Index Card, 11/1

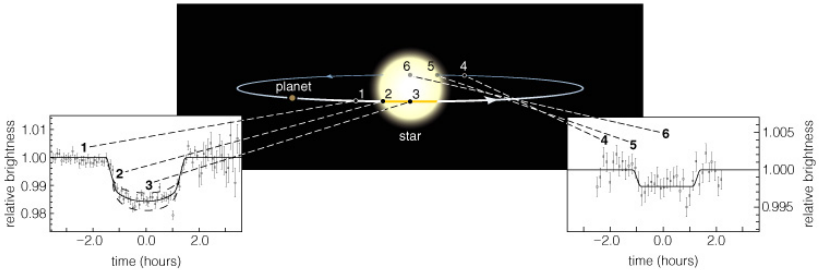
Take this opportunity to ask one or two specific questions on points that you don't understand, that will be included on the exam (see Study Guide 2).

A number of students simply repeated the questions on today's quiz (not very imaginative), or that have appeared on earlier cards & quizzes. Answers to these can be find on the respective feedback files. Others asked extremely broad, hence not useful questions. If you missed a week of class, you should find out about stellar aging by consulting the class slides.

Queries about Exoplanets

- "Which method for detecting exoplanets helps you find the planet's mass?" To measure mass you need to detect the gravity of the planet, by seeing its tugs on its parent star, usually via the Doppler method. If you don't know the orbital tilt, however, this gives only the minimum planet mass. (See slides & card from 10/11.)
- "Do interactions between multiple planets cause them to speed up or slow down?" Both. The planets attract each other through gravity, so they accelerate as they approach each other, then slow down as they try to move apart. But their gravity is too weak to pull them out of their orbits around the parent star.

Transit plus Doppler Method

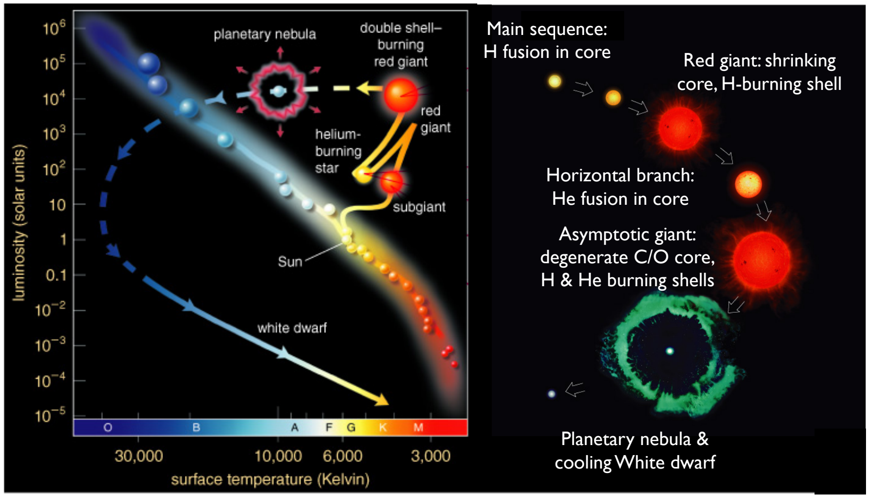


- A **transit** is when a planet crosses in front of a star
- The resulting (partial) eclipse reduces the star's apparent brightness and tells us planet's radius
- If you see transits, the orbit must be nearly edge-on; therefore the Doppler measurements of the system give you the actual planet mass, not just a minimum value.

