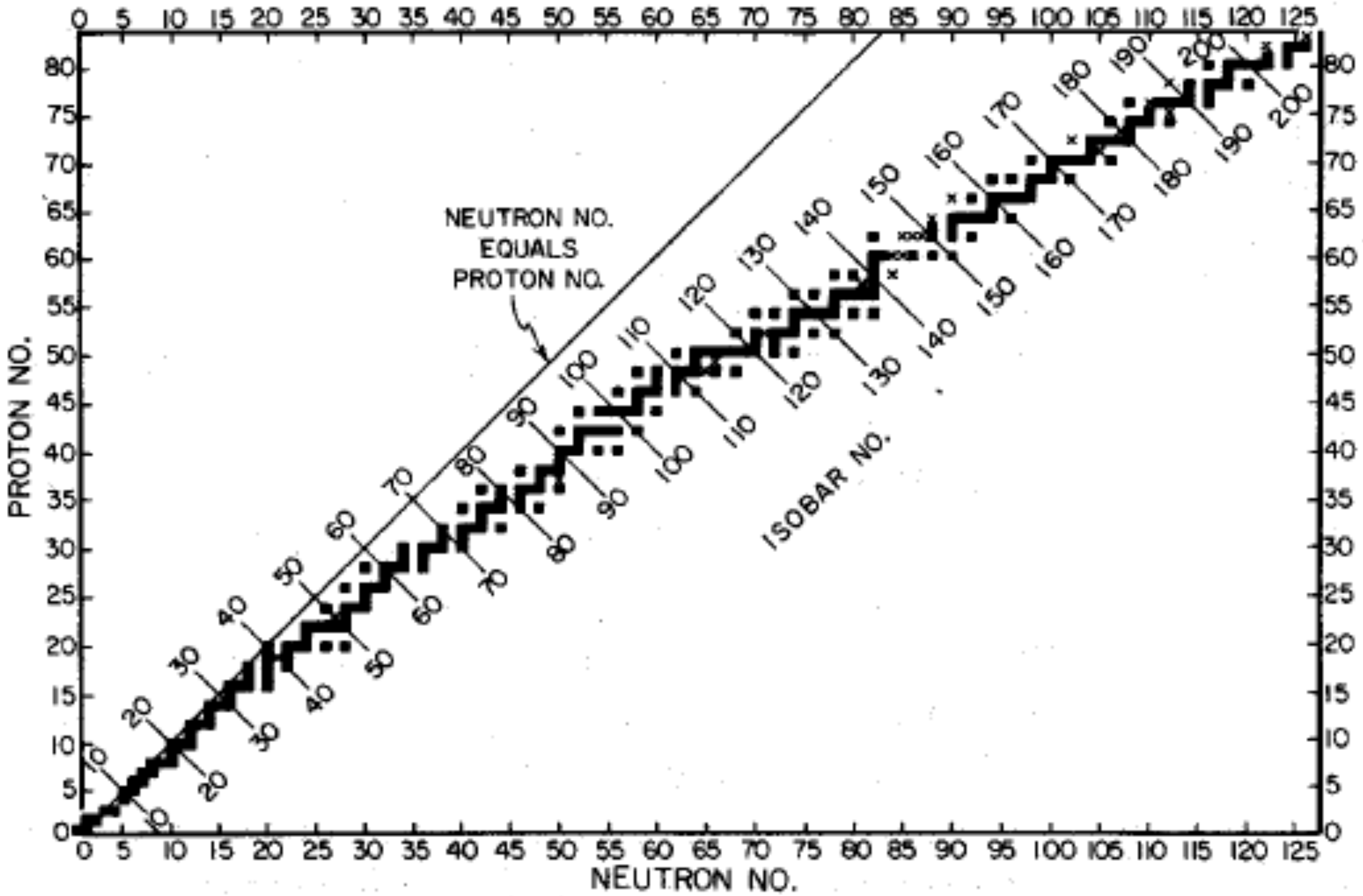
Nuclear Fusion in Stars

…and other processes that lead to the formation of the heavier elements

Where did all these elements come from?



