17. Star Stuff

I can hear the sizzle of newborn stars, and know anything of meaning, of the fierce magic emerging here. I am witness to flexible eternity, the evolving past, and know I will live forever, as dust or breath in the face of stars, in the shifting pattern of winds.

Joy Harjo (1951 –)
from Secrets From the Center of the World

Agenda

- Announce:
  - Project/extra credit descriptions by Tuesday
  - Homework 1: H-R tutorial
- Tests, grades, etc
- Chapter 17
- Discuss String lab

17.1 Lives in the Balance

Our goals for learning:

- What kind of pressure opposes the inward pull of gravity during most of a star's life?
- What basic stellar property determines how a star will live and die, and why?
- How do we categorize stars by mass?

Stellar Evolution

- Stars are like people in that they are born, grow up, mature, and die.
- A star's **mass** determines what life path it will take.
- We will divide all stars into three groups:
  - Low Mass ($0.08\ M_\odot < M < 2\ M_\odot$)
  - Intermediate Mass ($2\ M_\odot < M < 8\ M_\odot$)
  - High Mass ($M > 8\ M_\odot$)
- The H-R Diagram makes a useful roadmap for following stellar evolution.

Stellar Evolution

- The life of any star can be described as a battle between two forces:
  - Gravity vs. Pressure
- Gravity always wants to collapse the star.
- Pressure holds up the star.
  - the type of star is defined by what provides the pressure
- Remember Newton's Law of Gravity
  - the amount of gravitational force depends on the mass
  - gravitational potential energy is turned into heat as a star collapses

17.2 Star Birth

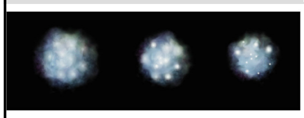
Our goals for learning:

- Where are stars born?
- What is a protostar?
- Summarize the "pre-birth" stages of a star's life.
- What is a brown dwarf ?

The Stellar Womb

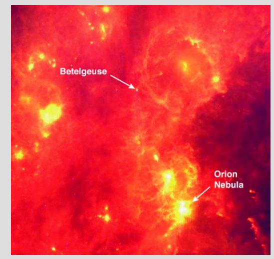
- Stars are born deep in **molecular clouds**.
  - cold (10 – 30 K) dense nebulae
  - so cold that H_2 can exist
- A cold cloud can fragment
  - gravity overcomes thermal pressure in dense regions
  - these regions (**cores**) become more dense and compact

dark molecular cloud in *Scorpius*



Stellar Gestation

- Something happens to perturb a molecular cloud and make it begin to fragment
- As a core of gas compresses, it traps outging radiation
  - it radiates infrared from its surface
  - **protostar**
- The protostar collapses until its core reaches 10^7 K in temperature
  - The proton – proton chain fusion reaction begins and ….



infrared image of *Orion*

A Star is Born!

Movie. Click to play.

Eagle Nebula
Hubble Space Telescope

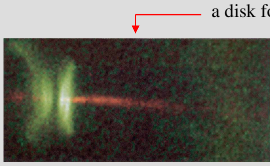
Pleiades

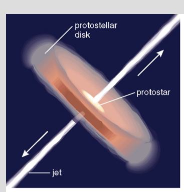
Star Formation

- As the protostar collapses, angular momentum is conserved
  - the protostar rotates faster
  - matter falling in to the protostar flattens into a (protostellar) disk
  - a planetary system could form from this disk

Direct Evidence of Disks & Jets

a disk forms

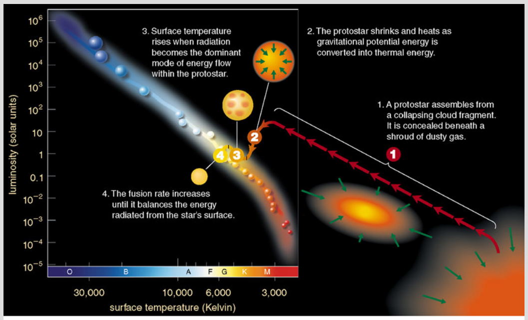




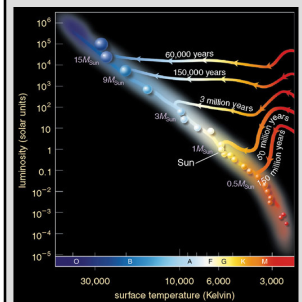
Star Formation

- As the protostar heats up, enough thermal energy is radiated away from surface to allow collapse to continue.
  - energy is transported to surface first via convection
  - as core gets even hotter, transport via radiation takes over
- The protostar must rid itself of angular momentum, or it will tear itself apart
  - magnetic fields drag on the protostellar disk
  - fragmentation into binaries
- Fusion reactions begin when core reaches 10^7 K

