Important Notes

- HW #3 is due today.
- Start and Finish Lifecycle of a Low Mass Star
- Topics for Exam #3, Exam #3 is next week (scantron 882E).
- HW# 4 will be posted after Exam #3 and due at the final.
- Final is in about 4 weeks: May 19th same time/place
- Extra credit is due a week before the final.
Star Systems begin as dense, cold **molecular clouds** of H₂ with temperatures of about 100 K
Parcels of gas within a molecular cloud feel the gravitational attraction of all other parts of the molecular cloud...

Net gravitational force...leading to a net gravitational force toward the cloud center of mass.

Center of mass of cloud
1. Molecular clouds are never uniform. Some regions inside the cloud are more dense than others.

2. Slightly denser regions collapse faster than their surroundings, and become more pronounced.
The collapsing cloud fragments into dense, star-forming cores.
• The Molecular cloud cores become **protostars** – young stellar (fluffy) objects that radiate thermal energy from continual gravitational collapse (*no fusion yet*).

• Thermal energy helps to support the protostar against gravity...

• ...but as the energy escapes (cools off), this causes the protostar to contract and shrink...
• The protostar heats up!
• ... the heating due to shrinking more than overcomes the cooling due to radiation,
• as the density increases the thermal energy has a harder time escaping,
• the central region of the protostar gets hotter and hotter until hydrogen fusion can begin
Once H-fusion begins, then you can call it a star!
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- the initial mass of the cloud cores determines whether or not it will become a star.
- the mass must be greater than 8% of the Sun’s mass for fusion to occur.
- If Jupiter were about 80 times more massive, it would be a star as well.
Once a stellar object becomes a star, it begins its life on the **Main Sequence** of the HR diagram.
• Just like the initial mass of the stellar object will determine whether or not it becomes a star...

• ...the initial mass of a star determines its fate.

• For now, we’ll focus on low mass stars – $0.08 \, M_\odot$ to $3 \, M_\odot$
This includes all the A,F,G,K,M stars. The vast majority being Red Dwarfs ($0.08 \, M_\odot$ to $0.5 \, M_\odot$).
From the blackbody model:
- the color of light emitted by a hot, dense object indicates its temperature...
- ...blue is the hottest and red the coolest
- What does this imply about the mass of blue stars and red stars?
• Blue stars are more massive (on the Main Sequence)!
• More mass means stronger gravity
• stronger gravity means higher central density and temperatures
• this makes for faster nuclear reactions and a hotter and more luminous star
Stars on the Main Sequence are in a stable state:

...they’re not collapsing or expanding.

The force from gravity balances out the radiation pressure from fusion in the core.
• Since a star radiates (from burning hydrogen), it’s losing mass.
• Eventually, it will run out of hydrogen to burn.
• What does this mean for the lifetime of a main sequence star?
Let’s consider the lifetime of a tank of gas...
Lifetime (tank of gas) = \frac{\text{Amount of fuel}}{\text{rate of fuel consumption}}
Example: if you have a 15-gallon tank and your engine is burning fuel at a rate of 3 gallons each hour...

...then you will use up all the gas in 5 hours.
• Stars are the same way.
• The tank of gas is the mass
• the rate of fuel consumption is the luminosity (same as fusion rate)

\[ \text{lifetime}_{MS} \propto \frac{\text{mass}}{\text{luminosity}} \]
The center of these low-mass stars is not hot enough to fuse the products of hydrogen fusion ($^4\text{He}$) into heavier elements.

As a result, inert helium ash starts to build in the core.
• When a star runs out of hydrogen in the core to burn, it leaves the Main Sequence.
• Stars spend the vast majority of their lives on the MS (fusing H into He)
• The Sun will spend 10 billion years on the MS, it’s got about 5 billion years left!
When the Sun formed (∼5 billion years ago) the composition was 70% H, and 30% He.

Today it’s estimated that 65% of the core’s mass is He.
main-sequence star

expanding subgiant

photosphere

expanding photosphere

hydrogen-burning core

contracting inert helium core

hydrogen-burning shell
• At some point, the star will run out of H in the core
• there will only exist some lump of inert He
• but remember, it was the radiation pressure from fusion that supported the star against the force of gravity
• with no fusion, the balance that has lasted for so long is broken...
• ...so the star begins to collapse and crush the He core
Recall: atoms are mostly empty space.
So is the Sun! even at the core
• At the center of the Sun, all the electrons have been stripped off the atoms from highly energetic collisions.
• The size of the nuclei is very much less than the distances between them
• so the Sun is also mostly empty space
• The He core continues to get crushed. . .
• . . . but there’s a limit
• eventually the density of the core will increase and will no longer be mostly empty
• the volume will be ‘effectively’ filled and compression will stop
• the matter in the core will be then electron-degenerate matter
• the H immediately around the He core will get closer to central region of the core as the He nugget gets crushed
• Once the nugget becomes degenerate matter, the H shell will be at density that will once again allow for H fusion.
• This is called H-shell burning and more He ash is added to the nugget.
• Degenerate matter does not behave like normal matter
• As the He ash builds in the core, it becomes more massive
• the increase in mass shrinks the He nugget!
- the growing-shrinking He core causes the H-shell to experience a greater gravitational force
  \[ F_g \propto M/d^2 \]
- this increases the pressure and density of the H-shell
- so fusion in the shell increases at a faster rate than when the star was on the MS!
- faster fusion rate = more luminosity
As the star runs out of fuel, it responds by becoming more luminous!

The increase in energy generation heats the outer layers and causes the star to expand to a fluffy, luminous giant.
Because the star is larger, the surface becomes \textit{cooler} and thus \textit{redder}.

