Stars IV
Stellar Evolution
Attendance Quiz

Are you here today?

(a) yes
(b) no
(c) my views are evolving on the subject
Today’s Topics

Stellar Evolution

• An alien visits Earth for a day
• A star’s mass controls its fate
• Low-mass stellar evolution ($M < 2 \, M_\odot$)
• Intermediate and high-mass stellar evolution
  ($2 \, M_\odot < M < 8 \, M_\odot; \, M > 8 \, M_\odot$)
• Novae, Type I Supernovae, Type II Supernovae
An Alien Visits for a Day

- Suppose an alien visited the Earth for a day
- What would it make of humans?
- It might think that there were 4 separate species
  - A small creature that makes a lot of noise and leaks liquids
  - A somewhat larger, very energetic creature
  - A large, slow-witted creature
  - A smaller, wrinkled creature
- Or, it might decide that there is one species and that these different creatures form an evolutionary sequence (baby, child, adult, old person)
Stellar Evolution

• Astronomers study stars in much the same way
• Stars come in many varieties, and change over times much longer than a human lifetime (with some spectacular exceptions!)
• How do we know they evolve?
• We study stellar properties, and use our knowledge of physics to construct models and draw conclusions about stars that lead to an evolutionary sequence
• As with stellar structure, the mass of a star determines its evolution and eventual fate
A Star’s Mass Determines its Fate

- How does mass control a star’s evolution and fate?
- A main sequence star with higher mass has
  - Higher central pressure
  - Higher fusion rate
  - Higher luminosity
  - Shorter main sequence lifetime
  - Larger radius
  - Higher surface temperature
- Stars with different masses live different times on the main sequence, and evolve differently when their main sequence lifetime is done
- There are three major categories we can define for discussing stellar evolution
  1) Low mass stars ($M < 2 \, M_{\odot}$)
  2) Intermediate mass stars ($2 \, M_{\odot} < M < 8 \, M_{\odot}$)
  3) High-mass stars ($M > 8 \, M_{\odot}$)
Hydrogen Shell Burning & Red Giants

- The majority (90%) of a low-mass star’s life is spent fusing $\text{H} \rightarrow \text{He}$
- Eventually the hydrogen runs out, fusion stops, and the temporary reprieve from the crush of gravity has ended
- What happens next?
- When hydrogen fusion stops, the inert helium core shrinks until something called *degeneracy pressure* halts the contraction
- This core contraction carries fresh H into regions hot enough to start *hydrogen shell burning* (fusion)
- This occurs at much higher temperatures than before so the fusion rate is higher
- The luminosity rises so much that the star’s energy transport cannot keep up, the internal pressure rises, and the star expands, and the surface cools, creating a *red giant*
- For a star like the Sun $T \sim 3000 \text{ K}$, $R \sim 170 R_\odot \sim 0.8 \text{ AU}$ and $L \sim 2000 L_\odot$
Helium fusion (the triple-alpha process)

- What finally ends this progression?
- After several 100 million years, the core has shrunk and heated until the temperature reaches 100 million K
- At this temperature, helium nuclei (also called α-particles) can fuse
- Recall that nuclei have to be moving fast enough to overcome the electrical repulsion of the protons
- Since α-particles have a +2 charge, two of them repel $2 \times 2 = 4$ times as much as two hydrogen nuclei (protons)
- Since $^8\text{Be}$ is unstable, three α-particles have to fuse to become $^{12}\text{C}$, called the triple-alpha process
- When He fusion begins, a huge burst of energy is released (the helium flash)
Helium Burning Stars

• In a normal gas, this burst of energy would heat the core, the pressure would rise, the core would expand and cool, and the fusion rate and luminosity would drop (recall the Solar thermostat).

• In a degenerate gas (like in the helium core of a Red Giant), a rise in temperature does not lead to a rise in pressure, so the energy merely heats the gas further, leading to a runaway effect.

• This runaway goes until the temperature reaches 350 million K when the degeneracy pressure is converted to normal thermal pressure: the core then expands explosively, cools, the fusion rate quickly drops, and the star shrinks, until equilibrium is reached.

• This configuration is known as a helium-burning star, and is a main sequence analog.
Red Supergiant Phase

- After about 100 million years (~100 × shorter than the MS lifetime), the helium for fusion runs out, and the process repeats, with one difference
- The inert carbon core contracts until degeneracy pressure halts the collapse
- He and H shell burning begin, and the luminosity and radius again grow even more than the first time
- The luminosity of a 1 M\(_\odot\) star grows to 3,000 L\(_\odot\), the radius grows to 200 R\(_\odot\), (about the size of Earth’s orbit) and the surface temperature drops, creating a **double-shell burning red giant**
- The difference is that the core never gets hot enough to fuse carbon - the end is near!
A Rich Source of Carbon

- As the H-burning shell drops He “ash” on the degenerate He-burning shell, it undergoes “flashes” like the He core did.
- These He flashes, which occur every few 1000 years, blow off the tenuous outer layers of the star into an expanding shell of gas.
- During these “flashes”, carbon is dredged up from the core and ejected with the other material into interstellar space.
- This is one of the primary sources of carbon in the interstellar medium, which is later incorporated into new stars, planets, and you and me!
What happens to the Earth?