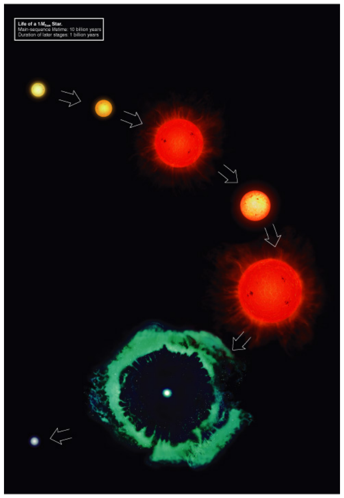
Queries about Low-Mass Stars

- "Differences between horizontal branch & asymptotic giant stars?" The horizontal branch phase is when He is fusing in the star's *core*. It is sort of like a rerun of the Main Sequence, when H fuses in the core. The asymptotic giant stage follows the horizontal branch. AGB stars have a dense C/O core, that becomes degenerate, with a He-burning shell around it, and an H-burning shell above it. See the Quiz 6 feedback file.
- "Difference between a red giant and red supergiant." Red giants are evolved lower-mass stars; the term red supergiant usually means an evolved high-mass star. Only the lower-mass stars become AGB stars.

Life Stages of a Low-Mass Star



Overview: Life Story of a Low-Mass Star

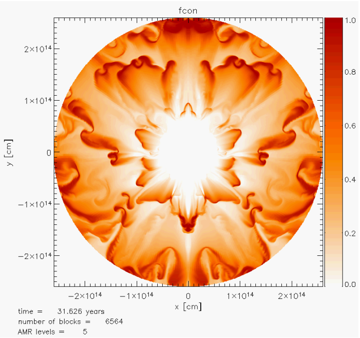


1. Main Sequence: H core-burning: H → He in core
2. Red Giant: H shell-burning: H → He outside the He core
3. Horizontal Branch: He → C in the core, H → He in shell
7. AGB or Double Shell Burning: H and He both fuse in shells, CO core becomes degenerate
5. Planetary Nebula lifts off, leaves white dwarf behind

10/23/12

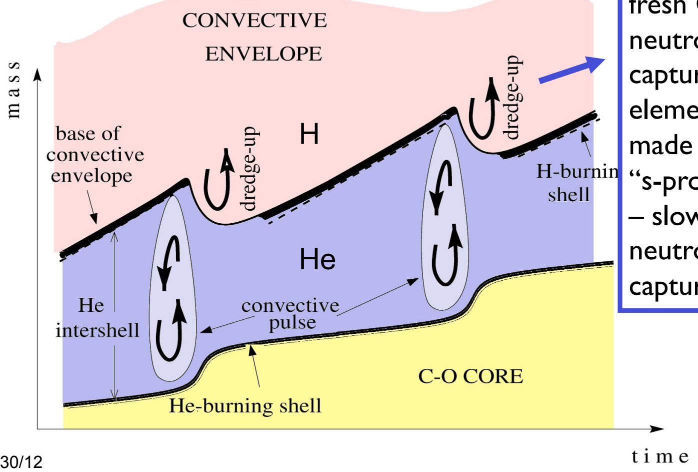
He-Shell Flashes and "Dredge-up"

- AGB stars are rather unstable.
- Every few thousand years, the He-burning shell flares up in brief nuclear runaways called He shell-flashes or *thermal pulses,* which release a burst of energy inside the star.
- With each flash, convection scoops or "dredges" C and other products up from core and transports it to surface.



10/30/12

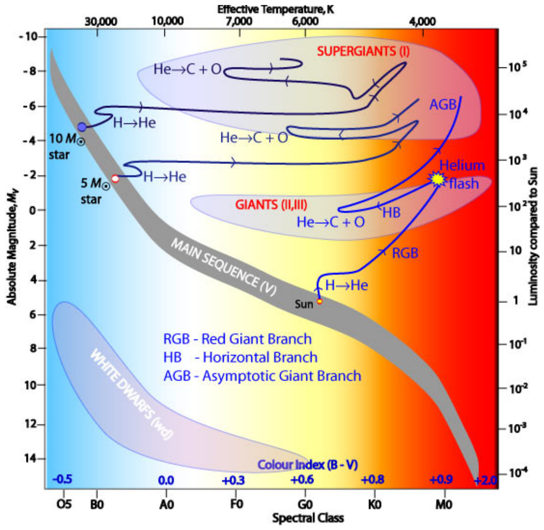
"Dredge-up" in AGB Stars



At the stellar surface: you see fresh C and neutron capture elements made by the "s-process" – slow neutron captures

