**Summary: When a Low-Mass Star runs out of Hydrogen in its Core**

1. With fusion no longer occurring in the core, gravity causes core collapse.
3. Under degenerate conditions, core becomes hot enough to fuse Helium: Helium Flash.

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**Clicker Question**

What Will Happen When There Is No More Helium in the Core?

A. The core will cool down.
B. Carbon fusion will start immediately.
C. The star will explode.
D. The core will start to collapse.
E. The hydrogen fusing shells will go out.
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When helium runs out….

- Carbon core collapses and heats up
- Burning in helium AND hydrogen shells
  - Shell burning now unstable = Thermal Pulses
    - Energy generation becomes much higher again
    - Outer layers lift and cool again
    - Star becomes very luminous again
      - Class II
- Degeneracy pressure reached before T=600 million K
  - No carbon fusion
- Stellar winds blow material from the outside including some carbon
  - Outer layers thrown off in a big puff around the inert carbon core
    - Big puff = Planetary Nebula
    - Inert carbon core = White Dwarf
      - Slowly cools and fades until it becomes a nearly invisible “black dwarf”
**IC 418:** The Spirograph Nebula

**NGC 6826:** The Blinking Eye Nebula

**NGC 2392:** The Eskimo Nebula

**NGC 7293:** The Helix Nebula
More Planetary Nebulae

Life of a Low-Mass Star

END STATE:
PLANETARY NEBULA + WHITE DWARF

Planetary Nebulae – White dwarfs

What is a white dwarf?

- Exposed core of a low-mass star that has died
- Mostly made of Carbon and Oxygen
- No fusion to maintain heat and pressure to balance gravity pull
- Electron degeneracy pressure balances inward crush of its own gravity
- Very high density and hence gravity
- Maximum mass=1.4 $M_{\text{sun}}$ (Chandrasekar limit)
Size Of A White Dwarf

- Hubble Space Telescope spies 12-13 billion year old white dwarfs
  - Formed less than 1 billion years after the creation of the universe

Funky properties of white dwarf material

1 Kg chocolate cake

2 Kg chocolate cake

0.4 $M_{\odot}$ white dwarf

0.8 $M_{\odot}$ white dwarf

Clicker Question

Which is correct order for some stages of life in a low-mass star?

A. protostar, main-sequence star, red giant, planetary nebula, white dwarf
B. protostar, main-sequence star, red giant, supernova, neutron star
C. main-sequence star, white dwarf, red giant, planetary nebula, protostar
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Clicker Question

The Big Bang produced only hydrogen and helium. Suppose the universe contained only low mass stars. Would elements heavier than Carbon and Oxygen exist?

A. Yes
B. No
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B. No

Lives of Intermediate/High-Mass Stars

- Low mass: < 2 times the Sun
- Intermediate mass: 2-8 times the Sun
- High mass: > 8 times the Sun

General Principles Are the Same: Battle Between Pressure and Gravity

- Main sequence lifetimes are much shorter
- Early stages after main sequence
  - Similar to a low mass star, but happen much faster
    - No helium flash

Intermediate-Mass Stars ($2M_{\odot} < M < 8M_{\odot}$)

- May burn up to carbon but do not have enough mass to get temperatures high enough to go any higher up the periodic table
- Degeneracy pressure stops the core from collapsing and heating enough: particles are squashed together as much as possible
- End their lives with planetary nebulae, white dwarfs, similarly to low-mass stars.
High-Mass Stars ($M > 8 \, M_{\odot}$)

- Sequence of expansion/contraction repeats as higher and higher elements begin to fuse
- Each heavier element requires higher core temperatures to fuse
- Core structure keeps on building successive shell
  - Like an onion
- Lighter elements on the outside, heavier ones on the inside