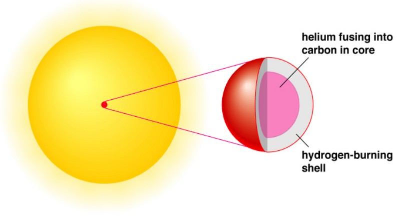
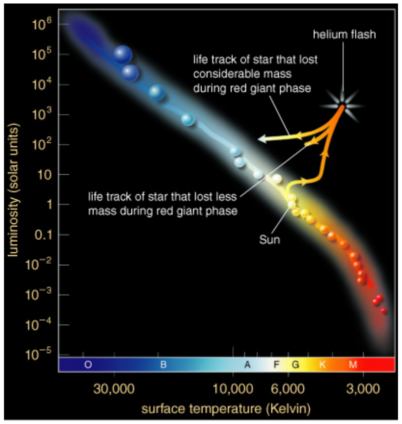
Agenda for Ast 309N, Oct. 23

- Evolution of low-mass stars, continued
- Synthesis of the elements in stars
- Video excerpt, Tyson's "Forged in the Stars"
- Planetary Nebulae and White Dwarfs
- Participation card
- Reading:
    - Kaler, pp. 145-155 (today), ch.6 (Thursday)
    - Wheeler, ch. 6.1 – 6.5 (Thursday)

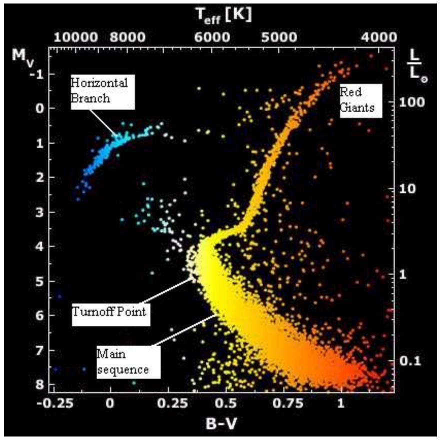
Core Helium-Burning Stage

When He fusion begins in the core, the star becomes smaller and hotter - moves onto what we call the 'horizontal branch.'





The Horizontal Branch in Clusters



- Old star clusters (globular clusters) show low-mass stars in late stages of their evolution
- Helium-burning stars are found on a *horizontal branch* that extends quite far to the blue of the red giants

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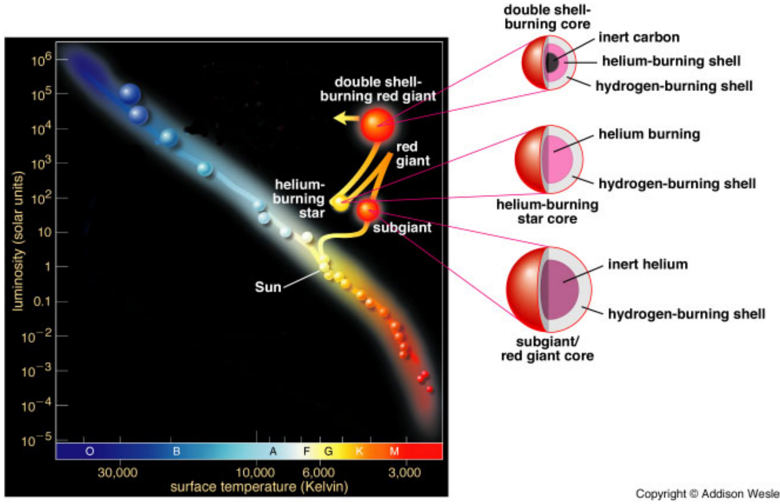
He-Core Exhaustion: The Asymptotic Giant Branch ("AGB" Star)

When all the He is used up in the core, the core begins contracting again, which heats it up, causing He fusion to occur in a shell above the core.

This is the "double shell-burning" phase, which has an inner He-burning and and outer H-burning shell.

This is called the "Asymptotic Giant Branch." The star becomes even cooler, larger (in diameter), and more luminous. Its path in the HR Diagram asymptotically approaches the red giant branch.