10/30/12

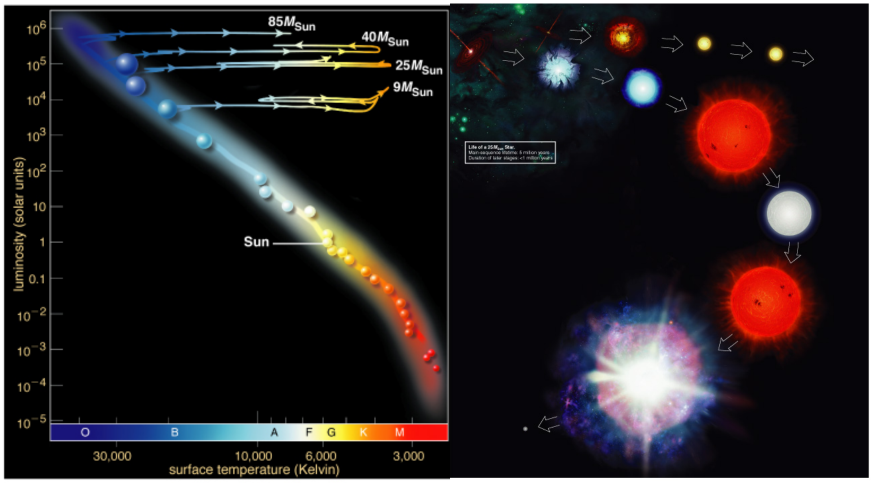
Evolutionary Tracks for Various Masses



Queries about High-Mass Stars

- "Do we need to know the specific shells in a high-mass star in order, e.g. Ne, Mg, Si?" No, just that they are the products of H-fusion, He (triple alpha), extra alpha additions, and eventually Fe.
- "Why does the core collapse when there is low pressure?" Stars fight a continual battle between gravity, which is directed inward, and pressure, which supplies an outward push to balance gravity. Stars will contract until the two forces are equal.
- "Explain photodisintegration and neutronization. How do they stop the collapse?" See slides from Oct. 25, and the following.

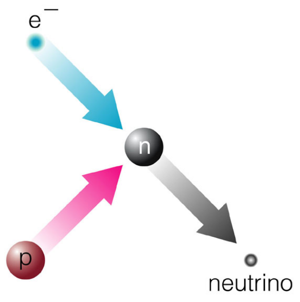
Life Cycle of a High-Mass Star



The "Iron Catastrophe"

- The non-degenerate iron core contracts & heats;
- No new energy-producing fusion reactions possible
- Instead, the nuclei *disintegrate*: Fe ⇒ He, p+, e^-, n's
- But this *uses up* energy, so the thermal pressure falls.
- When you take away the pressure support, gravity "wins" the eternal battle of the forces, and
- an even faster collapse takes place (0.25 sec)

Birth of a Neutron Star



A neutron star is the ball of neutrons left behind when the core of a massive star collapses, leading to a supernova explosion.

Deep in its collapsing core, the electrons and protons combine, making neutrons *and neutrinos*.

The neutrons collapse until the core is so dense that neutron degeneracy pressure stops the collapse; the core is then a ***neutron star.***

Queries about High-Mass Stars

- "Difference between regular neutron stars and pulsars? How do we see neutron stars that aren't pulsars?" Once a neutron star is formed, it remains a neutron star. If it starts out as a pulsar, emitting radio "blips," it will start losing steam over time: the rotation will gradually slow down (period gets long) and the magnetic field will get weaker, so eventually the radio beams will fade away. The neutron star is still a tiny, dense, hot object, so it will emit (some) X-rays and gamma rays, for example Geminga (see Nov. 1).
- "How do pulsars emit bursts? What comes out of the jets?" See the following slides.