Review…

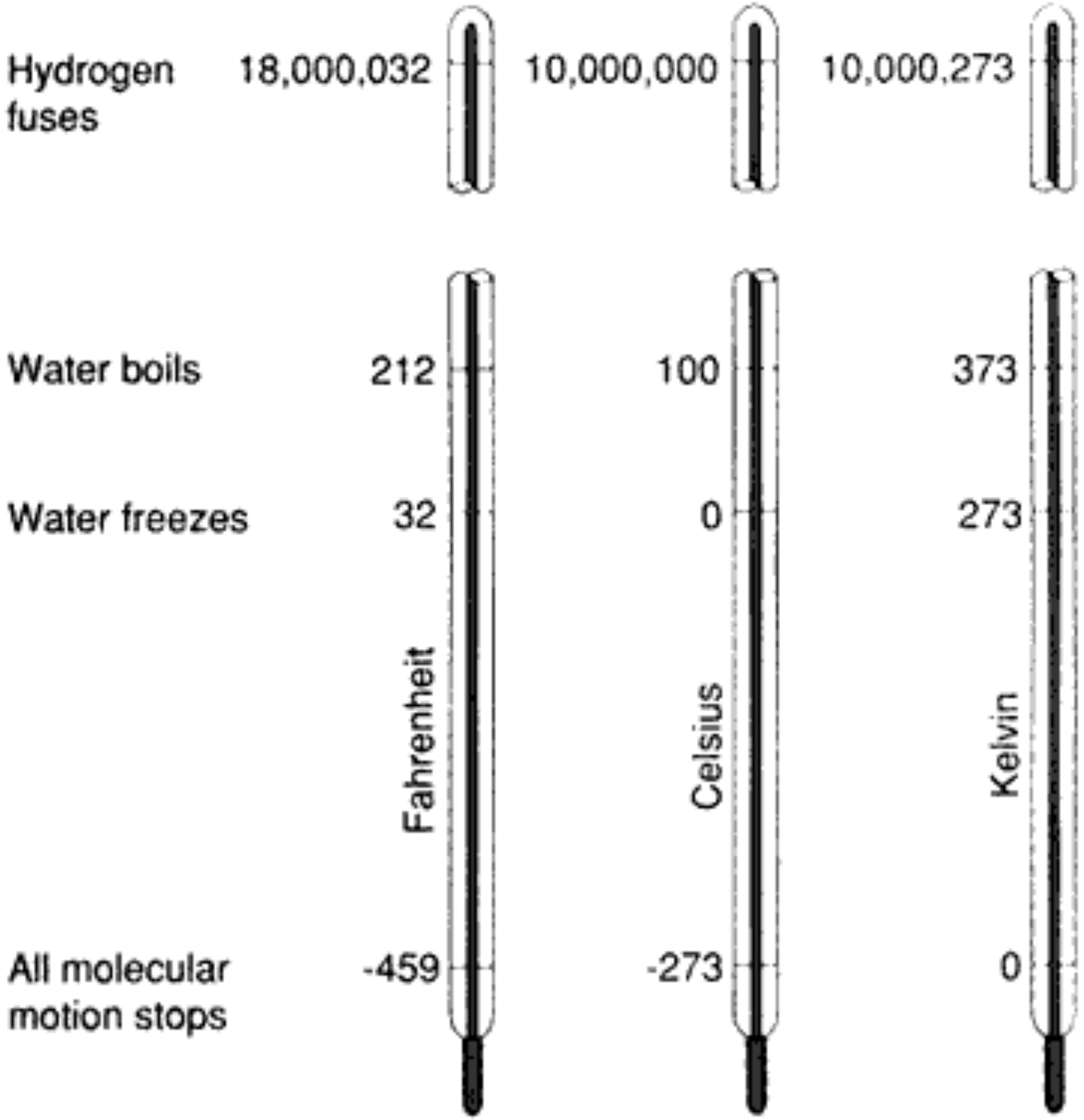
- Nuclear strong force holds nuclei together (works less well for larger nuclei)
- Nuclear weak force governs the n $\leftrightarrow$ $p^+ + e^-$ interconversion (~equal p^+ and e^-)
- "Coulomb" force (electrostatic): More and more important for heavier elements (more proton-proton repulsion)
- Tends toward more neutrons than protons at high mass

Why should geologists understand?