Second Red Giant Phase: AGB or Double Shell-Burning Star



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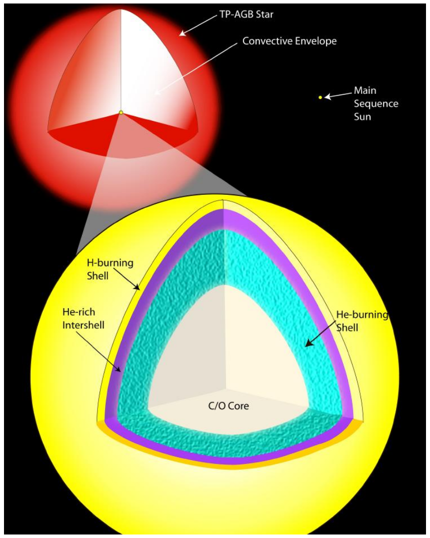
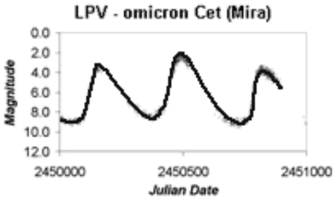
Interior of an AGB Giant Star

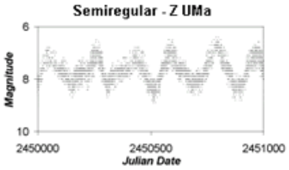
AGB stars have tiny, dense cores and vast, distended outer layers (called the "envelope").

Their internal composition is complex, due to previous nuclear reactions.



AGB Giants as Variable Stars





AGB stars have a tendency to *pulsate:* they alternately swell up and contract with periods of 1 – 2 years.

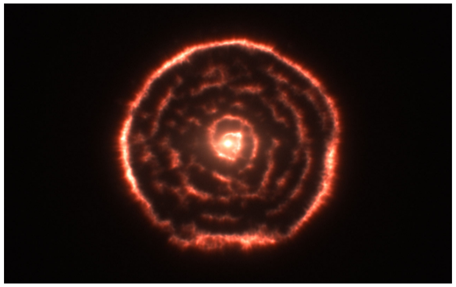
The most famous example is Mira, the "wonderful." At maximum brightness it can be seen with the naked eye but at minimum it fades below visibility.

Dust Formation and Mass Loss

- The outer layers of the AGB star are sufficiently cool and clumpy that certain elements start condensing into small solid particles called "dust grains."
- Stars in which C > O produce carbon dust of various forms: graphite, soot, amorphous carbon.
- Stars in which C < O make silicate flakes (like rocks on the Earth).
- These will eventually be expelled into space, where they cause extinction and reddening of starlight; they also form the "seeds" of future planets.

Stellar Winds and Mass Loss

- The outer layers swell and contract, and mass starts leaking away in a flow called a “stellar wind.”
- Once dust forms, the flow becomes a “superwind.”
- Example: R Sculptoris, imaged with the new ALMA telescope http://www.eso.org/public/news/eso1239



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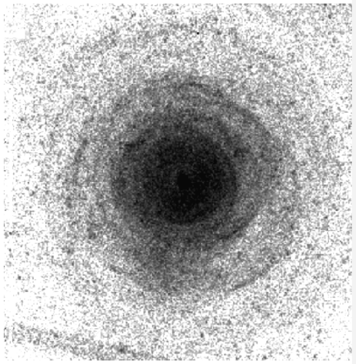
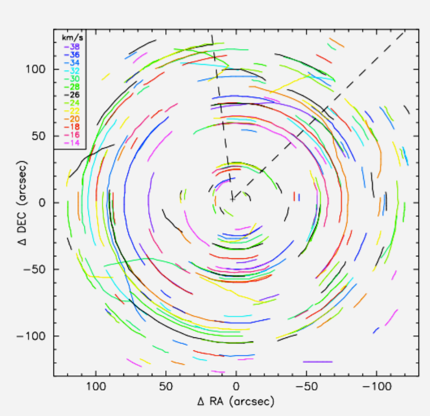
IRC+10216: A C-rich AGB Star

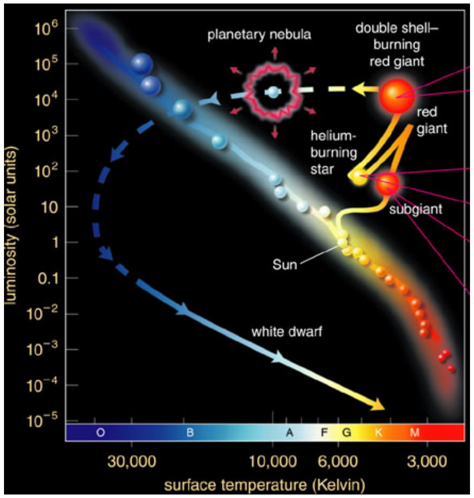
Dust Shells in Scattered Light
(Mauron & Huggins 1999)



CO “Arcs” (distinct velocities)
(D. Fong, APN3)



The Final Gasps of a Low-Mass Star



The AGB giant phase ends when most of the envelope is removed, revealing the hotter layers deep in the star’s interior. Everything except the core is expelled in an outflow, at first in a wind, later as a planetary nebula.

