The structure and evolution of a star is determined by physical laws:

- Hydrostatic equilibrium
- Energy transport
- Conservation of mass*
- Conservation of energy* 

*(E = mc² → conservation of mass + energy)

A star’s mass – and chemical composition – completely determine its properties

This is why stars initially all line up along the main sequence
Maximum Masses of Main-Sequence Stars

\[ M_{\text{max}} \sim 100 \, M_{\text{Sun}} \]

a) More massive clouds fragment into smaller pieces during star formation

b) Very massive stars lose mass through strong stellar winds

Example: Eta Carinae, binary system of a 60 \( M_{\text{Sun}} \) and a 70 \( M_{\text{Sun}} \) star \( \Rightarrow \) dramatic mass loss; major eruption in 1843 created double lobes
Minimum Mass of Main-Sequence Stars

\[ M_{\text{min}} = 0.08 \, M_{\text{Sun}} \]

At masses below 0.08 \( M_{\text{Sun}} \), protostars do not get hot enough to “ignite” thermonuclear fusion

\( \Rightarrow \) Brown Dwarfs
Brown Dwarfs

Hard to find because they are very faint and (comparatively) cool ➔ emit mostly in the infrared

Many have been detected in star forming regions like the Orion Nebula
Evolution on the Main Sequence (1)

Main sequence stars live by fusing H to He

Finite supply of H \( \Rightarrow \) finite life time

Zero-Age Main Sequence (ZAMS)
Evolution on the Main Sequence (2)

A star’s **life time** $T \sim$ energy reservoir / luminosity

Energy reservoir $\sim M$

Luminosity $L \sim M^{3.5}$

$T \sim \frac{M}{L} \sim \frac{1}{M^{2.5}}$

**Table 12-2** Main-Sequence Stars

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Mass (sun = 1)</th>
<th>Luminosity (sun = 1)</th>
<th>Approximate Years on Main Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>O5</td>
<td>40</td>
<td>405,000</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>B0</td>
<td>15</td>
<td>13,000</td>
<td>$11 \times 10^6$</td>
</tr>
<tr>
<td>A0</td>
<td>3.5</td>
<td>80</td>
<td>$440 \times 10^6$</td>
</tr>
<tr>
<td>F0</td>
<td>1.7</td>
<td>6.4</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>G0</td>
<td>1.1</td>
<td>1.4</td>
<td>$8 \times 10^9$</td>
</tr>
<tr>
<td>K0</td>
<td>0.8</td>
<td>0.46</td>
<td>$17 \times 10^9$</td>
</tr>
<tr>
<td>M0</td>
<td>0.5</td>
<td>0.08</td>
<td>$56 \times 10^9$</td>
</tr>
</tbody>
</table>

⇒ Massive stars have short lives.
Evolution off the Main Sequence: Expansion into a Red Giant

When the H in the core is completely converted into He:

- "Hydrogen burning" (i.e., fusion of H into He) ceases in the core
- H burning continues in a shell around the core
- He core + H-burning shell produce more energy than needed for pressure support

Expansion and cooling of the outer layers of the star → Red Giant
Expansion onto the Giant Branch

Expansion and surface cooling during the phase of an inactive He core and a H- burning shell

The Sun will expand beyond Earth's orbit (!)
Degenerate Matter

Matter in the He core has no energy source left

- Not enough thermal pressure to resist and balance gravity

- Matter assumes a new state, called **degenerate matter**

Pressure in the degenerate core is due to the fact that electrons can not be packed arbitrarily close together and have small energies.
Red Giant Evolution

Red Giant Evolution

H-burning shell keeps dumping He onto the core

He-core gets denser and hotter until the next stage of nuclear burning can begin in the core:

He fusion through the “Triple-Alpha Process”

\[ ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} + \gamma \]

\[ ^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C} + \gamma \]
Helium Flash

The onset of Helium fusion occurs very rapidly, in an event called the **Helium Flash**
Red Giant Evolution (5 $M_{\text{Solar}}$ Star)

Helium in the core exhausted; development of He-burning shell

Development of carbon-oxygen Core

Helium ignition in the core

Red giant

Expansion to red giant

Main Sequence
Fusion into heavier elements than C and O requires very high temperatures, and occurs only in very massive stars (more than 8 $M_{\text{Sun}}$).