- The relative abundance of different elements and isotopes provides strong clues as to the origins of the elements and the solar system, which has direct bearing right down to our natural resources (not much Uranium and Gold relative to oxygen and carbon).
- Understanding “nucleosynthesis” also helps us understand Earth history (Faint Young Sun)

Nuclear Fusion Needs…

- Fuel (say, hydrogen – but other elements too)
- Extremely high temperature (overcome proton-proton repulsion)
- Extremely high pressure (lots of particles in a small volume, increases collisions per time)


Hydrogen fuses
18,000,032
10,000,000
10,000.273
Water boils
212
100
373
Water freezes
32
0
273
Fahrenheit
Celsius
Kelvin
All molecular motion stops
-459
-273
0

Fuel in our Sun

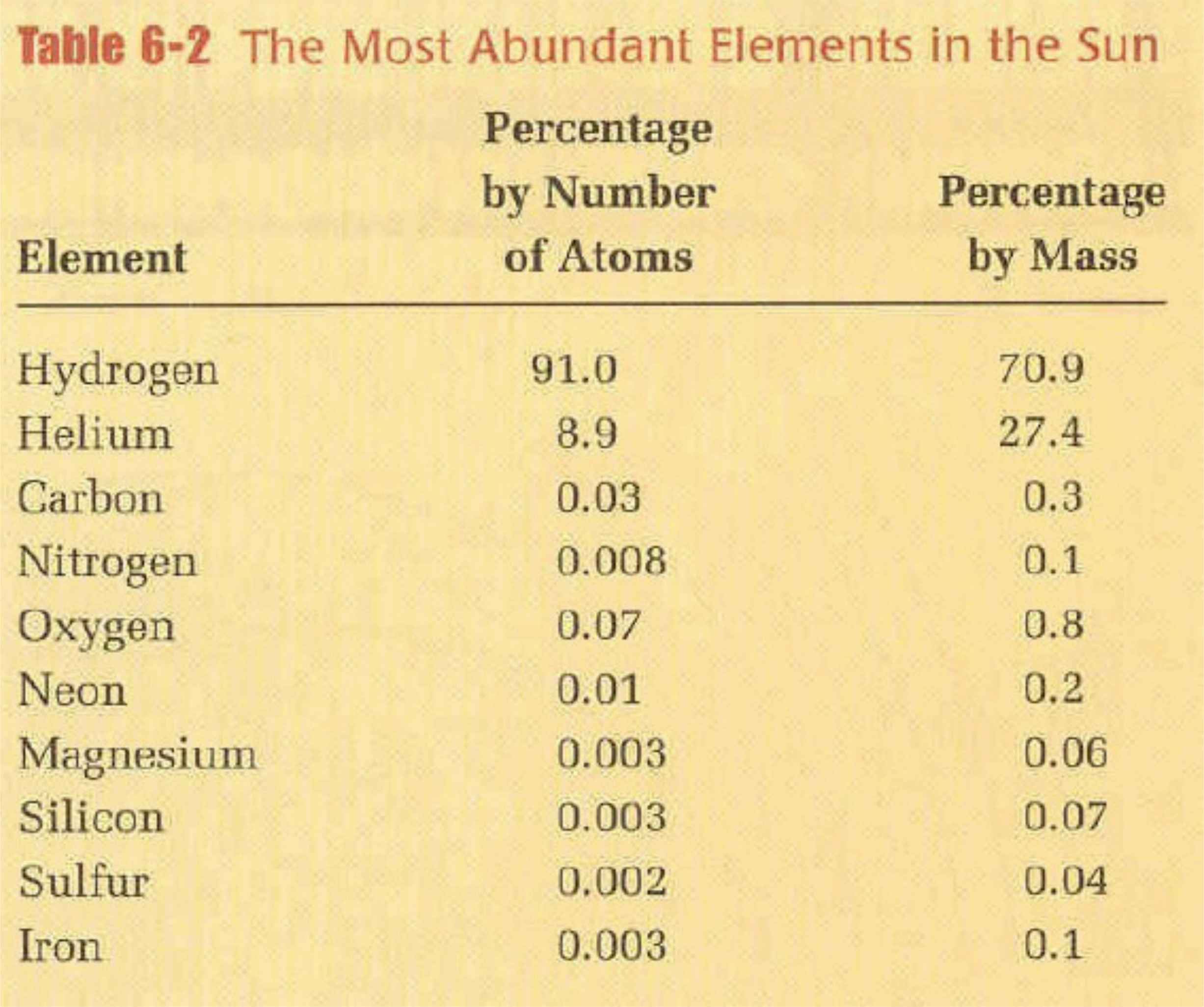
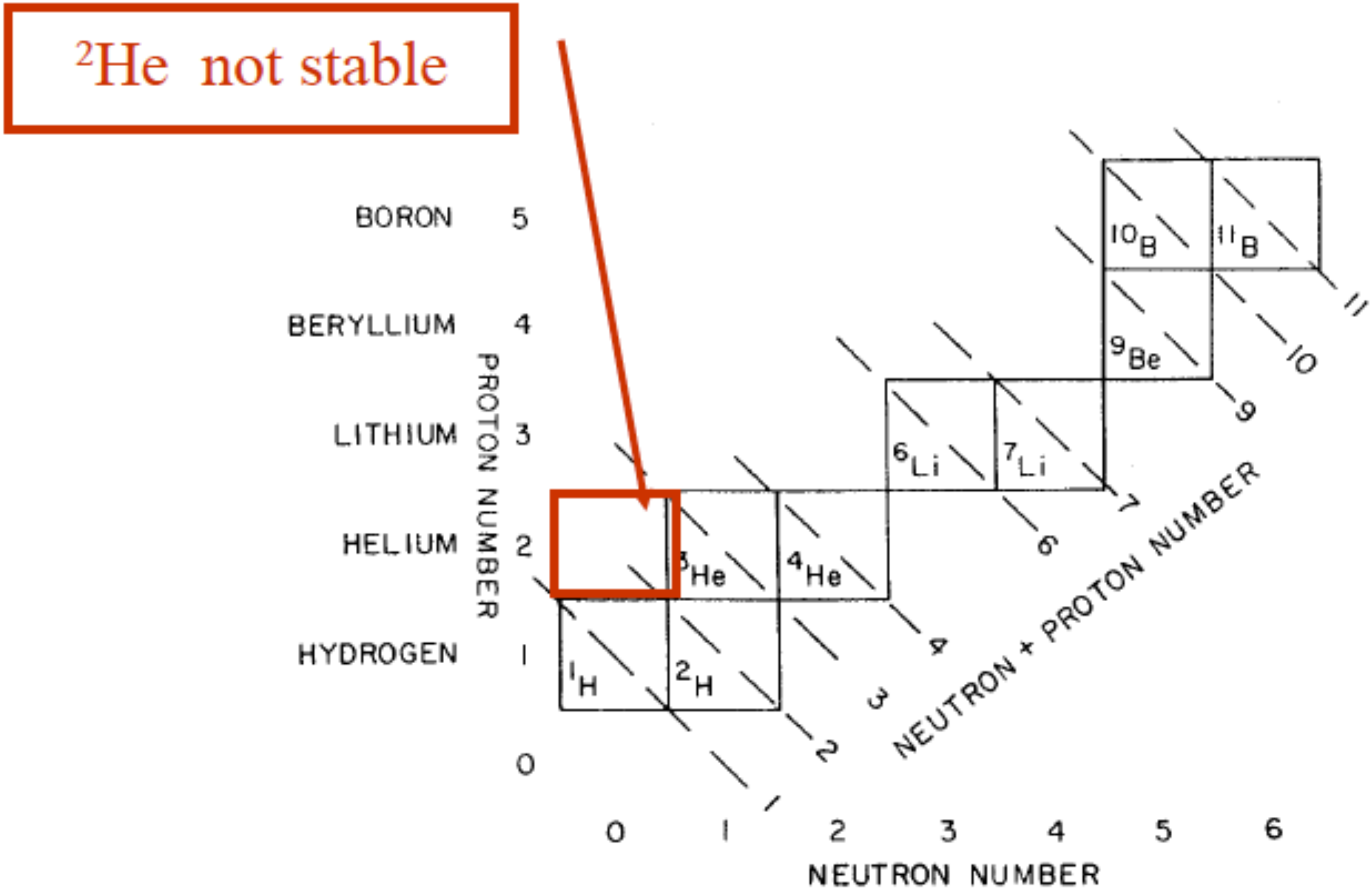