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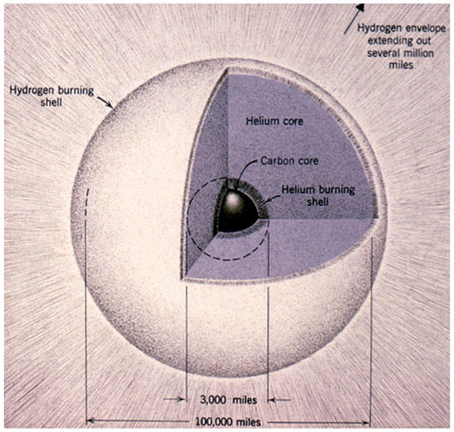
The White Dwarf in the AGB Giant



The structure of a star in the helium-burning phase

The core (composed of C and O made by earlier reactions) contracts to high density, essentially building a white dwarf in the middle of the star. The core is supported by electron degeneracy pressure, which prevents it from contracting any further.

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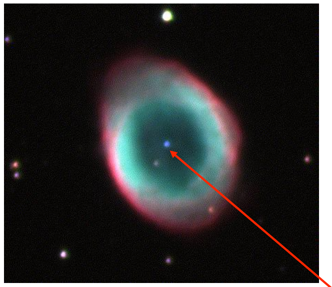
From Red Giant to White Dwarf



The nebula of hot gas is the cast-off outer layers of the former AGB star, ionized by the central star

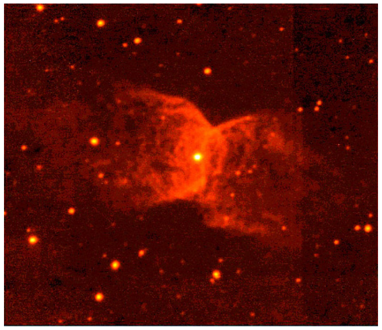
The small, hot central star is a “pre-white dwarf,” which is the nearly degenerate stellar core

The collapsing Carbon core becomes a White Dwarf

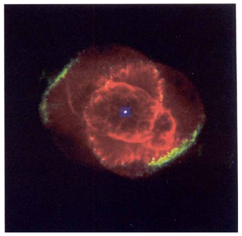
Planetary Nebula Morphologies

What shape would you expect for a planetary nebula?

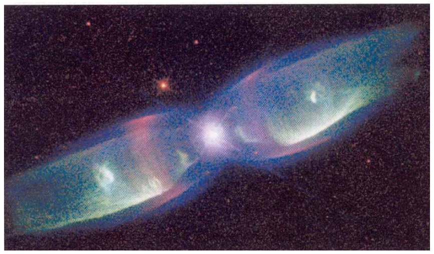
Many have very different shapes, such as “butterfly” morphologies.



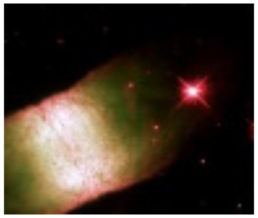
Gallery of Planetary Nebulae



Cat’s Eye Nebula



Twin Jet Nebula



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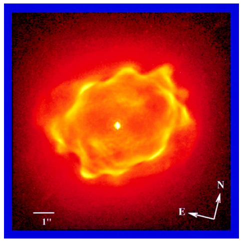
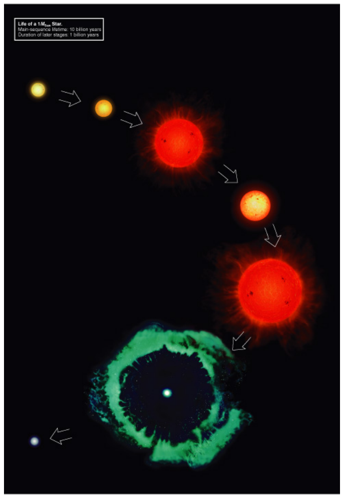


