HNRS 228 - Astrobiology
Chapter 11
The Life Cycle of Stars
Dr. Harold Geller

Stellar Inquiries
1. Why do astronomers think that stars evolve (bad use of term – this is about the birth, life and death of stars and that is NOT evolution)?
2. What kind of matter exists in the spaces between the stars?
3. In what kind of nebulae do new stars form?
4. What steps are involved in forming a star like the Sun?
5. When a star forms, why does it end up with only a fraction of the available matter?
6. What do star clusters tell us about the formation of stars?
7. Where in the Galaxy does star formation take place?
8. How can the death of one star trigger the birth of many other stars?

Understanding how stars evolve requires both observations and ideas from physics

• Because stars shine by thermonuclear reactions, they have a finite life span
  - They fuse lighter elements into heavier elements
    - When the lighter elements are depleted, there is nothing left to fuse
• The theory of stellar evolution (again, not in the same sense as biological evolution, but more like life cycle development, like growing up) describes how stars form and change during that life span

Interstellar gas and dust is ubiquitous the Galaxy

• Interstellar gas and dust, which make up the interstellar medium (ISM), are concentrated in the disk of the Galaxy
• Clouds within the interstellar medium are called nebulae
  - Dark nebulae are so dense that they are opaque
    - They appear as dark blots against a background of distant stars
• Emission nebulae, or H II regions, are glowing, ionized clouds of gas
  - Emission nebulae are powered by ultraviolet light that they absorb from nearby hot stars
• Reflection nebulae are produced when starlight is reflected from dust grains in the interstellar medium, producing a characteristic bluish glow
Protostars form in cold, dark nebulae

- Star formation begins in dense, cold nebulae, where gravitational attraction causes a clump of material to condense into a protostar.
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing.

Protostars develop into main-sequence stars

- A protostar’s relatively low temperature and high luminosity place it in the upper right region on an H-R diagram.
- Further evolution of a protostar causes it to move toward the main sequence on the H-R diagram.
- When its core temperatures become high enough to ignite steady hydrogen burning, it becomes a main sequence star.

iClicker Question

- Before a star reaches the main sequence, its energy is generated primarily by
  - A chemical reactions.
  - B gravitational contraction.
  - C helium fusion.
  - D hydrogen fusion.
  - E nuclear fission.

iClicker Question

- A new star begins to form when
  - A an existing star is broken apart
  - B an interstellar cloud collapses by its own gravity
  - C fresh material falls onto the core of a previously dead star
  - D nuclear reactions start inside a large planet
  - E new stars don’t form anymore
During the birth process, stars both gain and lose mass

- In the final stages of pre-main-sequence contraction, when thermonuclear reactions are about to begin in the core, a protostar may eject large amounts of gas into space.
- Low-mass stars that vigorously eject gas are called T Tauri stars.

**iClicker Question**

- Once a star has reached the main sequence, its energy is generated primarily by:
  - A  chemical reactions
  - B  gravitational contraction
  - C  helium fusion
  - D  hydrogen fusion
  - E  nuclear fission

- Star-forming regions appear when a giant molecular cloud is compressed.
- This can be caused by the cloud’s passage through one of the spiral arms of our Galaxy, by a supernova explosion, or by other mechanisms.
**O and B Stars and Their Relation to H II Regions**

- The most massive protostars rapidly become main sequence O and B stars.
- O and B stars emit strong ultraviolet radiation.
  - UV ionizes hydrogen in the surrounding cloud.
  - Creating the reddish emission nebulae called H II regions.
- Ultraviolet radiation and stellar winds from the O and B stars at the core of an H II region create shock waves.
  - Shock waves move outward through the gas cloud, compressing the gas and triggering the formation of more protostars.

**Supernovae can compress the interstellar medium and trigger star birth**

**More Stellar Inquiries**

1. How will our Sun change over the next few billion years?
2. Why are red giants larger than main-sequence stars?
3. Do all stars evolve into red giants at the same rate?
4. How do we know that many stars lived and died before our Sun was born?
5. Why do some giant stars pulsate in and out?
6. Why do stars in some binary systems evolve in unusual ways?