Stages of Star Formation on the H-R Diagram



Arrival on the Main Sequence

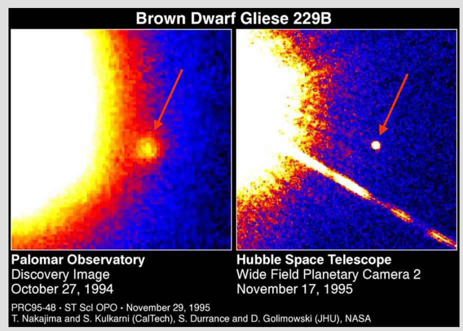


- The mass of the protostar determines:
  - how long the protostar phase will last
  - where the new-born star will land on the MS
  - i.e., what spectral type the star will have while on the main sequence

Missing the Main Sequence

- If the protostar has a mass < 0.08 $M_\odot$:
  - It does not contain enough gravitational energy to reach a core temperature of 10^7 K
  - No fusion reactions occur
  - The star is **stillborn**!
- We call these objects Brown Dwarfs.
- They are very faint, emit infrared, and have cores made of Hydrogen
  - degenerate cores

The First Brown Dwarf Discovery



17.3 Life as a Low Mass Star

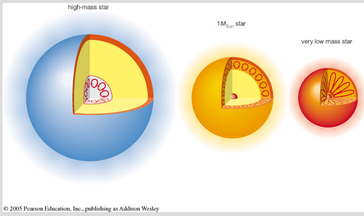
Our goals for learning:

- What are the major phases of life of a low-mass star?
- How did past red giant stars contribute to the existence of life on Earth?
- What prevents Carbon from fusing to heavier elements in low-mass stars?

Life on the Main Sequence

- Where a star lands on the MS depends on its **mass**
  - O dwarfs (O V) are most massive
  - M dwarfs (M V) are least massive
- MS stars convert H ⇨ He in their cores
- The star is stable, in balance
  - Gravity vs. pressure from H fusion reactions

Life on the Main Sequence



The internal structure is different for MS stars of different masses.

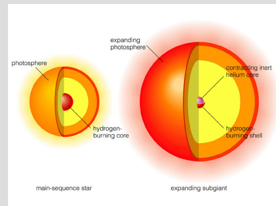
How long do these stars stay on the MS?

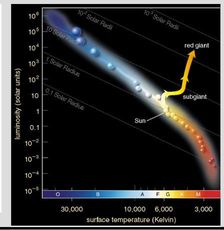
Until they burn up their fuel (H)!!

Massive stars have more fuel, but they are also brighter, so they use it up faster.

Leaving the Main Sequence

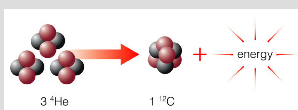
- The core begins to collapse
  - H shell heats up and H fusion begins there
  - there is less gravity from above to balance this pressure
  - so the outer layers of the star expand
  - the star is now in the **subgiant** phase of its life





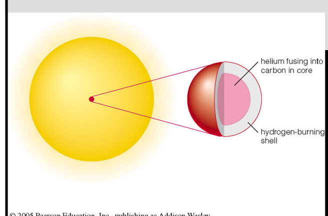
Red Giants

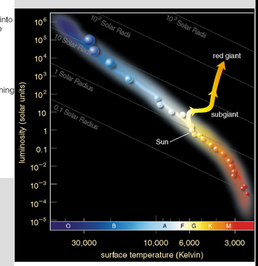
- The He core collapses until it heats to 10^8 K
  - He fusion begins (He ⇨ C)
  - sometimes called the "triple-α process"



- The star, called a Red Giant, is once again stable.
  - gravity vs. pressure from He fusion reactions
  - red giants create and release most of the Carbon from which organic molecules (and life) are made

