Assignments

• For Fri. Oct. 30:
  – Read Ch. 14 + Do Online Exercise 11 (“Stellar Evolution" tutorial)

– For lab this week, see Inbok’s Canvas announcement:

A student has found that the web site used for the transit lab cycles through the same data eventually. Meaning, there is only a couple of transits you can observe. This seems to be due to the fact that all the data have already been analyzed, and so they closed down the data except for a few. Because of that, you only have to find 5 screenshots and transit for the lab.
Life Track of a Sun-Like Star
Evolutionary Tracks off the Main Sequence

- **Supergiants (I)**
- **Helium flash**
- **Giants (II,III)**
- **RGB - Red Giant Branch**
- **HB - Horizontal Branch**
- **AGB - Asymptotic Giant Branch**

- Effective Temperature, K
- Luminosity compared to Sun
- Absolute Magnitude, $M_v$
- Spectral Class
- Colour Index (B - V)
What is the final state of a star with an initial mass $M=4 \, M_\text{sun}$?

A. Brown dwarf
B. White dwarf
C. Supernova
D. Neutron star
E. Black hole
What is the final state of a star with an initial mass $M = 4 \, M_{\text{sun}}$?

A. Brown dwarf
B. White dwarf
C. Supernova
D. Neutron star
E. Black hole
What is the final state of a star with an initial mass of $M=40 \, M_{\text{sun}}$?

A. Brown dwarf
B. White dwarf
C. Supernova
D. Neutron star
E. Black hole
What is the final state of a star with an initial mass of $M=40\ M_{\text{sun}}$?

A. Brown dwarf
B. White dwarf
C. Supernova
D. Neutron star
E. Black hole
Life Stages of High-Mass Stars

- Late life stages of high-mass stars are similar to those of low-mass stars:
  - Hydrogen core fusion (main sequence)
  - Hydrogen shell fusion (supergiant)
  - Helium core fusion (supergiant)
Big Bang made 75% H, 25% He—stars make everything else.
Helium fusion can make carbon in low-mass stars.
How do high-mass stars make the elements necessary for life?
Helium Capture

- High core temperatures allow helium to fuse with heavier elements.
**Helium capture builds C into O, Ne, Mg ...**
Advanced Nuclear Burning

- Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron.
Advanced reactions in stars make elements such as Si, S, Ca, and Fe.
Multiple Shell Burning

• Advanced nuclear burning proceeds in a series of nested shells.
Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)
Evidence for helium capture:

Higher abundances of elements with even numbers of protons

Even-numbered elements made by helium capture are common.

Elements heavier than iron are rare because energy is required to make them.
How does a high-mass star die?
Iron builds up in the core until degeneracy pressure can no longer resist gravity.

The core then suddenly collapses, creating a supernova explosion.
Supernova Explosion

- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a neutron star.
Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U.
Supernova Remnant

- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.
### Origin of the elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Big Bang fusion</td>
</tr>
<tr>
<td>Li</td>
<td>Dying low-mass stars</td>
</tr>
<tr>
<td>Be</td>
<td>Merging neutron stars</td>
</tr>
<tr>
<td>Na</td>
<td>Exploding massive stars</td>
</tr>
<tr>
<td>Mg</td>
<td>Exploding white dwarfs</td>
</tr>
<tr>
<td>K</td>
<td>Cosmic ray fission</td>
</tr>
<tr>
<td>Ca</td>
<td></td>
</tr>
<tr>
<td>Sc</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td></td>
</tr>
<tr>
<td>Ga</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td></td>
</tr>
<tr>
<td>As</td>
<td></td>
</tr>
<tr>
<td>Se</td>
<td></td>
</tr>
<tr>
<td>Br</td>
<td></td>
</tr>
<tr>
<td>Kr</td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td></td>
</tr>
<tr>
<td>Tc</td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td></td>
</tr>
<tr>
<td>Cs</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td></td>
</tr>
<tr>
<td>Hf</td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td></td>
</tr>
<tr>
<td>Os</td>
<td></td>
</tr>
<tr>
<td>Ir</td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>Tl</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td></td>
</tr>
<tr>
<td>Bi</td>
<td></td>
</tr>
<tr>
<td>Po</td>
<td></td>
</tr>
<tr>
<td>At</td>
<td></td>
</tr>
<tr>
<td>Rn</td>
<td></td>
</tr>
<tr>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>Ra</td>
<td></td>
</tr>
<tr>
<td>La</td>
<td></td>
</tr>
<tr>
<td>Ce</td>
<td></td>
</tr>
<tr>
<td>Pr</td>
<td></td>
</tr>
<tr>
<td>Nd</td>
<td></td>
</tr>
<tr>
<td>Pm</td>
<td></td>
</tr>
<tr>
<td>Sm</td>
<td></td>
</tr>
<tr>
<td>Eu</td>
<td></td>
</tr>
<tr>
<td>Gd</td>
<td></td>
</tr>
<tr>
<td>Tb</td>
<td></td>
</tr>
<tr>
<td>Dy</td>
<td></td>
</tr>
<tr>
<td>Ho</td>
<td></td>
</tr>
<tr>
<td>Er</td>
<td></td>
</tr>
<tr>
<td>Tm</td>
<td></td>
</tr>
<tr>
<td>Yb</td>
<td></td>
</tr>
<tr>
<td>Lu</td>
<td></td>
</tr>
<tr>
<td>Ac</td>
<td></td>
</tr>
<tr>
<td>Th</td>
<td></td>
</tr>
<tr>
<td>Pa</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td></td>
</tr>
<tr>
<td>Np</td>
<td></td>
</tr>
<tr>
<td>Pu</td>
<td></td>
</tr>
<tr>
<td>Wikipedia: Cmglee</td>
<td></td>
</tr>
<tr>
<td>Data: Jennifer Johnson (OSU)</td>
<td></td>
</tr>
</tbody>
</table>
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

X-ray Binary Black Holes

Known Neutron Stars

LIGO-Virgo Neutron Stars
Role of Mass

• A star’s mass determines its entire life story because it determines its core temperature.
• High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
• Low-mass stars have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.
Life Stages of Low-Mass Star

1. **Main Sequence**: H fuses to He in core
2. **Red Giant**: H fuses to He in shell around He core
3. **Helium Core Fusion**: He fuses to C in core while H fuses to He in shell
4. **Double Shell Fusion**: H and He both fuse in shells
5. **Planetary Nebula**: leaves white dwarf behind
Reasons for Life Stages

- Core shrinks and heats until it’s hot enough for fusion.
- Nuclei with larger charge require higher temperature for fusion.
- Core thermostat is broken while core is not hot enough for fusion (shell burning).
- Core fusion can’t happen if degeneracy pressure keeps core from shrinking.

```
Core shrinks and heats until it’s hot enough for fusion.
Nuclei with larger charge require higher temperature for fusion.
Core thermostat is broken while core is not hot enough for fusion (shell burning).
Core fusion can’t happen if degeneracy pressure keeps core from shrinking.
```

---

*Not to scale!*

---

© 2012 Pearson Education, Inc.
Life Stages of High-Mass Star

1. **Main Sequence**: H fuses to He in core
2. **Red Supergiant**: H fuses to He in shell around He core
3. **Helium Core Fusion**: He fuses to C in core while H fuses to He in shell
4. **Multiple Shell Fusion**: many elements fuse in shells
5. **Supernova leaves neutron star behind**