Pulsars in a Nutshell

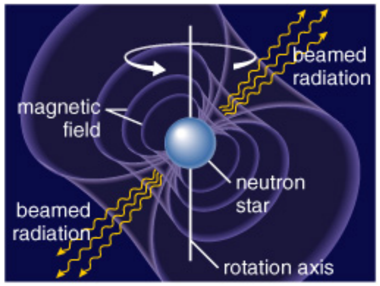
Pulsars are spinning neutron stars, formed by the core-collapse of a high-mass star going supernova.

What conditions must be met, in order for us to actually see pulses from a pulsar?

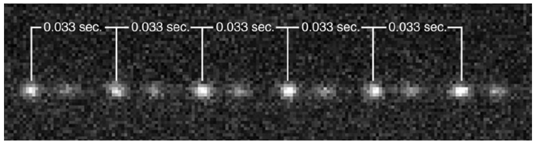
- It must be emitting in our direction at least some of the time (its beam must "cross" our direction)
–the spin axis must be different from the magnetic axis (that's true for the Earth!)
- It must not have lost most of its initial rotational and magnetic energy

---

The Lighthouse Model for Pulsars



When the beam is briefly pointed at us, the observers, we see a brighter star image than when it has swept past and points in a different direction. A time sequence of pictures looks like this:



For an animation, see the link below.

http://relativity.livingreviews.org/open?pubNo=lrr-1998-10&page=node3.html

Synchrotron Radiation is **Non-Thermal**

The electromagnetic radiation in the pulsar beams is ***not** thermal emission*. It has a different spectral shape from a blackbody, being very strong at radio wavelengths.

It *does* weaken with time, but not because of thermal cooling.

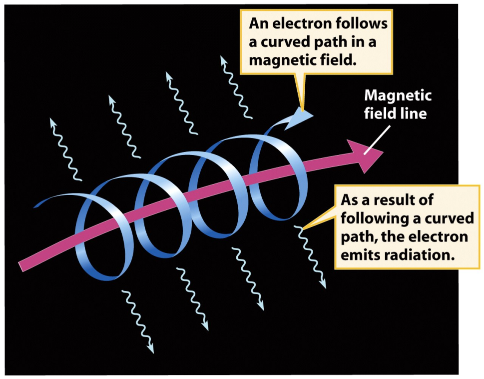


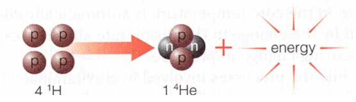
Figure 21-6a
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

Queries about Nucleosynthesis

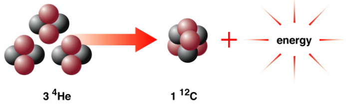
- "What is nucleosynthesis?" The creation of new elements from other, usually lighter ones.
- "What are the major nuclear reactions?"

  All Main Sequence stars fuse H to He, via the p-p chain or CNO cycle. Lower-mass stars continue to He fusion, the "triple-alpha" process, making C, O. Only the higher-mass stars continue with heavier even-numbered elements, up to Fe. The elements heavier than Fe are made by adding neutrons to pre-existing Fe nuclei. This happens in AGB stars via the slow or "s" process, or in supernovae via the rapid or "r" process. For more detail, see slides from Oct. 23.

