Work graded, available for pickup

All planetarium/observing reports turned in so far

- In general, good job.
- Reminder: these are *required*.
- Total points: 10 (out of 200)

Corrections, quiz 4

- Those turned in on paper are graded.
- All emails were replied to this afternoon.
Quiz 5 is available for pickup in front

Extra credit corrections: for up to 4 of the questions you missed:

- Look up or figure out the correct answer.
- Write a sentence or two explaining what you did wrong or why the right answer is correct. **Just giving the answer will not earn credit!**
- Turn it in on paper at the beginning of class Monday, April 12.
- Or by email until midnight that night. If possible, please avoid attachments.

Distribution
Extra credit assignment 6 is now online at Mastering Astronomy

Covers this week’s material: birth, adulthood, death of stars

Due this Friday, 5:30 PM (can still work it after that but no credit)

Extra credit offered

• Up to 10 points toward the 200 for the course (same as planetarium & observatory requirement)

• Partial credit available

One more will be posted, due April 23
How stars work

Main-sequence stars work in the same way as the Sun.

- Balance between gravity and gas pressure
- Convert energy by fusion of hydrogen to helium
The more massive the star:

- The stronger its gravitational pull
- Therefore, it needs a hotter interior to generate the pressure to resist gravity.
- A hotter interior results in thermonuclear fusion proceeding more efficiently. Conversion of (stored) energy from mass into heat & light proceeds faster, so the star has a higher luminosity.

We’re talking about the theory of the structure of a star here, because we are using physical laws to draw conclusions about regions that we can’t observe directly.
Limits on stellar masses

- The largest mass that a star can have is around 100 Suns.
- The smallest mass that a star can have
  - If the central regions of a star are not hot enough, nuclear fusion will not occur.
  - The star’s gravitational pull is too small to generate enough heat for fusion if the star’s mass is less than about 0.08 Sun.
  - Indeed, the least massive stars known have masses of about 1/10 Sun.
So what exactly is a *star*?

- Definition of a *star*: gas sphere with enough mass to support fusion of hydrogen to helium. According to theory, at least 0.08 Sun (same as 80 Jupiter masses).

- Definition of a *brown dwarf*: gas sphere with enough mass to support fusion of deuterium to helium-3, but not enough to support fusion of hydrogen to deuterium. According to theory, between about 13 and about 80 Jupiters.

- Definition of a *planet*: too little mass to support any fusion at all, less than about 13 Jupiters.
Brown dwarfs begin life with gravitational contraction, just as stars do.

But they just get smaller and dimmer until the contraction is halted by degeneracy pressure.

So they are brightest and easiest to discover when young. Have been discovered mainly in star forming regions. 1 2

Also sometimes found in binary star systems.
Life spans of main-sequence stars

- In general, the more massive a main-sequence star, the shorter its life span.
- Reason: although massive stars have a larger fuel supply than less massive stars, they consume their fuel disproportionately quickly.
The most massive stars (30 Suns and up) live only a few million years, an extremely short time by stellar standards.

- They have not had time to move away from their birthplaces.
- If stars were being born a few million years ago, they probably still are.
- Stars are now being born in their vicinity; these stars are signposts for regions of star formation.
Inside a main-sequence star, changes are very slight and gradual.

End of the main-sequence phase of a star’s life: exhaustion of hydrogen in the star’s core

- Fusion slows down.
- Now the star’s energy loss must be made up by gravitational contraction.
- The core contracts gradually because its own gravitational pull is almost (not quite) counterbalanced by gas pressure.
- The contraction heats the core.
Cross-sectional view of star after core fusion has stopped:
• Nuclear fusion starts in a region outside the core—the “shell”—that was not hot enough before.

• With 2 energy sources, the star now generates more than enough energy to counterbalance gravity. Therefore, its outer layers expand.

• Because they expand, they cool. The star gradually becomes a red giant.
Before the main sequence: star birth

Regions of star formation are marked by massive, luminous main-sequence stars, which cannot live more than a few million years.

Interstellar gas and dust still abundant in region — the raw material of star formation

Nearest, best-studied example: the Orion Nebula

- About 1000 light years from us
- Contains a small cluster of hot main-sequence stars
• Their ultraviolet radiation output is partly absorbed by hydrogen atoms in the gas cloud around them. The atoms glow, creating the visible nebula.

• Also contains lower-mass stars, some surrounded by disks (*Hubble Space Telescope* discovery)

• Behind the nebula is a cold, dense cloud of gas and dust.
The dust scatters and absorbs electromagnetic radiation, especially of the shorter wavelengths.
Therefore, we have a hard time witnessing stars being born.

