How Stars Evolve

- The fate of the Sun
  - Nuclear ash
  - Red giant phase
  - Planetary nebula
  - White dwarf

- Ages of star clusters
What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

A. It would continue contracting, but its temperature would not change
B. Its mass would increase
C. Its internal temperature would increase
D. It would be happy
The Fate of the Sun

• How will the Sun evolve over time?
• What will be its eventual fate?
Sun’s Structure

- Core
  - Where nuclear fusion occurs

- Envelope
  - Supplies gravity to keep core hot and dense
Main Sequence Evolution

- Core starts with same fraction of hydrogen as whole star
- Fusion changes H → He
- Core gradually shrinks and Sun gets hotter and more luminous
Gradual change in size of Sun

The Sun 4.56 \times 10^9 \text{ years ago}

The Sun today

Now 40\% brighter, 6\% larger, 5\% hotter
Main Sequence Evolution

- Fusion changes $\text{H} \rightarrow \text{He}$
- Core depletes of $\text{H}$
- Eventually there is not enough $\text{H}$ to maintain energy generation in the core
- Core starts to collapse
Red Giant Phase

- **He core**
  - No nuclear fusion
  - Gravitational contraction produces energy

- **H layer**
  - Nuclear fusion

- **Envelope**
  - Expands because of increased energy production
  - Cools because of increased surface area
Sun’s Red Giant Phase

Now: hot core + warm surface; small size.

Future: very hot core + cool surface. Large size but less mass; very bright.
Giant phase is when core has been fully converted to Helium.
When hydrogen burning in the core stops, a star like the Sun begins to evolve

A) To higher surface temperature and higher luminosity
B) To lower surface temperature and higher luminosity
C) To higher surface temperature and lower luminosity
D) To lower surface temperature and lower luminosity
E) Up the main sequence to become an O star
Helium Flash

- **He core**
  - Eventually the core gets hot enough to fuse Helium into Carbon.
  - This causes the temperature to increase rapidly to 300 million K and there’s a sudden flash when a large part of the Helium gets burned all at once.
  - We don’t see this flash because it’s buried inside the Sun.

- **H layer**
- **Envelope**
After Helium Ignition

- He burning core
  - Fusion burns He into C, O
- He rich core
  - No fusion
- H burning shell
  - Fusion burns H into He
- Envelope
  - Expands because of increased energy production
Movement on HR diagram

- Planetary nebula
- Double shell-burning red giant
- Helium-burning star
- Red giant
- Sun
- White dwarf
- Double shell-burning core
- Helium burning
- Hydrogen-burning shell
- Helium-burning star core
- Inert helium
- Hydrogen-burning shell
- Subgiant/red giant core
- Inert carbon
- Helium-burning shell
- Hydrogen-burning shell
During double shell burning Sun loses mass via winds

- Creates a “planetary nebula”
- Leaves behind core of carbon and oxygen surrounded by thin shell of hydrogen – a white dwarf
White dwarf

- Star burns up rest of hydrogen
- Nothing remains but degenerate core of Oxygen and Carbon
- “White dwarf” cools but does not contract because core is degenerate
- No energy from fusion, no energy from gravitational contraction
- White dwarf slowly fades away…
1. The star ejects a doughnut-shaped cloud of gas and dust from its equator.

2. The star then ejects gas from its entire surface.

3. The doughnut channels the ejected gas into two oppositely directed streams.

(c) Gas ejected from the star

Star
Planetary Nebula IC 418
Hourglass nebula
How can we determine the age of a star cluster?
Formation time for different masses

- High-mass stars form fast
- Low-mass stars form slowly
Time on main sequence is set by mass.
Turn-off point of cluster reveals age