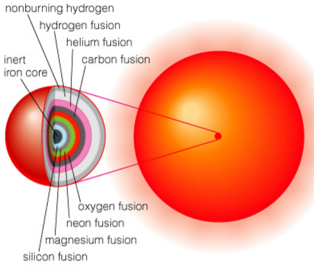
Synthesis of the Elements in Stars



H ⇒ He, Main Sequence phase



He ⇒ C, after first Red Giant phase

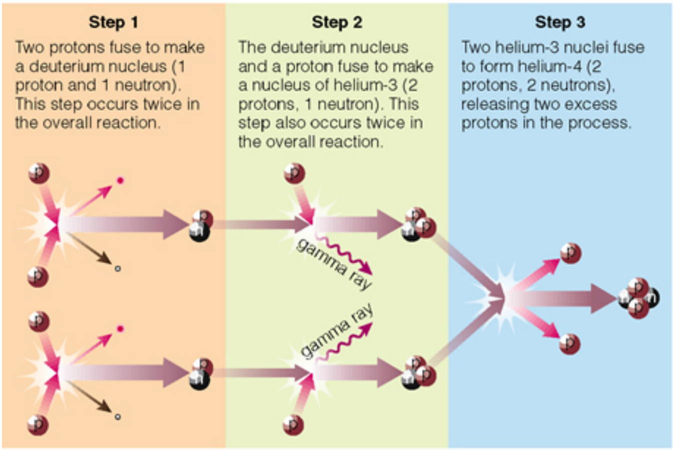


Stars with 8 or more solar masses produce many of the more common middle-weight elements such as O, Mg, Si, S, Fe

---

The "Main Highway" of H fusion (p-p I)

Hydrogen Fusion by the Proton–Proton Chain

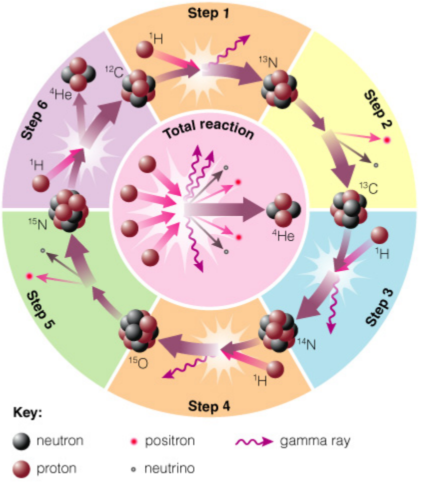


Step 1
Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

Step 2
The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

Step 3
Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

Alternate H-fusion method: CNO Cycle

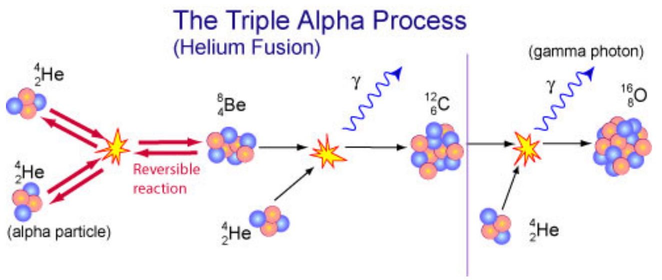


- Main Sequence stars of more than 1.5 $M_\odot$ fuse H into He using carbon as a *catalyst*, instead of through the familiar p-p reaction that happens in the Sun
- Higher core temperature enables nuclei to overcome the electric repulsion between the nuclei

---

He Fusion Reactions

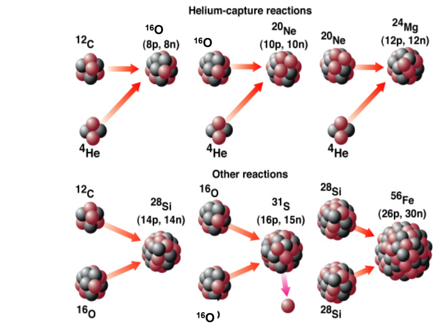
The next step, as in lower-mass stars, is the fusion of He into C (and sometimes on to O):



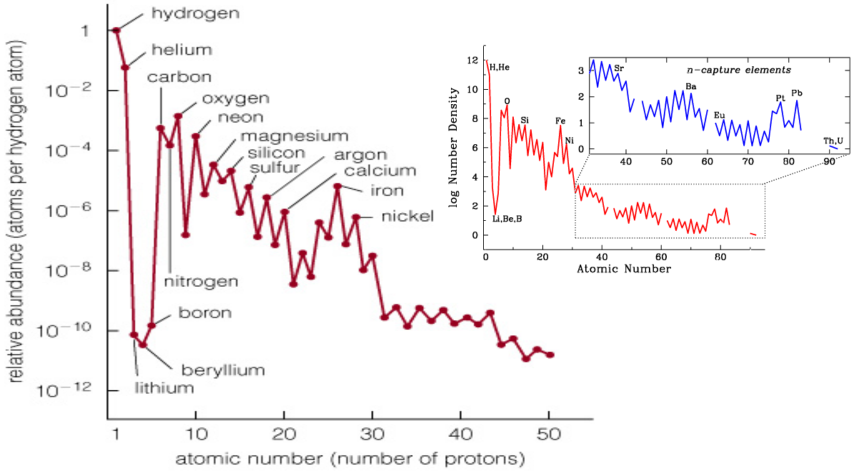
Later-Stage Nuclear Reactions in Stars

When a star with high enough mass exhausts its He fuel:

- It has sufficient gravitational energy to reach 6 x 10^8 K.
- This enables fusion reactions among even more highly charged nuclei to occur.
- The nuclei involved are mostly multiples of He:
- O ⇒ Ne ⇒ Mg ⇒ Si ⇒ Fe

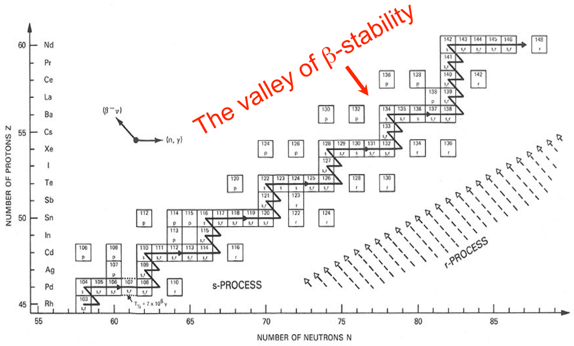


Nuclei beyond the Fe-peak are made by neutron-capture reactions



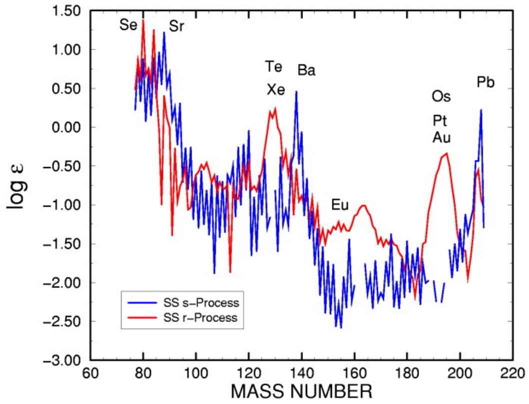
Two Neutron-Capture Reactions: fast vs. slow

- In the slow or “*s*-process,” neutrons are captured one at a time, followed by a “beta decay” which changes the element
- The rapid or “*r*-process” floods the pre-existing nuclei (mainly Fe) with neutrons, making neutron-rich isotopes



Trans-Iron Elements in the Solar System

About half the nuclei in the Solar Sytem heavier than iron came from the slow, or s-process in AGB stars, the other half the rapid, r-process from supernovae



Truran, Cowan, Pilachowski & Sneden PASP (2002)

Other Questions

- “What are the mass limits on white dwarfs, neutron stars, etc.?” See next slide for a summary table about compact stars – the cores of old stars. Try adding other objects to this table, e.g. brown dwarfs, Main Sequence stars, etc.
- “Which examples of individual objects do we need to know?” Objects discussed in detail, with 2 or more slides, are ones you should be familiar with. For example: the Crab Nebula, SN 1987A, Eta Carinae, 51 Peg b (the first exoplanet around a normal star).

Types of “Compact Objects”

Object	Supported by	Comes from	Made of	Approx. Radius	Maximum Mass*
White Dwarf	electron degeneracy pressure	AGB giant	C & O; free electrons	R_{earth} = 0.01 $R_\odot$	1.4 $M_\odot$
Neutron Star	neutron degeneracy pressure	core-collapse supernova	neutrons	10 – 12 km (small city)	2 – 3 $M_\odot$
Black Hole	not supported!	Gamma-ray burst?	mass	3 km x M in $M_\odot$	no limit

*There are no minimum masses, though nature seems to like to make 0.5 $M_\odot$ white dwarfs and ≈1.5 $M_\odot$ neutron stars.