- Visible light cannot penetrate the cloud — it is *opaque*.
- But *infrared images* reveal a cluster of stars within.
- Good guess: these are still forming.
- Later, their light output will destroy the cloud that gave birth to them.
Another well-known star forming region: the Eagle Nebula in the constellation Aquila

- Contains hot, luminous main-sequence stars (very young)
- Dark dust “fingers” or “pillars” pointing toward them, being evaporated by their ultraviolet light emission.
- Closeup of the “pillars” from Hubble Space Telescope shows that the dust pillars are being destroyed by the embedded stars as well.

Next: review theory of origin of solar system, applying it now to formation of stars in general.
Theory of star birth

Isolation of a small portion of an interstellar cloud of gas and dust (a denser clump)

Gravitational contraction, in which gravitational potential energy is converted into thermal energy and radiation

Formation of a hot protostar in the center
Amplification of existing rotation of the clump (conservation of angular momentum as it contracts)

Formation of an *accretion disk*

Continued gravitational contraction of the protostar with increasing temperature and density of interior; formation of planetary system out of disk
Beginning of nuclear fusion in core, end of gravitational contraction; beginning of main-sequence phase of star’s life.
Reality check: accretion disks in space

Infrared images from *Hubble Space Telescope*
Stellar maturity

Time spans for the Sun:

- Main-sequence stage: 10 billion years
- Red giant stage: 1 billion years
- Remaining life span: very short

Meaning of these time spans:

- Suppose you could compress the entire history of the solar system so far into one calendar year.
- Then each day of the year would represent a time span of about 13 million years.
Follow the life history of a 1-solar-mass star to its end.

As we saw, any star becomes a red giant after it uses up the hydrogen in its core.
Limitation on the contraction of the core

- The core of a star is an ionized gas — a mixture of free electrons and atomic nuclei that have been stripped of their electrons.
- Only a limited number of electrons can be squeezed into a given volume. When this limit is reached, the electrons resist further compression.
- They react to being squeezed too close by exerting extra pressure, so they stop the core from contracting.
- Electrons that have reached this limit are said to be degenerate.
The rest of the star continues as before: the regions outside the degenerate core get hotter and denser while the exterior regions expand and cool.
Fusion of helium into carbon begins in the core.

- When the core’s temperature reaches 100 million Kelvin, helium nuclei can fuse to produce carbon nuclei and release energy.

- Three helium-4 nuclei join to make carbon-12:

  ![Diagram of helium nuclei fusing into carbon-12]

- An additional helium-4 can fuse with carbon-12 to make oxygen-16.
• Compared to hydrogen fusion
  – Helium has twice as much electrical charge as hydrogen.
  – The nuclei need to collide at a higher speed to overcome their mutual repulsion.
  – A higher temperature is needed.
The end of helium fusion

- The star turns into a red giant for the second time: the core contracts while the outer layers expand.
- Again the contraction of the core stops when its electrons become degenerate.
- But this time, the outer layers expand even more.
  - The star can get up to 1000 times as big as the Sun is now.
  - Its luminosity can get up to 10,000 times as great as the Sun’s is now.
  - Its outer atmosphere becomes very cool (as stars go).
Loss of the star’s outer layers

- Because the star is so huge, its envelope is only weakly held in by gravity
- Small solid dust grains condense in the cool, outermost layers
- The star’s radiation pushing on these grains drives the envelope away.
- After a few thousand years, the former core is exposed.
- The central object continues to shed matter *slowly.*
- The ejected matter forms a cloud around the star.
- Eventually, only the degenerate carbon-oxygen core is left.
• This shrunken remnant is a white dwarf. It slowly loses energy to space and cools but otherwise doesn't change.

The cloud of ejected matter around a newly formed white dwarf is called a planetary nebula.

The name was given during the 18th century, in honor of the clouds' similarity to the blue-green disk of the planet Uranus, which had recently been discovered at the time.

Hubble Space Telescope images of these clouds show many interesting details not yet understood.
This story recounts the expected future of the Sun.

The story is theory, but it checks out well. We can observe examples of each stage in the life of a star.
Condensation of solids in solar nebula, 4.6 billion yrs ago

Oldest known stars: mid-2005

Earliest fossils

All of recorded history: last 30 seconds!

Hyades star cluster formed

Humans originate*

Orion Belt stars born

Orion Nebula stars born

Now