**A star’s lifetime on the main sequence is proportional to its mass divided by its luminosity**

<table>
<thead>
<tr>
<th>Mass (M)</th>
<th>Surface Temperature (°K)</th>
<th>Specialized</th>
<th>Luminosity (L☉)</th>
<th>Main-sequence Lifetime (10^9 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>37,000</td>
<td>B</td>
<td>0.01</td>
<td>100,000</td>
</tr>
<tr>
<td>1.5</td>
<td>50,000</td>
<td>D</td>
<td>1.0</td>
<td>100,000</td>
</tr>
<tr>
<td>2.0</td>
<td>53,000</td>
<td>D</td>
<td>10</td>
<td>9000</td>
</tr>
<tr>
<td>2.5</td>
<td>67,000</td>
<td>E</td>
<td>2</td>
<td>1400</td>
</tr>
<tr>
<td>3.0</td>
<td>75,000</td>
<td>E</td>
<td>20</td>
<td>4000</td>
</tr>
<tr>
<td>3.5</td>
<td>80,000</td>
<td>E</td>
<td>20</td>
<td>12,500</td>
</tr>
<tr>
<td>4.0</td>
<td>85,000</td>
<td>E</td>
<td>60</td>
<td>22,400</td>
</tr>
<tr>
<td>4.5</td>
<td>89,000</td>
<td>E</td>
<td>60</td>
<td>762,000</td>
</tr>
</tbody>
</table>

The main-sequence lifetimes were estimated using the relationship (age) = 5.58 × (Mass)^3.5 × (Luminosity)^-2.4.

- The duration of a star’s main-sequence lifetime depends on the amount of hydrogen in the star’s core and the rate at which the hydrogen is consumed.
- N.B. - The more massive a star, the shorter is its main-sequence lifetime.

During a star’s main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity.
When core hydrogen fusion ceases, a main-sequence star becomes a red giant

- Core hydrogen fusion ceases when the hydrogen has been exhausted in the core of a main-sequence star.
- This leaves a core of nearly pure helium surrounded by a shell through which hydrogen fusion works its way outward in the star.
- The core shrinks and becomes hotter, while the star’s outer layers expand and cool.
- The result is a red giant star.

After the helium flash, a low-mass star moves from the red-giant region of the H-R diagram to the horizontal branch.

- When the central temperature of a red giant reaches about 100 million K, helium fusion begins in the core.
- A process called the triple alpha process converts helium to carbon and oxygen.

Using this diagram, what location is closest to the Main Sequence?
- A
- B
- C
- D
- E

Using this diagram, what location is closest to the horizontal branch?
- A
- B
- C
- D
- E
• H-R diagrams and observations of star clusters reveal how red giants evolve.
• The age of a star cluster can be estimated by plotting its stars on an H-R diagram.

The cluster’s age can be estimated by the age of the main-sequence stars at the turnoff point (the upper end of the remaining main sequence).

As a cluster ages, the main sequence is “eaten away” from the upper left as stars of progressively smaller mass evolve into red giants.

Using the diagram, what is the best estimate for the age of NGC2362?
A less than 100 years old
B less than 100 million years old
C about 1 billion years old
D about 10 billion years old
E about 100 billion years old

What is the best estimate for the age of M3?
A less than 100 million years old
B about 100 million years old
C about 1 billion years old
D about 10 billion years old
E about 100 billion years old

What is the best estimate for NGC 752?
A less than 10 million years old
B about 100 million years old
C about 1 billion years old
D about 10 billion years old
E about 100 billion years old
Populations (generations) of stars

- Relatively young Population I stars are metal rich; ancient Population II stars are metal poor; and if you could find the very first stars, they would have no metals at all.
- The metals (heavy elements) in Population I stars were manufactured by thermonuclear reactions in an earlier generation of Population II stars, then ejected into space and incorporated into a later stellar generation.

Variable Stars

When a star's evolutionary track carries it through a region in the H-R diagram called the instability strip, the star becomes unstable and begins to pulsate.

There is a direct relationship between Cepheid periods of pulsation and their luminosities.

Mass transfer can affect the life cycle of close binary star systems.

Mass transfer in a close binary system occurs when one star in a close binary overflows its Roche lobe.
More Stellar Inquiries

1. What kinds of nuclear reactions occur within a star like the Sun as it ages?
2. Where did the carbon atoms in our bodies come from?
3. What is a planetary nebula, and what does it have to do with planets?
4. What is a white dwarf star?
5. Why do high-mass stars go through more evolutionary stages than low-mass stars?
6. What happens within a high-mass star to turn it into a supernova?
7. What SN 1987A taught, in visible and neutrino observations?
8. How do white dwarf stars give rise to certain types of supernovae?
9. What remains after a supernova explosion?
Bringing the products of nuclear fusion to a giant star’s surface

- As a low-mass star ages, convection occurs over a larger portion of its volume.
- This takes heavy elements formed in the star’s interior and distributes them throughout the star.

Sun-like stars “die” by gently ejecting their outer layers, creating planetary nebulae

- Helium shell flashes in an old, low-mass star produce thermal pulses during which more than half the star’s mass may be ejected into space.
- This exposes the hot carbon-oxygen core of the star.
- Ultraviolet radiation from the exposed core ionizes and excites the ejected gases, producing a planetary nebula.

Why do planetary nebulae look so different from one another?