Red Giants

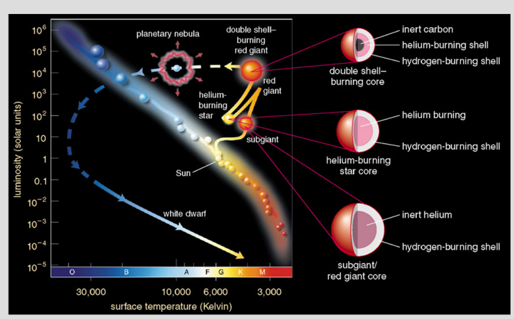




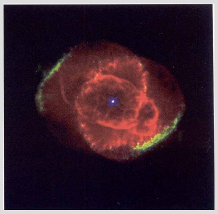
Planetary Nebulae

- When the Red Giant exhausts its He fuel
  - the C core collapses
  - Low & intermediate-mass stars don't have enough gravitational energy to heat to 6 x 10^8 K (temperature where Carbon fuses)
- The He & H burning shells overcome gravity
  - the outer envelope of the star is gently blown away
  - this forms a planetary nebula

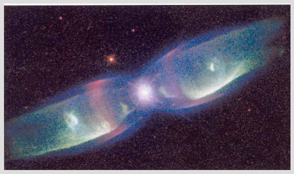
Planetary Nebulae



Planetary Nebulae

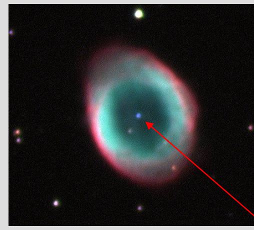


Cat's Eye Nebula

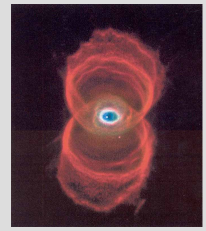


Twin Jet Nebula

Planetary Nebulae



Ring Nebula



Hourglass Nebula

The collapsing Carbon core becomes a White Dwarf

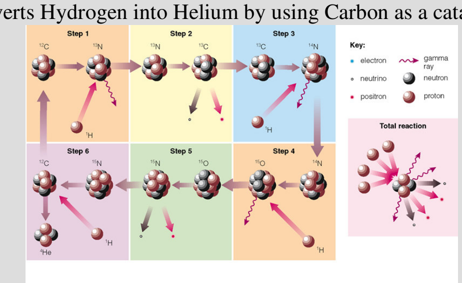
17.4 Life as a High Mass Star

Our goals for learning:

- State several ways in which high-mass stars differ from low-mass stars.
- How do high-mass stars produce elements heavier than carbon?
- What causes a supernova?
- Do supernovae explode near the Earth?

High Mass Main Sequence Stars

The CNO cycle is another nuclear fusion reaction which converts Hydrogen into Helium by using Carbon as a catalyst.



Effectively 4 H nuclei go IN and 1 He nucleus comes OUT.

High Mass Main Sequence Stars

CNO cycle begins at 15 million degrees and becomes more dominant at higher temperatures.

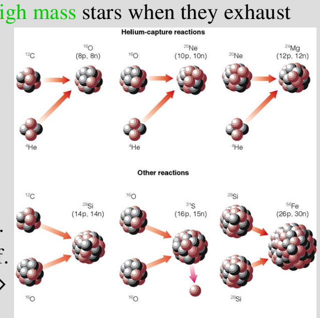
The C nucleus has a (+6) charge, so the incoming proton must be moving *even faster* to overcome the electromagnetic repulsion!!

The Sun (G2) -- CNO generates 10% of its energy
F0 dwarf -- CNO generates 50% of its energy
O & B dwarfs -- CNO generates most of the energy

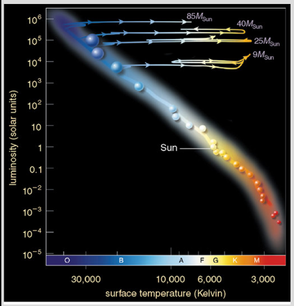
Supergiants

What happens to the high mass stars when they exhaust their He fuel?