In fact, the luminosity, $L$, of a star is related to its radius, $R$, and surface temperature, $T$:

\[ L \propto R^2 T^4 \]

A change in one will lead to a change in the other two.
• The star continues to expand and becomes a red giant.
• Luminosity skyrockets up to about $1000 \, L_\odot$.
• The radius grows to about $100 \, R_\odot$.
• The core continues to grow more massive, smaller, and hotter.
- Eventually, the nugget of He ash reaches temperatures of about 100 million K.
- Then, it’s hot enough to fuse He to C via the triple-$\alpha$ process.
- Remember that H is still fusing in a shell around the core.
1. The triple-alpha process begins when two $^{4}\text{He}$ nuclei fuse to form an unstable $^{8}\text{Be}$ nucleus.

2. If this nucleus collides with another $^{4}\text{He}$ nucleus before it breaks apart, the two will fuse to form a nucleus of carbon-12 ($^{12}\text{C}$).

3. The energy released is carried off both by the motion of the $^{12}\text{C}$ nucleus and by a gamma ray.
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$^8\text{Be}$ decays into $^4\text{He}$ after a trillionth of a second ($10^{-12}$ s).

If this nucleus collides with another $^4\text{He}$ nucleus before it breaks apart, the two will fuse to form a nucleus of carbon-12 ($^{12}\text{C}$).

The energy released is carried off both by the motion of the $^{12}\text{C}$ nucleus and by a gamma ray.
Once He burning begins in the core, the temperature in the core goes up but the core does not expand.
- The He nuclei are then slammed together with more frequency and more force.
- The nuclear reactions then become more vigorous.
- More vigorous reactions result in higher temperatures in the core... thermonuclear runaway.
- This is called the helium flash.
What it means to be a thermonuclear runaway

- He burning begins at 100 million K
- at 110 million K, the rate of burning has increased by 40 times
- at 200 million K, the rate of burning has increased 460 million times faster than at 100 million K!
- Helium flash is an explosion contained in a star
- The energy goes into puffing up and expanding the core
- The matter in core is now no longer degenerate but He burning is still taking place
- He burning is a lot slower now, causing the star to become less luminous
**HELIUM FLASH**

Runaway He burning: The degenerate helium core explodes within the star.

**HORIZONTAL BRANCH STAR**

- Stable He-burning core
- Hydrogen-burning shell
- Nonburning hydrogen envelope
• Over the next 100,000 years, the star settles into a stable structure, no longer a red giant
• He burns to C in a non-degenerate core
• H burns to He in a shell around the core
• the star responds to lower burning rate by shrinking in size from the force of gravity
• Can refer to this period as **Helium Main Sequence** (100 million years)
- Carbon ash is building up in the core.
- Eventually, He burning will cease and the energy from fusion does not balance the force of gravity.
- The C core is then crushed and becomes electron-degenerate (just like the He core did).
- The degenerate core drives up the gravitational force of the He and H shells.
- . . . which increases the pressure and temperature in the shells.
- Runaway He burning: The degenerate helium core explodes within the star. 
- Stable He-burning core
- Nonburning hydrogen envelope
- Hydrogen-burning shell
- Helium flash
• this drives up the reaction rate in the shells
• and the degenerate C core grows more rapidly
• sound familiar? so what happens next?
• Energy generation is tremendous now
• the star responds by puffing up and expanding to about the orbit of Mars
• the star is very luminous now (AGB star)
• but it never becomes hot enough to fuse C!
• this star is now really large and fluffy, and luminous
• Since the outer layers are now so very far away from the central massive region of the star...
• ...these layers are no longer gravitationally bound to the star
• and the star blows off its outer layers
So What Does This Look Like?
Abell 7 (Lepus)
Cat’s Eye (Draco)
Butterfly (Scorpius)
Hourglass (Musca)
NGC 5882 (Lupus)
Ring (Lyra)
Red Rectangle (Monoceros)
• The star ‘gently’ expels all of its outer layers until only the very hot (100,000 K), degenerate C core remains

• Wien’s law says that at this temperature the core (**White Dwarf**) emits UV radiation

• the expanding shell (layers) of gas form very symmetrical shapes and glow from the UV light (**Planetary Nebula**)  

• The White Dwarf is no longer fusing anything, and eventually cools off
• White Dwarfs have a mass range of 
  \(0.2 \, M_\odot \, \text{to} \, 1.4 \, M_\odot\)
• There are about the size of Earth for a \(1 \, M_\odot\) star
• it is estimated that it would take 1000 trillion years for a White Dwarf to cool to 3 K.
Topics included in Exam #3
The Sun

- Properties of the Sun
- Solar Activity
- The Atmosphere
- Aurora on Earth
Parallax Angle

- How to use it to find distances to nearby stars
- includes using the appropriate units
Brightness of Stars

- apparent magnitude vs. absolute magnitude
- comparing the brightness between two stars (using magnitudes)
- what information does apparent magnitudes give you compared with absolute magnitudes
- Inverse Square Law of Astronomy - how is the observed brightness of a star related to its power (luminosity)?
Stellar Classifications

- Who are the Harvard Computers and What Did They Do?
- What are the different spectral types, what do they tell you about a star?
- Keenan-Morgan Luminosity classes
- H-R diagram question
The Story of a Low-Mass Star

- from beginning...
- ...to the end
SOURCES

Astronomical images courtesy of http://apod.nasa.gov/
http://www.nature.com/
http://www.stellarium.org/
http://www.skyandtelescope.com
http://www.earthsky.org