**Table 12-3  Nuclear Reactions in Massive Stars**

<table>
<thead>
<tr>
<th>Nuclear Fuel</th>
<th>Nuclear Products</th>
<th>Minimum Ignition Temperature</th>
<th>Main-Sequence Mass Needed to Ignite Fusion</th>
<th>Duration of Fusion in a 25-$M_{\odot}$ Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>$4 \times 10^6$ K</td>
<td>0.1 $M_{\odot}$</td>
<td>$7 \times 10^6$ yr</td>
</tr>
<tr>
<td>He</td>
<td>C, O</td>
<td>$120 \times 10^6$ K</td>
<td>0.4 $M_{\odot}$</td>
<td>$0.5 \times 10^6$ yr</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Na, Mg, O</td>
<td>$0.6 \times 10^6$ K</td>
<td>4 $M_{\odot}$</td>
<td>600 yr</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>$1.2 \times 10^6$ K</td>
<td>$\sim 8 M_{\odot}$</td>
<td>1 yr</td>
</tr>
<tr>
<td>O</td>
<td>Si, S, P</td>
<td>$1.5 \times 10^6$ K</td>
<td>$\sim 8 M_{\odot}$</td>
<td>$\sim 0.5$ yr</td>
</tr>
<tr>
<td>Si</td>
<td>Ni to Fe</td>
<td>$2.7 \times 10^6$ K</td>
<td>$\sim 8 M_{\odot}$</td>
<td>$\sim 1$ day</td>
</tr>
</tbody>
</table>
The Life “Clock” of a Massive Star (> 8 M\(_{\text{Sun}}\))

If we compressed a massive star’s life into one day…

- H \(\rightarrow\) He
- Life on the Main Sequence + Expansion to Red Giant: 22 h, 24 min
  - H burning
- H \(\rightarrow\) He
- He \(\rightarrow\) C, O
  - He burning: (Red Giant Phase) 1 h, 35 min, 53 s
The Life “Clock” of a Massive Star (2)

H → He

He → C, O

C → Ne, Na, Mg, O

C burning: 6.99 s

H → He

He → C, O

C → Ne, Na, Mg, O

Ne → O, Mg

Ne burning: 6 ms

23:59:59.996
The Life “Clock” of a Massive Star (3)

H $\rightarrow$ He
He $\rightarrow$ C, O

C $\rightarrow$ Ne, Na, Mg, O
Ne $\rightarrow$ O, Mg
O $\rightarrow$ Si, S, P

O burning:
3.97 ms

Si $\rightarrow$ Fe, Co, Ni

Si burning:
0.03 ms

The final 0.03 msec!

23:59:59.99997
Summary of Post Main-Sequence Evolution of Stars

Evolution of 4 - 8 $M_{\text{Sun}}$ stars is still uncertain:
Mass loss in stellar winds may reduce them all to $< 4 M_{\text{Sun}}$ stars

Red dwarfs: He burning never ignites
Evidence for Stellar Evolution: Star Clusters

Stars in a star cluster all have approximately the same age.

More massive stars evolve more quickly than less massive ones.

If you put all the stars of a star cluster on an H-R diagram, the most massive stars (upper left) will be missing...
H-R Diagram of a Star Cluster

The Hyades Star Cluster

The most massive stars have died

Only a few stars are in the giant stage.

Main sequence

The lower-mass stars are still on the main sequence.

The faintest stars were not observed in the study.

Temperature (K)

30,000 20,000 10,000 5000 3000 2000

L/L☉

10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6}
Example: H-R diagram of the star cluster M3
Estimating the Age of a Cluster

The lower the turn-off point on the Main Sequence, the older the cluster.

Globular cluster H-R diagrams resemble the last frame in the film, which tells you that globular clusters are very old.
Animation: Stellar Evolution in a Star Cluster
Evidence for Stellar Evolution: Variable Stars

Some stars show intrinsic brightness variations *not* caused by eclipsing in binary systems. An important example:

δ Cephei

Light curve of δ Cephei

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

5.36634 days
Cepheid Variables: The Period-Luminosity Relation

The variability period of a Cepheid variable is correlated with its luminosity.

The more luminous it is, the more slowly it pulsates.

- Measuring a Cepheid’s period, we can determine its absolute magnitude.
Pulsating Variables: The Instability Strip

For specific combinations of radius and temperature, stars can maintain periodic oscillations. Those combinations correspond to locations in the Instability Strip. Cepheids pulsate with radius changes of ~5 – 10%.
Class Announcements

- Lecture PDFs and other materials available from: web.science.mq.edu.au/~zucker/Astronomy_170.html
- If you did not attend one of the three observing practicals, please e-mail me ASAP
- Call for nominations to Physics Student Liaison Committee
Physics Student Liaison Committee
Meeting Sem1, 2010

Thursday 20 May, 12noon - Lunch will be provided

Purpose of the meeting
• is to seek student feedback on the current semester’s units and programs. Each undergraduate unit is invited to nominate two students as class representatives.

Student observers
• are welcome and should email Helen (helen@science.mq.edu.au) at least ten days prior to the meeting to advise her of your wish to attend.

Confirmation of invitation to attend
• will be emailed to your MQ student address.

Outcomes from the meeting
• will be incorporated into next year’s teaching and reported at next year’s SLC.

We look forward to seeing you there.
Associate Professor David Coutts, Head, Department of Physics and Engineering