finally, the Fe core exceeds $1.2 - 2 \, M_{\text{sun}}$:
  – Fe core begins to contract & heat up.
  – This collapse is final & catastrophic
Last Days of a Massive Star

• Burn a succession of nuclear fuels:
  – Hydrogen burning: 10 Myr
  – Helium burning: 1 Myr
  – Carbon burning: 1000 years
  – Neon burning: ~10 years
  – Oxygen burning: ~1 year
  – Silicon burning: ~1 day

• Build up an inert Iron core in the center.
Inside a Massive Star on the Brink:

- H Burning Shell
- He Burning Shell
- C Burning Shell
- Ne Burning Shell
- O Burning Shell
- Si Burning Shell
- Inert Fe-Ni Core
- Envelope: ~5 AU
- Core Radius: ~1 $R_{\text{earth}}$
Iron Core Collapse

• Iron core with $M \sim 1.2 - 2 \ M_{\text{sun}}$
  – Collapses & begins to heat up
  – Reaches $T > 10$ Billion K & density $\sim 10^{10} \text{ g/cc}$

• Two energy \textit{consuming} processes kick in:
  1) Nuclei photodisintegrate into He, p & n
  2) protons & electrons combine to form neutrons & neutrinos. Neutrinos escape.

• Both rob energy, hastening the core’s collapse
Catastrophic Collapse

• Start of Iron Core collapse:
  – Radius ~ 6000 km (~$R_{\text{earth}}$)
  – Density ~ $10^8$ g/cc

• Within 1 second:
  – Radius ~50 km
  – Density ~$10^{14}$ g/cc
  – Collapse Speed ~ 0.25 c!
Core Bounce

• Density of collapsing core hits $\sim 2.4 \times 10^{14} \text{ g/cc}$
  = density of atomic nuclei!

• Strong nuclear force comes into play!

• Inner $0.7M_{\text{sun}}$ of the core:
  – comes to a screeching halt
  – overshoots & springs back a little ("bounces")

• Infalling gas hits the bouncing core head-on!
Post-Bounce Shockwave

• Shockwave spreads out from core bounce:
  – Kinetic Energy is $\sim 10^{51}$ ergs!
  – *Stalls out* after only 25-40 millisec because of a traffic jam between in falling & outflowing gas.

• Meanwhile, *neutrinos* pour out of the core:
  – trapped by the dense surrounding gas
  – leads to rapid heating of the gas
  – in turn leads to violent convection
New, Improved Shockwave

- Violent convection breaks the traffic jam
- Shockwave is regenerated in ~300 millisec.
- Smashes out through the star:
  - Breakout speed ~0.1c!
  - Explosive nuclear fusion in wake of blast produces more heavy elements
  - Heats up and accelerates envelope gas
- In a few hours, shock breaks out of the surface
Supernova!

- At shock breakout:
  - Star brightens to \(~10 \text{ Billion } L_{\text{sun}}\) in minutes.
  - Can outshine an entire galaxy of stars!
- Outer envelope blasted off:
  - accelerated to a few \(\times 10,000 \text{ km/sec}\)
  - gas expands & cools off
- Supernova fades out over a few months.
Historical Supernovae

• **1054 AD:** “Guest Star” in Taurus observed by Chinese astronomers (Song dynasty).
  – Visible in daylight for 23 days.
• **1572:** Tycho Brahe’s Supernova
• **1604:** Johannes Kepler’s Supernova
• **6000-8000BC:** Vela supernova
  – observed by the Sumerians; appears in legends about the god Ea.
Crab Supernova
Supernova 1987a

• Nearest visible supernova since 1604.

• January 1987:
  – 15 M$_{\odot}$ Blue Supergiant Star SK-69°202 Exploded in the Large Magellanic Cloud.
  – Saw a pulse of neutrinos, then the blast.
  – Continued to follow it for the last decade.

• Wealth of information on supernova physics.
Nucleosynthesis

• Start with Hydrogen & Helium:
  – Fuse Hydrogen into elements up to Iron/Nickel
  – These accumulate in the core layers of stars.

• Supernova Explosion:
  – “explosive” nuclear fusion builds more light elements up to Iron & Nickel.
  – fast & slow neutron reactions build Iron & Nickel into heavy elements up to $^{254}$Cf
Top Ten Most Abundant Elements

- 10) Sulfur
- 9) Magnesium
- 8) Iron
- 7) Silicon
- 6) Nitrogen
- 5) Neon
- 4) Carbon
- 3) Oxygen
- 2) Helium
- 1) Hydrogen
Supernova Remnants

• What happens to the envelope?
  – Enriched with metals in the explosion
  – Expands at a few $\times 10,000$ km/sec

• Supernova Blast Wave:
  – Plows up the surrounding interstellar gas
  – Heats & stirs up the interstellar medium
  – Hot enough to shine as ionized nebulae up to a few thousand years after the explosion
Stardust

- Metal-enriched gas mixes with interstellar gas
  - Next generation of stars includes these metals.
  - Successive generations are more metal rich.
- Sun & planets (& us):
  - Contain many metals (iron, silicon, etc.)
  - Only ~5 Gyr old
- The Solar System formed from gas enriched by a previous generation of massive stars.
Cygnus Loop:
Scraps of an old Supernova Remnant
Summary:

• End of the Life of a Massive Star:
  – Burn H through Si in successive cores
  – Finally build a massive Iron core.
• Iron core collapse & core bounce
• Supernova Explosion:
  – Explosive envelope ejection
  – Main sources of heavy elements
Questions:

• Where did elements like U, Th, Pb, Au, Ag, etc. come from?
• Where did C, O, N, etc. come from?
• How did all that get mixed up in the Sun?
• Do Supernovae still explode in the Universe?
• What would happen if a Sn exploded near the Earth?