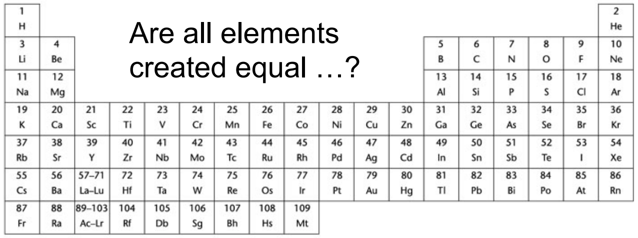
Henize 2-138

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. He Core Burning: He → C in the core, H → He in shell
7. Double Shell Burning: H and He both fuse in shells, core becomes degenerate
5. Planetary Nebula lifts off, leaves white dwarf behind

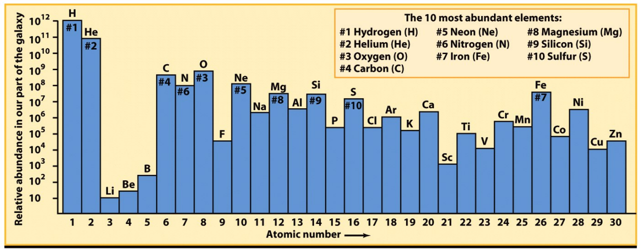
Two Views of the Elements



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57–71 La–Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89–103 Ac–Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									

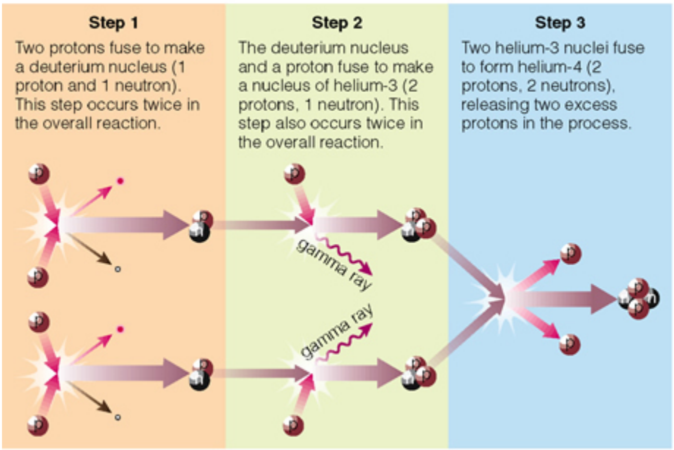
Are all elements
created equal …?

Some elements are more common than others.



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.

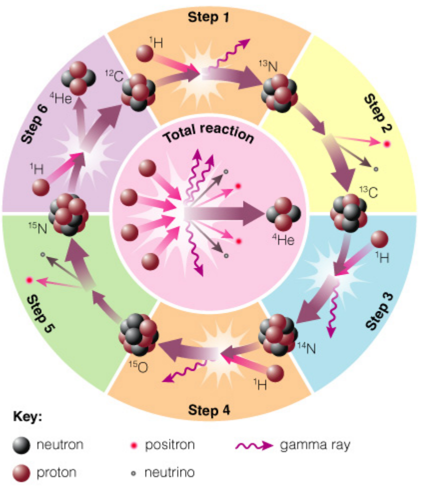
Step 2

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

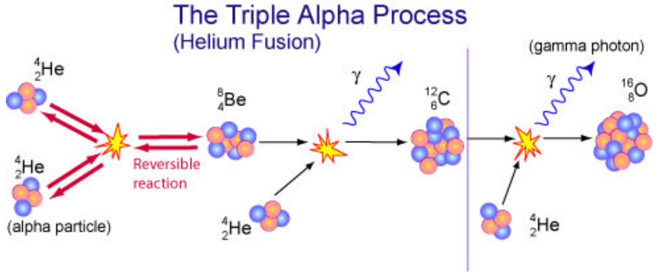


- Main Sequence stars of more than 1.5 $M_\odot$ fuse H into He using carbon as a *catalyst*, instead of through the familiar p-p reaction that happens in the Sun
- Higher core temperature enables nuclei to overcome the electric repulsion between the nuclei

What else does this require, besides a high temperature?