- Different elements are present in each nebula.
- The environment around each nebula is unique.
- The size and shape of each nebula can vary widely.

Expanding shell of ejected material

Star
The burned-out core of a low-mass star cools and contracts until it becomes a white dwarf.

- No further nuclear reactions take place within the exposed core.
- Instead, it becomes a degenerate, dense sphere about the size of the Earth and is called a white dwarf.
- It glows from thermal radiation; as the sphere cools, it becomes dimmer.

- A planetary nebula can best be defined as:
  A. a flat disk of material around a protostar.
  B. the final state of a star having a very small size.
  C. the evaporation of a planet when a star becomes a red giant.
  D. an expanding shell of gas around a dying star.
  E. a disk around a planet.

- Which of the following is the main source of energy for a white dwarf?
  A. Carbon fusion.
  B. Gravitational contraction.
  C. Helium fusion.
  D. Its stored heat.
  E. Iron fusion.

- What physical characteristic most determines the main sequence lifetime of a star?
  A. radius
  B. composition
  C. mass
  D. luminosity class
  E. none of the above

- When the solar core has mostly been transformed from hydrogen into helium, the Sun will move to the next phase of its life cycle, changing gradually into a
  A. different type of main sequence star
  B. planet
  C. protostar
  D. red giant
  E. white dwarf

- After a second red giant stage, an old solar-mass star will gently eject its outer layers, leaving behind a hot, small stellar remnant:
  A. nova
  B. planetary nebula
  C. pulsar
  D. supernova remnant
  E. T Tauri star.
High-mass stars create heavy elements in their cores

- High mass stars undergo an extended sequence of thermonuclear reactions in their cores and shells
- These include carbon fusion, neon fusion, oxygen fusion, and silicon fusion

<table>
<thead>
<tr>
<th>Stage</th>
<th>Core temperature (K)</th>
<th>Core density (g/cm³)</th>
<th>Duration of stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen fusion</td>
<td>4 x 10⁶</td>
<td>5 x 10¹⁴</td>
<td>7 x 10⁶ yrs</td>
</tr>
<tr>
<td>Helium fusion</td>
<td>6 x 10⁶</td>
<td>7 x 10¹⁴</td>
<td>7 x 10⁶ yrs</td>
</tr>
<tr>
<td>Carbon fusion</td>
<td>6 x 10⁶</td>
<td>2 x 10¹⁴</td>
<td>600 yrs</td>
</tr>
<tr>
<td>Neon fusion</td>
<td>1.5 x 10⁷</td>
<td>4 x 10¹⁴</td>
<td>1 year</td>
</tr>
<tr>
<td>Oxygen fusion</td>
<td>1.4 x 10⁸</td>
<td>10¹⁵</td>
<td>4 months</td>
</tr>
<tr>
<td>Silicon fusion</td>
<td>2.7 x 10⁸</td>
<td>3 x 10¹⁵</td>
<td>1 day</td>
</tr>
<tr>
<td>Core collapse</td>
<td>5 x 10⁹</td>
<td>3 x 10¹⁰</td>
<td>5 x 10⁵ yrs</td>
</tr>
<tr>
<td>Core bounce</td>
<td>2.3 x 10⁹</td>
<td>4 x 10¹⁵</td>
<td>milliseconds</td>
</tr>
<tr>
<td>Eruption (super):</td>
<td>above 10⁸</td>
<td>varies</td>
<td>10 seconds</td>
</tr>
</tbody>
</table>

- In the last stages of its life, a high-mass star has an iron-rich core surrounded by concentric shells hosting the various thermonuclear reactions
- The sequence of thermonuclear reactions stops here, because the formation of elements heavier than iron requires an input of energy rather than causing energy to be released

High-mass stars violently blow apart in a supernova explosion

- A high-mass star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space at high speeds
- The luminosity of the star increases suddenly by a factor of around 10⁸ during this explosion, producing a supernova
- The matter ejected from the supernova, moving at supersonic speeds through interstellar gases and dust, glows as a nebula called a supernova remnant

In 1987 a nearby supernova gave us a close-up look at the death of a massive star

Material was ejected in “blobs” from the supernova that produced the Cassiopeia A supernova remnant.
Neutrinos emanate from supernovae like SN 1987A.

More than 99% of the energy from such a supernova is emitted in the form of neutrinos from the collapsing core.

White dwarfs in close binary systems can also become supernovae.

- An accreting white dwarf in a close binary system may become a supernova when carbon fusion ignites explosively throughout the degenerate star.

Type Ia supernovae are those produced by accreting white dwarfs in close binaries.

Type II supernovae are created by the deaths of massive stars.
Most supernovae in our Galaxy are hidden from our view by interstellar dust and gases but a supernova remnant can be detected at many wavelengths for centuries after the explosion.