By here, a runaway greenhouse effect has heated the earth so that the oceans have boiled away.

The earth’s surface is now over 1000 K (compared to 300 K today).

Get out!

1 A.U.

The Sun’s Radius

- present radius of Earth’s orbit
- contraction of protostar
- helium flash
- leaves main sequence
- transition to white dwarf
- ejection of planetary nebula

radius (times present value)

0 1 10 100

the Sun’s age (billions of years)

0 5 10 12.1 12.2 12.3 12.3650 12.3655
Planetary Nebulae

• Eventually all the outer gas is ejected, leaving a tiny, hot exposed degenerate carbon core with no fusion at all; a white dwarf

• For the Sun, $R \sim 0.01 \, \text{R}_\odot \sim \text{R}_{\text{Earth}}$, and $M \sim 0.6 \, \text{M}_\odot$, so its density is very, very high

• One teaspoon of white dwarf material would weigh 5 tons on Earth

• Because it is so small, its surface temperature is very high ($\sim 10\text{-}30,000 \, \text{K}$), so most of its energy is emitted in the UV

• This UV radiation ionizes and excites the atoms in the expanding shell of gas, creating a planetary nebula (or PN)

• There are $\sim 1600$ PNs observed in the Milky Way, and about 50,000 are believed to exist

• Over time, white dwarfs cool into black dwarfs and disappear (along with their PNs)
What happens to nuclear fusion when the hydrogen in a star’s core runs low?

a) It stops
b) It shifts from the core to a shell around the core
c) Other elements start to fuse
d) The star goes out of balance and becomes a red giant
e) (b) and (d)
Stellar Evolution Quiz II

After the Sun becomes a red giant star and makes carbon in its core, why will it not make heavier elements?

a) It will have run out of fuel
b) It’s near the end of its life and doesn’t have time
c) It is not massive enough to make it hot enough for further reactions
d) The heavier elements will all go into a planetary nebula
e) (a) and (b)
Low-mass Stellar Evolution - A Summary
Intermediate and high-mass stellar evolution

- Everything happens faster in high-mass stars
- At higher temperatures, a different mechanism exists to fuse H → He, the CNO cycle
- This cycle requires higher temperatures so that the H nuclei can get close enough to the C and N nuclei to fuse; fusion rate $\propto T^{20}$
- Carbon, nitrogen and oxygen act as catalysts, and the reaction $4p \rightarrow ^4\text{He}$ can run much faster than in the pp chain
- These higher fusion rates lead to the short main-sequence lives of high-mass stars
- For example, a 25 M$_\odot$ star can fuse H into He for only a few million years
When the Hydrogen runs out

- When the hydrogen runs out, the sequence is very similar to that for low-mass stars with a few (important) exceptions
- The inert He core contracts and heats
- The temperature becomes high enough to fuse He $\rightarrow$ C before the core becomes degenerate, so no helium flash
- As the fusion rate rises, the star swells into a red supergiant (like Betelgeuse in Orion) with a radius $R \sim 500$-$1000$ R$_\odot$, which is 2.5-$5$ AU!
- In a few 100,000 to 1 million years an inert carbon core is left
- This core also collapses until the temperature gets high enough for further fusion to occur
High-mass nucleosynthesis

• Once the temperature in the core becomes high enough, fusion can continue via **He-capture reactions**
• Each reaction adds 2 protons, so **even-numbered nuclei predominate**
• This can be seen in Solar abundances
• Intermediate-mass stars (2 $M_{\odot}$<$M$<8 $M_{\odot}$) stop at $^{16}$O, $^{20}$Ne, or $^{24}$Mg because the core becomes degenerate halting further contraction
• Thus, they end their lives as white dwarfs
• High-mass stars ($M$ > 8 $M_{\odot}$) can continue fusion all the way to $^{56}$Fe (iron)
• Why stop there?
• $^{56}$Fe is the most tightly bound nucleus there is, so no further fusion can occur without an input of energy - this is the true end of the line for the star
• Note this leads to a high abundance of Fe
## Timescales of Stellar Evolution