He Fusion Reactions

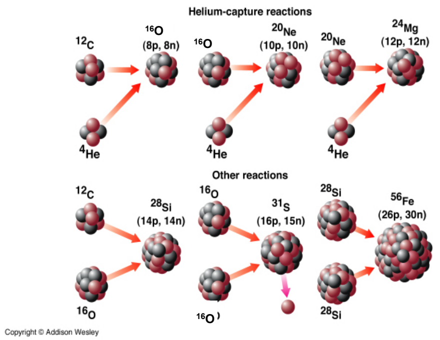
The next step, as in lower-mass stars, is the fusion of He into C (and sometimes on to O):



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



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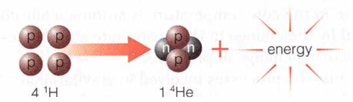
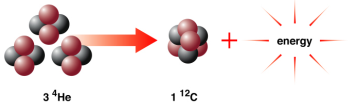
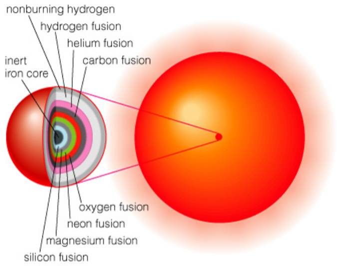
Synthesis of the Elements in Stars



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

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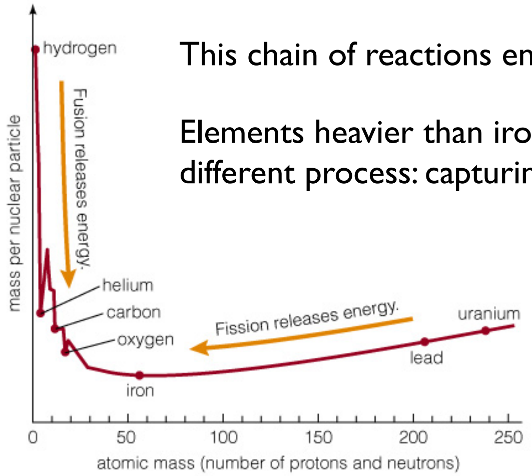
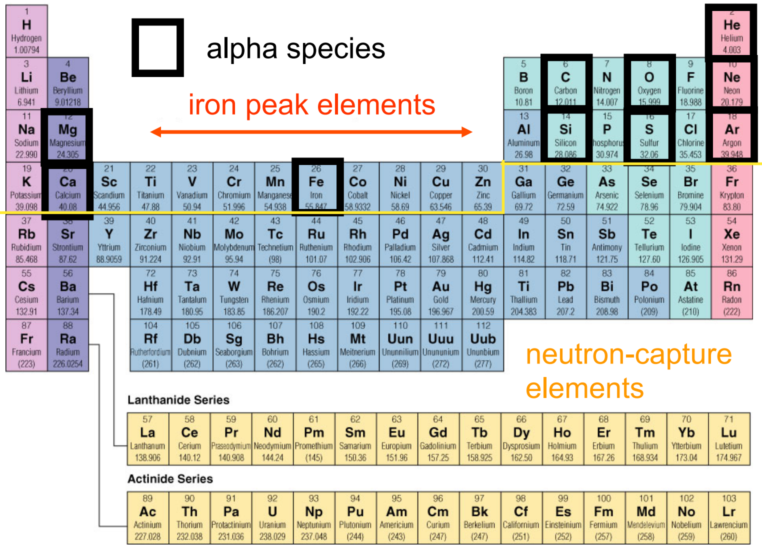
Iron is a "Dead End" for Standard Fusion (Charged-Nuclei Reactions)



This chain of reactions ends with Fe.

Elements heavier than iron are made by a different process: capturing neutrons.