Table 6-2 The Most Abundant Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.1

From : Horizons, by Seeds

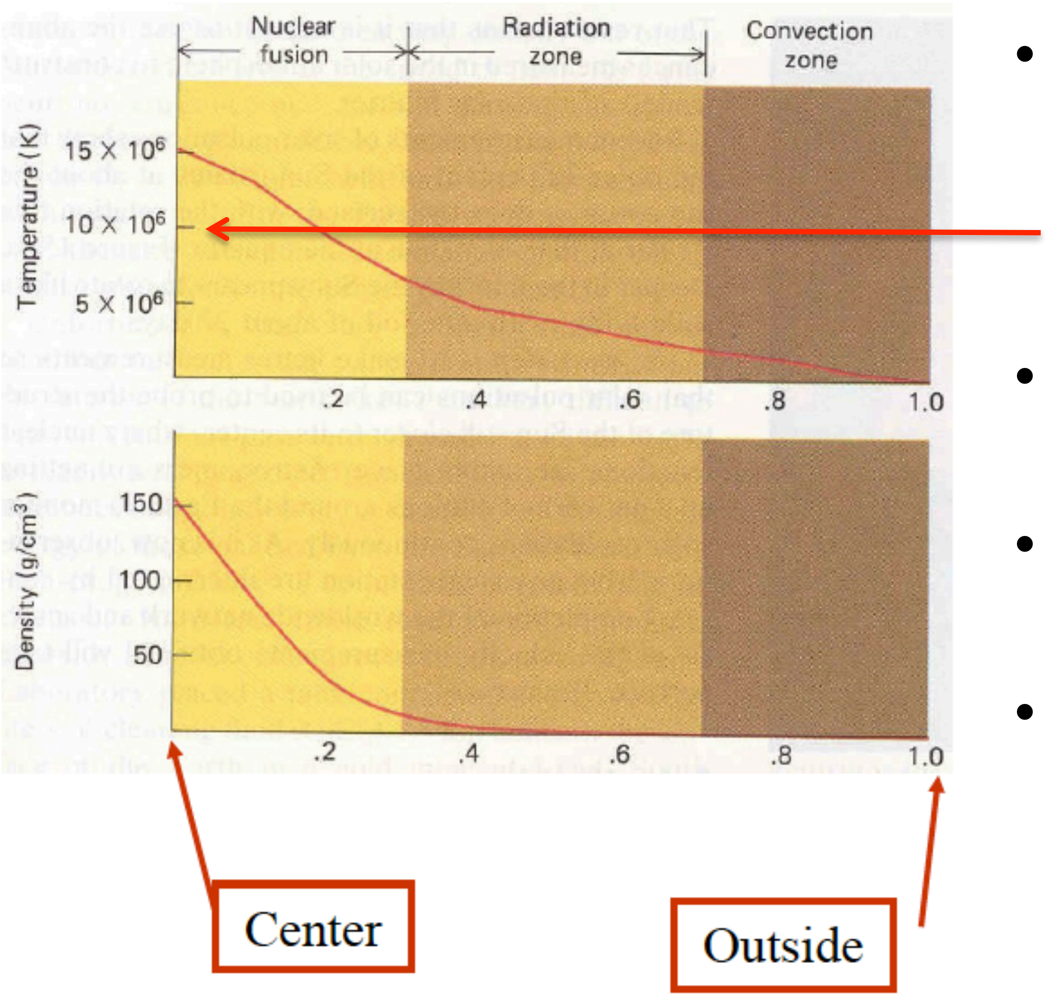
- Put two protons together, they tend to fly apart (fusion isn't so easy!):



Constraints on Fusion

- ^{4}He and ^{3}He are stable because neutrons provide extra Strong Force to hold protons together
- Hydrogen bombs and controlled fusion experiments use ^{2}H and ^{3}H as fuel because they already have needed neutrons
- In our Sun, however, ^{2}H was used up long ago, so **fusion must proceed using ^{1}H as fuel**