<table>
<thead>
<tr>
<th></th>
<th>Low-mass star (1 M☉)</th>
<th>High-mass star (20 M☉)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen fusion</td>
<td>10 billion yrs</td>
<td>10 million yrs</td>
</tr>
<tr>
<td>H → He</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium fusion</td>
<td>100 million yrs</td>
<td>1 million yrs</td>
</tr>
<tr>
<td>He → C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon fusion</td>
<td>—</td>
<td>300 yrs</td>
</tr>
<tr>
<td>C → O, Ne, Ng, Na, Si</td>
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<td></td>
</tr>
<tr>
<td>Oxygen fusion</td>
<td>—</td>
<td>&lt; 1 yr</td>
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<tr>
<td>O → S, P, Ng, Si</td>
<td></td>
<td></td>
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<tr>
<td>Silicon fusion</td>
<td>—</td>
<td>2 days</td>
</tr>
<tr>
<td>Si → Fe</td>
<td></td>
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</tr>
</tbody>
</table>
High-mass stellar death

- When a high-mass star runs out of energy to resist gravity, its core collapses catastrophically.
- Because the core has a mass $M > 1.4 \, M_\odot$ (a number we will return to) normal (electron) degeneracy pressure cannot halt its contraction.
- If the core has a mass $1.4 \, M_\odot < M < 3 \, M_\odot$, it continues to collapse until all the protons and electrons are squeezed together to make neutrons, and neutron degeneracy pressure halts the contraction.
- At this point, the core has a mass larger than the Sun compressed into a sphere of radius 10-20 km, the size of a city.
- It is essentially a ball of neutrons at the density of a nucleus - a neutron star.
- At this density, all of humanity would fit into a cube half an inch on a side!
Supernova!

- The matter above the core falls onto this immensely dense object and bounces; all the GPE of that fall is turned into a gigantic explosion - a **supernova**!
- A supernova releases, in a few seconds, 100 times the energy the Sun produces in its entire MS lifetime!
- A supernova can briefly outshine an entire galaxy of 100s of billions of stars!
- These explosions have two important consequences
  1. Large amounts of the elements heavier than He created in the star’s nuclear furnace are returned to the interstellar medium, able to be made part of future stars, planets, etc.
  2. The SN energy provides the energy needed to create elements heavier than iron (Fe); hence SNe produce all the elements from Fe → U
- *All* the elements heavier than carbon come from SNe: the iron in the Earth’s core, the oxygen we breathe, the calcium in our bones; we are *literally* star stuff!
## Stellar Evolution Summary

<table>
<thead>
<tr>
<th>Stellar Mass ( (M_\odot) )</th>
<th>Low Mass ( (M_\odot) )</th>
<th>Intermediate Mass ( (M_\odot) )</th>
<th>High Mass ( (M_\odot) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar Mass ( (M_\odot) )</td>
<td>(&lt; 0.08)</td>
<td>(0.08-0.5)</td>
<td>(0.5-2.0)</td>
</tr>
<tr>
<td>(&lt; 0.08)</td>
<td>(0.08-0.5)</td>
<td>(0.5-2.0)</td>
<td>(2.0-5.0)</td>
</tr>
<tr>
<td>Brown Dwarf</td>
<td>He WD</td>
<td>C WD</td>
<td>C-O WD</td>
</tr>
<tr>
<td>Event</td>
<td>Planetary Nebula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core Mass</td>
<td>(&lt; 1.4 M_\odot)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Novae, Type I and Type II Supernovae

- The supernova created by a high-mass star is called a **Type II supernova**
- When a **white dwarf** is part of a close binary, especially where the other star is a **red giant**, accretion can occur from the large star onto the small star
- Eventually, this hydrogen gas can become hot enough to ignite, causing a **relatively minor explosion** called a **nova**
- This process can repeat over and over, so novae are often periodic events
- As mass is added to the white dwarf, it can be pushed over the limit ($1.4 \, M_\odot$) causing it to collapse, igniting the carbon (like the helium flash), and causing a **Type I supernova**, which **completely destroys** the star, leaving nothing behind
Lecture Tutorial:
*Stellar Evolution*, pp. 133-134

- Work with one or more partners - not alone!
- Get right to work - you have **10 minutes**
- Read the instructions and questions carefully.
- Discuss the concepts and your answers with one another. **Take time to understand it now!!!!**
- Come to a consensus answer you all agree on.
- Write clear explanations for your answers.
- If you get stuck or are not sure of your answer, ask another group.
- If you get really stuck or don’t understand what the Lecture Tutorial is asking, ask me for help.
Homework

• For homework
  • Complete the Lecture Tutorial *Stellar Evolution* (if necessary)
  • Complete the ranking tasks, *Stellar Evolution #2 and #3* (available on the class website)