Products of Stellar Nucleosynthesis

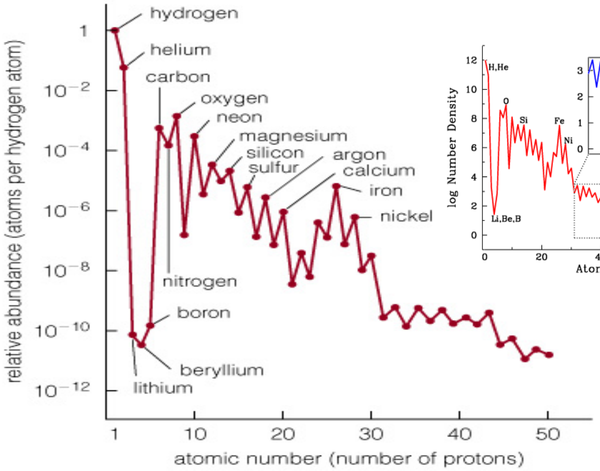


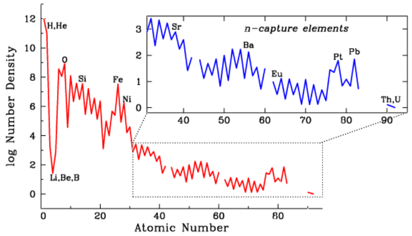
alpha species

iron peak elements

neutron-capture elements

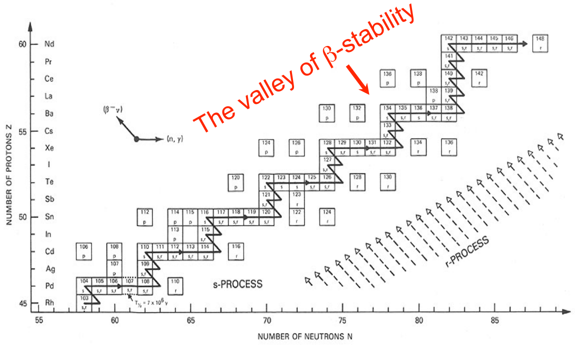
Nuclei beyond the Fe-peak are made by neutron-capture reactions





Two Neutron-Capture Reactions: fast vs. slow

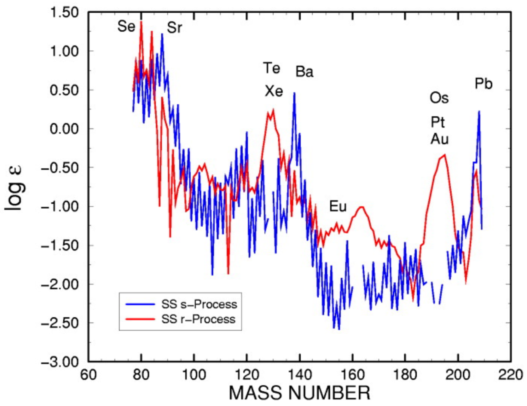
- In the slow or "*s*-process," neutrons are captured one at a time, followed by a "beta decay" which changes the element
- The rapid or "*r*-process" floods the pre-existing nuclei (mainly Fe) with neutrons, making neutron-rich isotopes



The valley of β-stability

Trans-Iron Elements in the Solar System

About half the nuclei heavier than iron in the Solar System came from AGB stars, the other half from supernovae



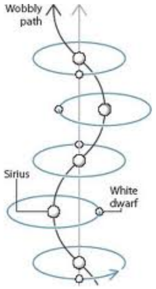
Truran, Cowan, Pilachowski & Sneden PASP (2002)

Stellar Recycling and Element Enrichment

- Stars make heavy elements.
- They send them into space in:
  - stellar winds (from red giants)
  - planetary nebulae
  - supernova explosions

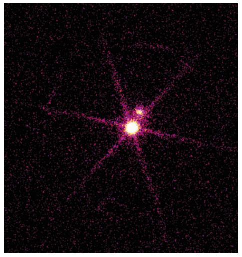
- Lower-mass stars make C, N, He, and some trans-iron elements.
- High-mass stars make O and other "alpha" nuclei, iron & heavier elements.

The Discovery of White Dwarfs

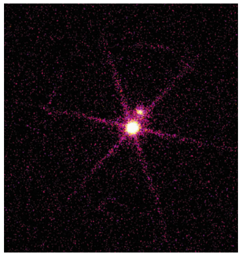


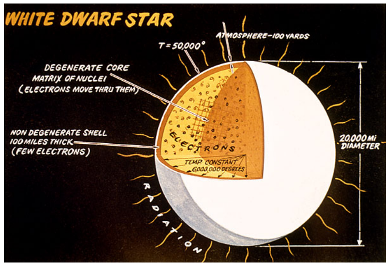
- In 1844, Bessel noticed the strange motions of a couple of the brightest stars in the sky: Sirius and Procyon.
- This was an early example of "dark matter": something that had gravity but no light.
- Telescope maker Alvan Clark was able to resolve Sirius A and B; dim but not dark!

- Sirius A is 800 X brighter than B, yet they have the same temperature.
- Sirius B is a "white dwarf."
- This discovery was 150 years ago!