Temperature and density profiles of Sun



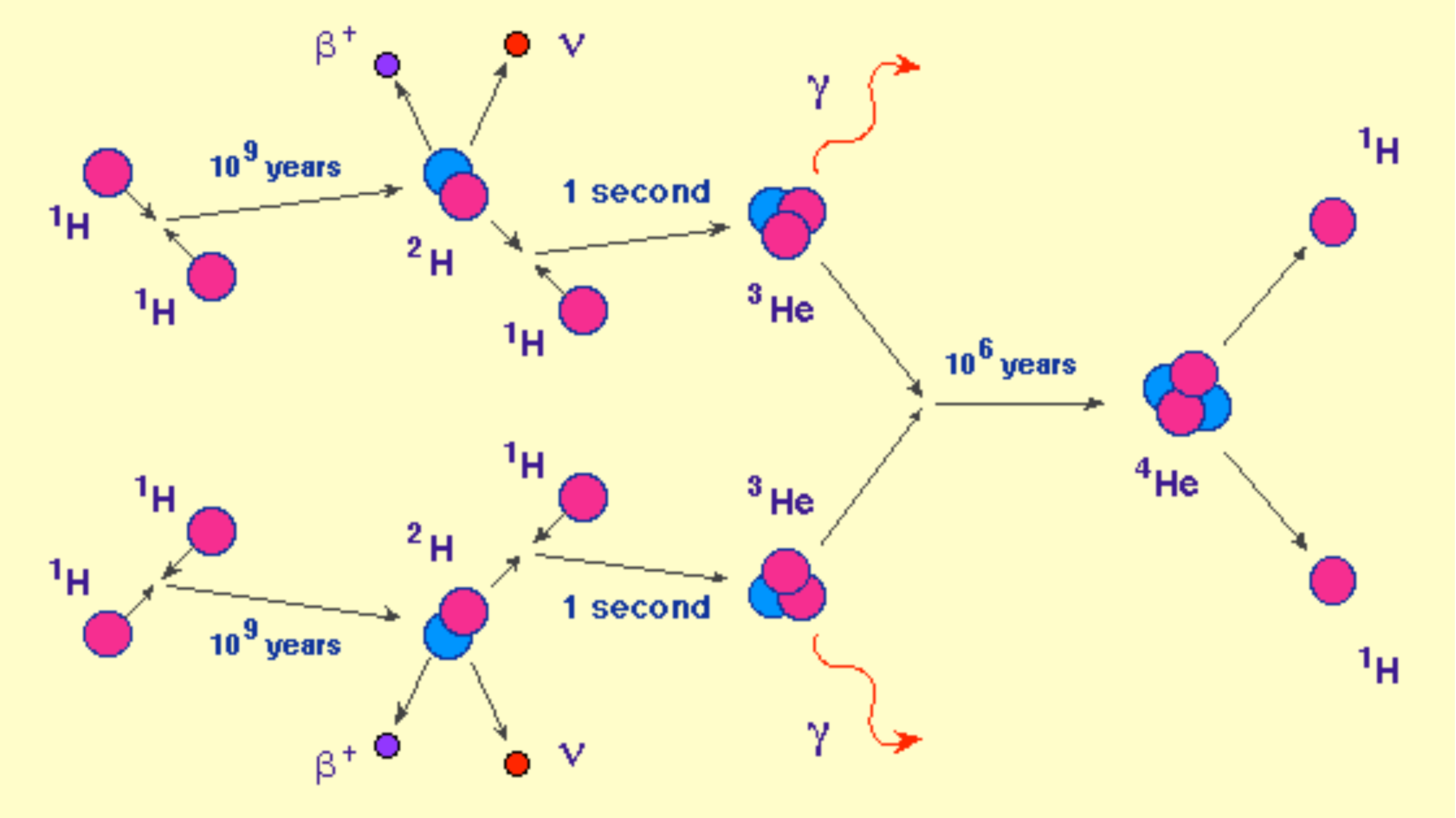
From Realm of the Universe by Abell et al.