---

**LIFE OF A HIGH-MASS STAR (25M☉)**

1. **Protostar**: A star system forms when a cloud of interstellar gas collapses under gravity.
2. **Main Sequence**: A high-mass star, after a hydrogen-burning core begins to fuse hydrogen in the core, leading to a single helium nucleus by the series of reactions known as the CNO cycle.
3. **Red Supergiant**: After core hydrogen is exhausted, core structure is filled with helium. Helium fusion begins around the red helium core, causing the star to expand into a red supergiant.
4. **Helium Core Fusion Supergiant**: Helium fusion begins when the core temperature becomes hot enough to fuse helium into carbon. The carbon then explodes, driving the fire of hydrogen fusion and allowing the outer layers to shrink.
5. **Multiple Shell Fusion Supergiant**: After the core runs out of helium, carbon, and oxygen, and helium, oxygen, and heavier elements begin to fuse. Later in life, the star fuses many different elements in a series of shells while the core collects in the core.
6. **Supernova**: The core collapses, providing the energy to fuse heavier elements. The core collapses, leading to the catastrophic explosion of the star.
7. **Neutron Star or Black Hole**: The core collapses into a ball of neutrons or a black hole, leaving the neutron star or collapsing further to make a black hole.

**Actual Length of Stage**
- 40,000 years
- 5 million years
- 100,000 years
- 1 million years
- 10,000 years
- a few months
- indefinitely

**Time on Cosmic Calendar**
- 12:00 AM → 12:01 AM
- 12:01 AM → 12:02 AM
- 3:12 AM → 3:14 AM
- 3:14 AM → 3:15 AM
- 3:52 AM → 3:52 AM
- 3:52 AM → 3:52 AM
- Indefinite
Chapter 14
The Bizarre Stellar Graveyard
What is a white dwarf?

However, Sirius A is relatively dim in ultraviolet and X rays...

...while Sirius B outshines Sirius A in ultraviolet and X rays.
White Dwarfs

- White dwarfs are the remaining cores of dead low-mass stars.
- Electron degeneracy pressure supports them against gravity.

However, *Sirius A* is relatively dim in ultraviolet and X rays...

...while *Sirius B* outshines *Sirius A* in ultraviolet and X rays.
White dwarfs cool off and grow dimmer with time.
Size of a White Dwarf

- White dwarfs with the same mass as the Sun are about the same size as Earth.
- Higher-mass white dwarfs are smaller.
The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.

- As a white dwarf’s mass approaches $1.4M_{\text{Sun}}$, its electrons must move at nearly the speed of light.

- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{\text{Sun}}$, the white dwarf limit (also known as the Chandrasekhar limit).
What can happen to a white dwarf in a close binary system?
A star that started with less mass gains mass from its companion.

Eventually, the mass-losing star will become a white dwarf.

What happens next?
Nova

- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.

- **Fusion** begins suddenly and explosively, causing a *nova*. 
Nova

- The nova star system temporarily appears much brighter.

- The explosion drives accreted matter out into space.
Thought Question

What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{\text{Sun}}$ limit?

A. It explodes.
B. It collapses into a neutron star.
C. It gradually begins fusing carbon in its core.
Thought Question

What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{\text{Sun}}$ limit?

A. It explodes.
   B. It collapses into a neutron star.
   C. It gradually begins fusing carbon in its core.
Two Types of Supernova

**Massive star supernova:**

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing an explosion.

**White dwarf supernova:**

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing a total explosion.
One way to tell supernova types apart is with a light curve showing how luminosity changes with time.
Nova or Supernova?

- Supernovae are MUCH MUCH more luminous than novae (about 10 million times)!!!

- Nova: H to He fusion of a layer of accreted matter; white dwarf left intact

- Supernova: complete explosion of white dwarf; nothing left behind
Supernova Types: Massive Star or White Dwarf?

- Light curves differ

- Spectra differ (exploding white dwarfs don’t have hydrogen absorption lines)
What is a neutron star?
A neutron star is the ball of neutrons left behind by a massive-star supernova.

The degeneracy pressure of neutrons supports a neutron star against gravity.
Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

Neutrons collapse to the center, forming a **neutron star**.
A neutron star is about the same size as a small city.
• Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.
• The pulses were coming from a spinning neutron star—a pulsar.
A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.
Pulsar at center of Crab Nebula pulses 30 times per second
Pulsars

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.