White Dwarfs: Stellar Embers





- White dwarfs are the leftover cores of (lower-mass) stars that have finished their Main Sequence and giant phases
- Electron degeneracy pressure supports white dwarfs against gravity: they cannot contract
- They no longer generate energy by fusion reactions
- So they just sit there, radiate, and cool, but cannot contract due to degeneracy pressure

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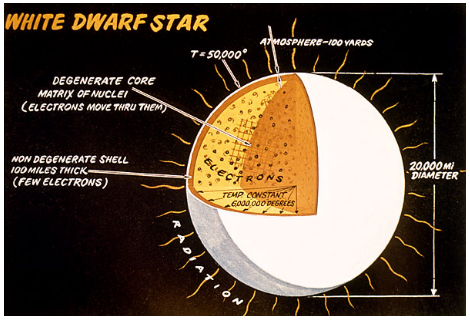
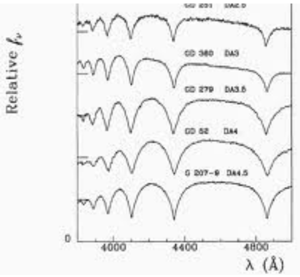
White Dwarfs: Structure

- The electrons are degenerate and support the star.
- The nuclei are *not* degenerate, so they they lose thermal energy as the star radiates away its stored heat.



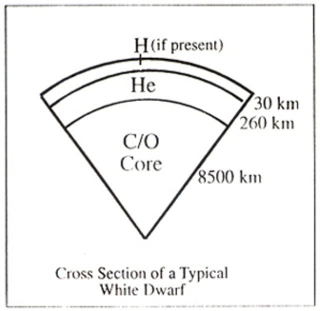
Eventually, the nuclei "crystallize" – the white dwarf really is "like a diamond in the sky"

White Dwarfs: Surface Layers



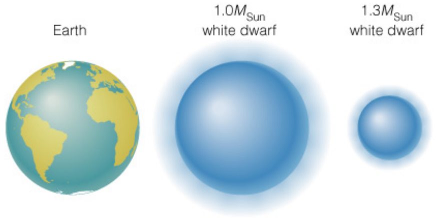
Kaler calls these "weird atmospheres." Spectral types DA (strong H lines), DBs show He lines, etc.

Unusual conditions allow a new effect to operate: gravitational "settling." Because of the strong surface gravity and calm conditions, *heavier species actually sink* towards the interior



Cross Section of a Typical White Dwarf

White Dwarf *Inverse* Mass-Radius Relation

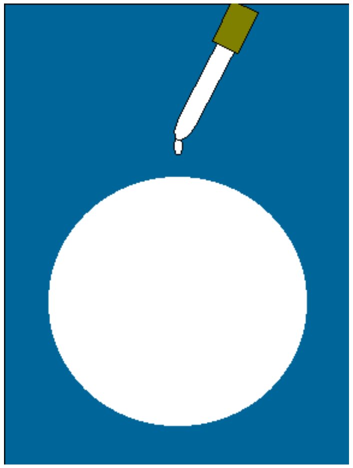


White dwarfs of 1 solar mass are about the same size as the Earth, but degenerate stars obey an inverse mass-radius relation: thus, higher-mass white dwarfs are actually *smaller*.

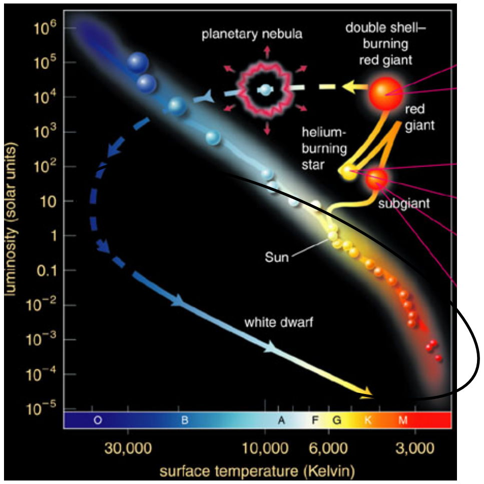
Maximum Mass of a White Dwarf

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.
- As a white dwarf's mass approaches $1.4M_\odot$, its electrons must move at nearly the speed of light.
- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_\odot$.
- This is the maximum mass that a white dwarf can have, and is called the *Chandrasekhar limit*.

Maximum Mass of a White Dwarf



White Dwarf Cooling Tracks



This summarizes the evolutionary track that eventually produced a white dwarf.

Once the rest of the star's mass has been removed, the white dwarf cools off and grows dimmer with time, sliding down along a line of constant radius in the H-R diagram.