Stellar Evolution Study Aid

Silver Medal Edition

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This study aid for AST 104 – *Stars & Galaxies* is available in three editions; *Gold Medal (Over-Achiever's)*, *Silver Medal (Plebeian)*, and *Bronze Medal (Slacker's)*.

Sun image from SOHO-EIT. Nucleosynthesis periodic table from Ted Bunch and James Wittke, Northern Arizona University. All others from Hubble Space Telescope.

Version 1.0

Material from Big Bang → **Interstellar Medium** (70%$_{mass}$ H, 28%$_{mass}$ He) ← Material recycled from earlier generations of stars

Diffusion / Dissipation ←

Gravitational collapse
Self-shielding

Molecular Cloud

Diffusion / Dissipation ←

Gravitational collapse
Fragmentation

Cloud fragments

Gravitational collapse
Radiation trapping

Accretion disks
Bipolar jets

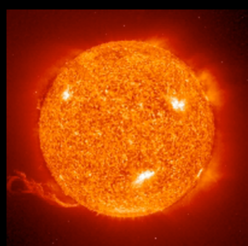
Protostars

< 0.08 M$_\odot$ → **Brown Dwarfs**

> ~150 M$_\odot$ → **Cannot form due to radiation pressure**

Core reaches 10,000,000K
Ignition of hydrogen fusion; stars join Main Sequence
Stars in balance between gravity and radiation pressure.

< 2 M$_\odot$: Low-Mass Main Sequence Stars



Proton-proton chain dominates

$^1H + ^1H \rightarrow ^2H + \beta^+ + \nu$
$^1H + ^2H \rightarrow ^3He + \gamma s$
$^3He + ^3He \rightarrow ^4He + ^1H + ^1H$

When H exhausted in core, H-fusion stops in core, continues in shell.
Without radiation pressure to balance gravity, core shrinks, heats up.
Extra heat makes outer layers expand, which cools them.

Red Giants

Core reaches 100 million K, Ignition of He-fusion.
Electron degeneracy pressure dominates, so temperature increase not relieved by expansion, causing helium flash.
Core temperature spikes, letting thermal pressure dominate, allowing core to expand, reducing luminosity.
Outer layers contract, heat up.

Triple-alpha process

$^4He + ^4He \rightarrow ^8Be$
$^4He + ^8Be \rightarrow ^{12}C + \beta^- + \beta^+$
$^4He + ^{12}C \rightarrow ^{16}O + \gamma$

When He in core exhausted, core shrinks, heats up. H- and He-fusion continues in shells. He shell fusion rate pulses. Star expands to larger, hotter, brighter red giant.

Pulses drive outer layers from core

Outer layers diffuse away → **Planetary Nebulae** → Diffusion / Dissipation

C, O core exposed → **White Dwarfs**

Color Coding

The color coding is designed to help you decipher this admittedly complicated flowchart. (*As I'm fond of saying in class, science seeks the simplest possible explanations for a complicated universe.*)

Evolutionary track arrows
Stellar masses for each branch
Nuclear or particle reactions

The boundary box around each type of astronomical object is a rough indication of the color of light emitted by that object.

> 2 M$_\odot$: Intermediate- and High-Mass Main Sequence Stars

CNO cycle dominates

$^1H + ^{12}C \rightarrow \gamma s + ^{13}N \rightarrow ^{13}C + \beta^+ + \nu$
$^1H + ^{13}C \rightarrow ^{14}N + \gamma s$
$^1H + ^{14}N \rightarrow \gamma s + ^{15}O \rightarrow ^{15}N + \beta^+ + \nu$
$^1H + ^{15}N \rightarrow ^{12}C + ^4He$

H-fusion stops in core, continues in shell. Core shrinks, heats up, outer layers expand.

Supergiants

Thermal pressure dominates, He-fusion ignites w/o He flash.
When He exhausted, core shrinks, outer layers expand.
End of He- and C-burning.

< 8-10 M$_\odot$: Outer layers → **Planetary Nebulae** → Diffusion / Dissipation; Core → **White Dwarfs**

> 8-10 M$_\odot$:

Production of heavy elements to Fe by serial fusion with He. When Ni is reached, a radioactive isotope of Ni decays back into Fe, and fusion stops. When Ni/Fe core reaches Chandrasekhar limit (1.38 M⦿), β- degeneracy is overcome, core collapses.

Type II Supernovae

Core collapses @ ¼ c
Photodisintegration
Fe, Ni + $\gamma \rightarrow ^4He$, n
Electron capture
1H + β- → n + ν
Neutron degeneracy stops collapse, rebound produces shock wave, producing supernova explosion.

Recycled into new stars.

< 20 M$_\odot$ → **Neutron stars**

> 20 M$_\odot$ → Black Holes