- They have enough gravitational energy to heat up to 6 x 10^8 K.
  - C fuses into O
- C is exhausted, core collapses until O fuses.
- The cycle repeats itself.
  - O ⇨ Ne ⇨ Mg ⇨ Si ⇨ Fe



Supergiants on the H-R Diagram

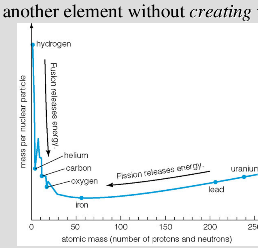


- As the shells of fusion around the core increase in number:
  - thermal pressure overbalances the lower gravity in the outer layers
  - the surface of the star expands
  - the surface of the star cools
- The star moves toward the upper right of H-R Diagram
  - it becomes a red supergiant
  - example: *Betelgeuse*
- For the most massive stars:
  - the core evolves too quickly for the outer layers to respond
  - they explode before even becoming a red supergiant

The Iron (Fe) Problem

- The supergiant has an inert Fe core which collapses & heats
  - Fe can not fuse
  - It has the lowest mass per nuclear particle of any element
  - It can not fuse into another element without *creating* mass

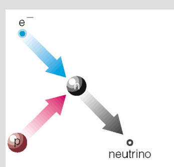
So the Fe core continues to collapse until it is stopped by electron degeneracy. (like a White Dwarf)



Supernova

- **BUT**… the force of gravity increases as the mass of the Fe core increases
  - Gravity overcomes electron degeneracy
  - Electrons are smashed into protons ⇨ neutrons

- The neutron core collapses until abruptly stopped by neutron degeneracy
  - this takes only seconds
  - The core recoils and sends the rest of the star flying into space



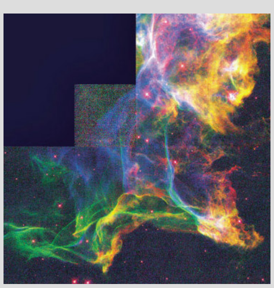
Supernova

Crab Nebula in *Taurus*
supernova exploded in 1054

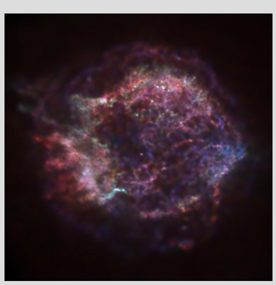
The amount of energy released is so great, that most of the elements **heavier** than Fe are instantly created

In the last millennium, four supernovae have been observed in our part of the Milky Way Galaxy: in 1006, 1054, 1572, & 1604

Supernovae



Veil Nebula



Tycho's Supernova (X-rays)
exploded in 1572

Summary of the Differences between High and Low Mass Stars

- Compared to low-mass stars, high-mass stars:
  - live much shorter lives
  - have convective cores, but no other convective layers
    - while low-mass stars have convection layers at their surfaces
  - have a significant amount of pressure supplied by radiation
  - fuse Hydrogen via the CNO cycle instead of the p-p chain
  - die as a supernova; low-mass stars die as a planetary nebula
  - can fuse elements heavier than Carbon
  - may leave either a neutron star or black hole behind
    - low-mass stars leave a white dwarf behind
  - are far less numerous

17.5 Lives of Close Binary Stars

Our goals for learning:

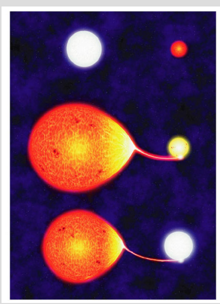
- Why are the life stories of close binary stars different from those of single, isolated stars?
- What is the Algol Paradox?

Close Binary Stars

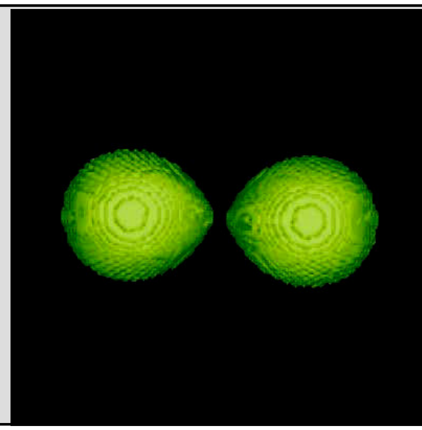
- Most stars are not single – they occur in binary or multiple systems.
  - binary stars complicate our model of stellar evolution
- Remember that mass determines the life path of a star.
  - two stars in a binary system can be close enough to transfer mass from one to the other
  - gaining or losing mass will change the life path of a star
- For example, consider the star *Algol* in the constellation *Perseus.*
  - *Algol* is a close, eclipsing binary star consisting of…
  - a main sequence star with mass = 3.7 $M_\odot$ & a subgiant with mass = 0.8 $M_\odot$
  - since they are in a binary, both stars were born at the same time
  - yet the less massive star, which should have evolved more slowly, is in a more advanced stage of life
- This apparent contradiction to our model of stellar evolution is known as the ***Algol Paradox***.

