Lecture 17: The life of a high-mass star

Astronomy 111
High mass stars

- **O & B Stars** \((M > 4 \, M_{\odot})\):
  - 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

- Luminosity ($L_{\text{sun}}$)
- Temperature (K)

Graph showing the relationship between luminosity and temperature for stars, with a line indicating the transition from the Main Sequence to the Supergiant Branch. The graph highlights the transition from a red color to a supergiant status as the temperature and luminosity decrease.
Red Supergiant Star

- Inert He Core
- H Burning Shell
- Cool, Extended Envelope

Not to Scale
Variable stars

• As stars move horizontally across HR diagram they get brighter and fainter—variable stars

• Cepheid variables
  – High mass stars
  – Obey a Period-Luminosity relationship
  – Use as distance indicators

• RR Lyrae
  – Low mass stars
High-mass stars move horizontally back and forth across the H-R diagram after leaving the main sequence.

As stars pass through the "instability strip," they become pulsating variable stars.
Pulsating Cepheid variable

1. The star falls inward. As the star contracts...
2. Thermal energy is used to ionize helium, lowering the temperature...
3. ...until helium has all recombined. The star coasts until it stops and begins to fall back inward.
4. ...robbing the star of pressure support, allowing it to fall through its equilibrium size...
5. ...adding to the pressure, which pushes the star past its equilibrium size...
6. As it expands, recombining helium releases energy, driving up the temperature...
7. ...stopping the contraction. The star “bounces.”
8. Equilibrium radius

Luminosity

Time

Net force due to gravity and pressure (blue)

Velocity (red)
Helium burning

- 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

Blue Supergiant

Main Sequence

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

Temperature (K)

$10^{-4}$

$10^{-2}$

$10$  

$10^2$  

$10^4$  

$10^6$  

$40,000$  

$20,000$  

$10,000$  

$5,000$  

$2,500$  

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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

- Luminosity ($L_{\text{sun}}$) vs. Temperature (K)
- Log scale for both axes
- Main Sequence path on the diagram
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 $\sim 1000$ years before C runs out
End of Carbon burning phase
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:
  – $T_{\text{core}} \sim 1.5 \text{ Billion K}$
  – density $\sim 10^7 \text{ g/cc}$

• 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 $\sim$ few $\times 10^7$ g/cc

• Ignite Oxygen burning:
  – reaction network making Si, S, P, & others
  – Huge neutrino losses: $> 100,000 \text{ L}_*!$
  – 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:
  – $T_{\text{core}} \sim 3.5$ Billion K
  – density $\sim 10^8$ g/cc

• Ignite Silicon burning:
  – Si melts into a sea of $^4$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:

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

Core Radius: $\sim 1 \, R_{\text{earth}}$

Envelope: $\sim 5 \, \text{AU}$
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

Core Radius: ~1 \( R_{\text{earth}} \)

Envelope: ~ 5 AU
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 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 0.7\( M_{\text{sun}} \) 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 \( \sim 10 \text{ Billion } L_{\text{sun}} \) 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
For one second, more energy than in an entire galaxy!
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 god Ea
Crab supernova
Supernova 1987a

- Nearest visible supernova since 1604
- January 1987:
  - $15 \, M_{\text{sun}}$ 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
Supernova 1987A

HST - WFPC2

Feb. '94  Sept '94  Mar. '95  Feb '96

PRC97-03 • ST ScI OPO • January 14, 1997
J. Pun (NASA/GSFC), R. Kirshner (CfA) and NASA
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 $^{254}\text{Cf}$
### Top Ten Most Abundant Elements

<table>
<thead>
<tr>
<th>Rank</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>2</td>
<td>Helium</td>
</tr>
<tr>
<td>3</td>
<td>Oxygen</td>
</tr>
<tr>
<td>4</td>
<td>Carbon</td>
</tr>
<tr>
<td>5</td>
<td>Neon</td>
</tr>
<tr>
<td>6</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>7</td>
<td>Silicon</td>
</tr>
<tr>
<td>8</td>
<td>Iron</td>
</tr>
<tr>
<td>9</td>
<td>Magnesium</td>
</tr>
<tr>
<td>10</td>
<td>Sulfur</td>
</tr>
</tbody>
</table>
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 a Supernova Remnant
Neutron stars