The ***Algol Paradox*** Explained

- This paradox can be explained by **mass exchange**.
- The 0.8 $M_\odot$ subgiant star *used to be* the more massive of the two stars.



- When the *Algol* binary formed:
  - it was a 3 $M_\odot$ main sequence star…
  - with a 1.5 $M_\odot$ main sequence companion
- As the 3 $M_\odot$ star evolved into a red giant
  - tidal forces began to deform the star
  - the surface got close enough to the other star so that gravity…
  - pulled matter from it onto the other star
- As a result of mass exchange, today…
  - the giant lost 2.2 $M_\odot$ and shrunk into a subgiant star
  - the companion is now a 3.7 $M_\odot$ MS star



What have we learned?

- What kind of pressure opposes the inward pull of gravity during most of a star's life?
  - Thermal pressure, owing to heat produced either by fusion or gravitational contraction, opposes gravity during most of a star's life.
- What basic stellar property determines how a star will live and die, and why?
  - A star's mass determines its fate, because it sets both the star's luminosity and its spectral type.
- How do we categorize stars by mass?
  - Low-mass stars are those born with less than about 2 M_{Sun}. Intermediate-mass stars are those born with mass between about 2–8 M_{Sun}. High-mass stars are those born with greater than about 8 M_{Sun}.

What have we learned?

- Where are stars born?
  - Stars are born in cold, relatively dense molecular clouds — so-named because they are cold enough for molecular hydrogen (H_2) to form.
- What is a protostar?
  - Gravitational contraction of a molecular cloud fragment can create a protostar, a compact clump of gas that will eventually become a star. A protostar in the early stages of becoming a star is usually enshrouded in gas and dust. Because angular momentum must be conserved, a contracting protostar is often surrounded by a protostellar disk circling its equator., Outflowing matter from a protostar, in either a protostellar wind or two oppositely directed jets, eventually clears away the shroud of gas and dust.

What have we learned?

- Summarize the "pre-birth" stages of a star's life.
  - (1) Protostar assembles from a cloud fragment and is bright in infrared light because gravitational contraction rapidly transforms potential energy into thermal energy. (2) Luminosity decreases as gravitational contraction shrinks protostar's size, while convection remains the dominant way by which thermal energy moves from the interior to the surface. (3) Surface temperature rises and luminosity levels off when energy transport switches from convection to radiative diffusion, with energy still generated by gravitational contraction. (4) Core temperature and rate of fusion gradually rise until energy production through fusion balances the rate at which the protostar radiates energy into space. At this point, the forming star becomes a main-sequence star.

What have we learned?

- What is a brown dwarf?
  - A brown dwarf is a "star" that never gets massive enough for efficient nuclear fusion in its core. Degeneracy pressure halts its gravitational contraction before the core gets hot enough for fusion.

What have we learned?

- What are the major phases of life of a low-mass star?
  - Main sequence, in which the star generates energy by fusing hydrogen in the core. Red giant, with hydrogen shell-burning around an inert helium core. Helium-core burning, along with hydrogen shell burning (star on horizontal branch on HR diagram). Double shell-burning of hydrogen and helium shells around an inert carbon core. Planetary nebula, leaving a white dwarf behind.
- How did past red-giant stars contribute to the existence of life on Earth?
  - Red giants created and released much of the carbon that exists in the universe, including the carbon that is the basis of organic molecules on Earth.

What have we learned?

- What prevents carbon from fusing to heavier elements in low-mass stars?
  - Electron degeneracy pressure counteracts the crush of gravity, preventing the core of a low-mass star from ever getting hot enough for carbon fusion.

What have we learned?

- State several ways in which high-mass stars differ from low-mass stars.
  - High-mass stars live much shorter lives than low-mass stars. High-mass stars have convective cores but no other convective layers, while low-mass stars have convection layers that can extend from their surface to large depths. Radiation supplies significant pressure support within high-mass stars, but this form of pressure is insignificant within low-mass stars. High-mass stars fuse hydrogen via the CNO cycle, while low-mass stars fuse hydrogen via the proton-proton chain. High-mass stars die in supernovae, while low-mass stars die in planetary nebulae. Only high mass stars can fuse elements heavier than carbon. A high-mass star may leave behind a neutron star or a black hole, while a low-mass star leaves behind a white dwarf. High-mass stars are far less common than low-mass stars.

What have we learned?

- How do high-mass stars produce elements heavier than carbon?
  - Late in their lives, high-mass stars undergo successive episodes of fusion of ever-heavier elements, producing elements as heavy as iron. Elements heavier than iron are produced during by these stars when they die in supernovae.
- What causes a supernova?
  - As a high-mass star ages, carbon and heavier elements can fuse via helium capture and other processes to form ever heavier elements. Shells of increasingly heavy element fusion are created, like onion skins inside the star. However, since fusion of iron uses up energy instead of releasing energy, an iron core cannot support the weight of the outer layers. The collapse of this core — which occurs in a fraction of a second — results in a supernova that nearly obliterates the star (perhaps leaving a black hole or a neutron star).

What have we learned?

- Do supernovae explode near the Earth?
  - At least four supernovae have been observed in our Milky Way galaxy during the last thousand years, in 1006, 1054, 1572, and 1064. Another supernova called Supernova 1987A was observed to explode in the Large Magellanic Cloud, a companion galaxy to the Milky Way, in 1987.

What have we learned?

- Why are the life stories of close binary stars different from those of single, isolated stars?
  - The transfer of mass from one star to its companion affects the life history (evolution) of both stars.
- What is the Algol Paradox?
  - The star Algol is a binary star in which the lower mass star is in a more advanced stage of life than the higher mass star. This is a paradox, because both stars must have been born at the same time and lower-mass stars should live longer, not shorter lives. The explanation is that the lower mass star was once the higher mass star, but as it grew into a giant it transferred much of its mass to its companion.

Suppose the universe contained only low-mass stars. Would elements heavier than carbon exist?

a. Yes, all stars create heavier elements than carbon when they become a supernova.
b. Yes, but there would be far fewer heavier elements because high-mass stars form elements like iron far more prolifically than low-mass stars.
c. No, the core temperatures of low-mass stars are too low to fuse other nuclei to carbon, so it would be the heaviest element.
d. No, heavy elements created at the cores of low-mass stars would be locked away for billions of years.
e. No, fission reactions would break down all elements heavier than carbon.

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What would stars be like if hydrogen, rather than iron, had the lowest mass per nuclear particle?

a. Stars would rapidly burn all their hydrogen and have very short lifetimes.
b. Nuclear fusion would be impossible so stars would not shine after they had contracted to their final state.
c. Nuclear fission would be impossible and elements heavier than iron would not exist.
d. Stars would continue burning heavier and heavier elements and the universe would have far more lead and uranium.
e. Stars would be much less dense, and therefore larger, but otherwise the same.

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A protostellar cloud spins faster as it contracts, even though its angular momentum stays the same.

a. Yes, angular momentum is conserved and if the cloud contracts, it must spin faster.
b. Yes, clouds spin faster as they contract but their angular momentum must also increase.
c. No, if the angular momentum stays the same, the cloud must spin at the same rate.
d. No, if the angular momentum stays the same, the cloud cannot contract.

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If you could look inside the Sun today, you'd find that its core contains a much higher proportion of helium and a lower proportion of hydrogen than it did when the Sun was first born.

a. Yes, because the Sun is about halfway through its hydrogen-burning life, it has turned about half its core hydrogen into helium.
b. No, the proportion of helium only increases near the end of the Sun's life.
c. No, the proportion of helium in the Sun will always be the same as when it first formed.
d. No, the lighter helium will rise to the surface and the proportion of hydrogen in the core will remain the same.

If you could look inside the Sun today, you'd find that its core contains a much higher proportion of helium and a lower proportion of hydrogen than it did when the Sun was first born.

a. Yes, because the Sun is about halfway through its hydrogen-burning life, it has turned about half its core hydrogen into helium.
b. No, the proportion of helium only increases near the end of the Sun's life.
c. No, the proportion of helium in the Sun will always be the same as when it first formed.
d. No, the lighter helium will rise to the surface and the proportion of hydrogen in the core will remain the same.