- Remnant cores of massive stars:
  - $8 < M_* < 18 \, M_{\text{sun}}$ (???)
  - Leftover core of a core-bounce supernova

- Held up by **Neutron Degeneracy Pressure**:
  - Mass $\sim 1.2 - 2 \, M_{\text{sun}}$ (???)
  - Radius $\sim 10 \, \text{km}$ (small city)
  - Density $\sim 10^{14} \, \text{g/cc}$
Structure of a neutron star

- At densities > $2 \times 10^{14}$ g/cc:
  - nuclei melt into a sea of subatomic particles.
  - protons & electrons combine into neutrons.
- Surface is cooler:
  - Solid, crystalline crust.
- Inside is exotic matter:
  - superfluid neutrons, superconducting protons...
Inside a Neutron Star

- Neutron Superfluid
- Superconducting Protons
- Crystalline Iron Crust
Surface of a Neutron Star

- What is it like on a neutron star’s surface?
  - Surface gravity: \(\sim 10^{11}\) g’s
  - Escape velocity: \(\sim 0.5\) c
  - Temperature: \(\sim 1\) Million K
  - Magnetic Field Strength: \(\sim 10^{12}\) Gauss
    - (Earth is \(\sim 0.5\) Gauss)
  - Rotation Rate: 6000 rpm (100 rotations/second)

- You would be squashed flat and vaporized.
First predicted by theory

• 1934:
  Baade & Zwicky propose that supernovae are stars transforming into neutron stars. Most observers thought this was crazy.

• 1938:
  Oppenheimer & Serber (US) and Landau (USSR) calculate the properties of neutron stars. Most theorists were dubious, too.
• **1967:**
  Jocelyn Bell (Cambridge grad student) & Anthony Hewish (her advisor) discover pulsating radio sources while looking for something else.

• **“Pulsars”** = Pulsating Radio Sources
  Emitted 0.001 sec-long pulses every second.
Pulsars

- Rapidly spinning, magnetized neutron stars.
- **Lighthouse Model:**
  - Spinning magnetic field generates a strong electric field.
  - Electric field rips electrons off the surface & accelerates them along the magnetic poles.
- **Result:** twin beams of radiation
Pulsar Model

Spin

Axis

Radiation Beam

Magnetic Field

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Crab nebula pulsar

Crab Nebula

Palomar

PRC96-22a · ST ScI OPO · May 30, 1996
J. Hester and P. Scowen (AZ State Univ.) and NASA

HST · WFPC2
Crab nebula pulsar
Pulsar evolution

- Pulsars spin slower as they age.
  - lose rotational energy
- Young neutron stars:
  - fast spinning pulsars.
  - found in supernova remnants (e.g., Crab pulsar)
- Old neutron stars:
  - cold and hard to find.
Over the top?

• What if the remnant core is very massive?
  • $M_{\text{core}} > 2 - 3 \ M_{\text{sun}}$
• (original star had $M > 18 \ M_{\text{sun}}$)
  – Neutron degeneracy pressure fails.
  – Nothing can stop gravitational collapse.
  – Collapses to zero radius and infinite density.
• Becomes a Black Hole.
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
Summary:

• **White Dwarf:**
  – Remnant of a star $< 8 \, M_{\odot}$
  – Held up by Electron Degeneracy Pressure
  – Maximum Mass $\sim 1.4 \, M_{\odot}$

• **Neutron Star:**
  – Remnant of a star $< 18 \, M_{\odot}$
  – Held up by Neutron Degeneracy Pressure
  – Pulsar = rapidly spinning neutron star
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?
Questions:

- Do we see white dwarfs?
- Do we see neutron stars?
- Do we see black holes?
- What happens if you add mass to a White Dwarf?