- Fusion only in core of Sun (>10^7 K so ^{1}H nuclei collide with enough force to overcome repulsion
- Most of Sun is insulation for central fusion
- The part of the outer Sun we see is “only” ~ 5,800K
- Sun is GAS throughout (ionized gas, plasma) but with high density in the core (~150 g/cm^3)

Fusion is slow…

- To make ^{1}H fusion work, we need to luck out and get two ^{1}H nuclei to fuse to ^{2}He
- ^{2}He is not very stable, reverts to ^{1}H
- …SO: we also need the weak force to turn a proton into a neutron to make ^{2}H almost simultaneously with ^{2}He formation.
- Once we have ^{2}H, we can make ^{4}He comparatively easily
- This is a comparatively rare event, limits fusion rate

- $^{2}H + {}^{1}H \rightarrow {}^{3}He$ $(p^{+}n + p^{+} \rightarrow p^{+}p^{+}n)$
- $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2{}^{1}H$
- The net effect is: $4{}^{1}H \rightarrow {}^{4}He$



Accounting: $E = mc^2$

- 6.693×10^{-27} kg (4 ^{1}H) - 6.645×10^{-27} kg (1 ^{4}He) = 0.048×10^{-27} kg of mass lost!
- $E = mc^2 = (0.048 \times 10^{-27}\ \mathrm{kg})(3 \times 10^{8}\ \mathrm{m/s})^2 = 0.43 \times 10^{-11}\ \mathrm{kgm^2/s^2}$ (Joules)
- The energy to ionize H (to make H^+ ion) is only 2.2×10^{-18} Joules
- 2 million times more energy from fusion than from chemistry involving hydrogen atoms!

How long will the Sun last?

- Sun power: 3.8 x 10^{26} Watts (Joules/second)

$$4H/He \times \frac{3.8 \times 10^{26} J/s}{4.3 \times 10^{-12} J/He} = 3.5 \times 10^{38} \text{ H atoms/second}$$

$$\frac{Mass_{Sun}}{m_H} = \frac{2x10^{30} kg}{1.67x10^{-27} kg/H} = 1.2x10^{57} \text{ H atoms}$$

$$\frac{1.2 \times 10^{57} Hatoms}{3.5 \times 10^{38} Hatoms/s} = 3.4 \times 10^{18} s = 110 billionyears$$

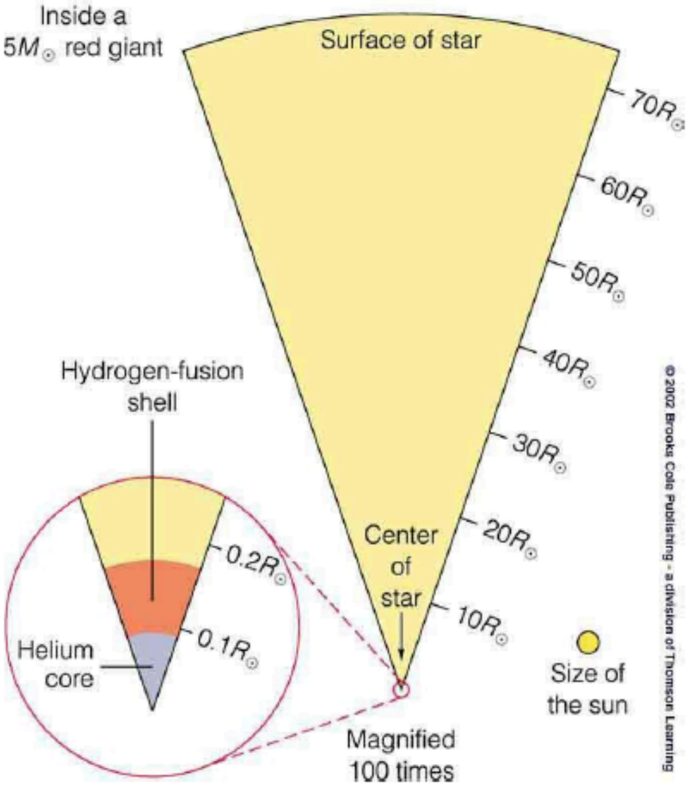
- In reality, only atoms near the core are available, so really only about 10 billion years of solar lifetime

What happens when H runs out?

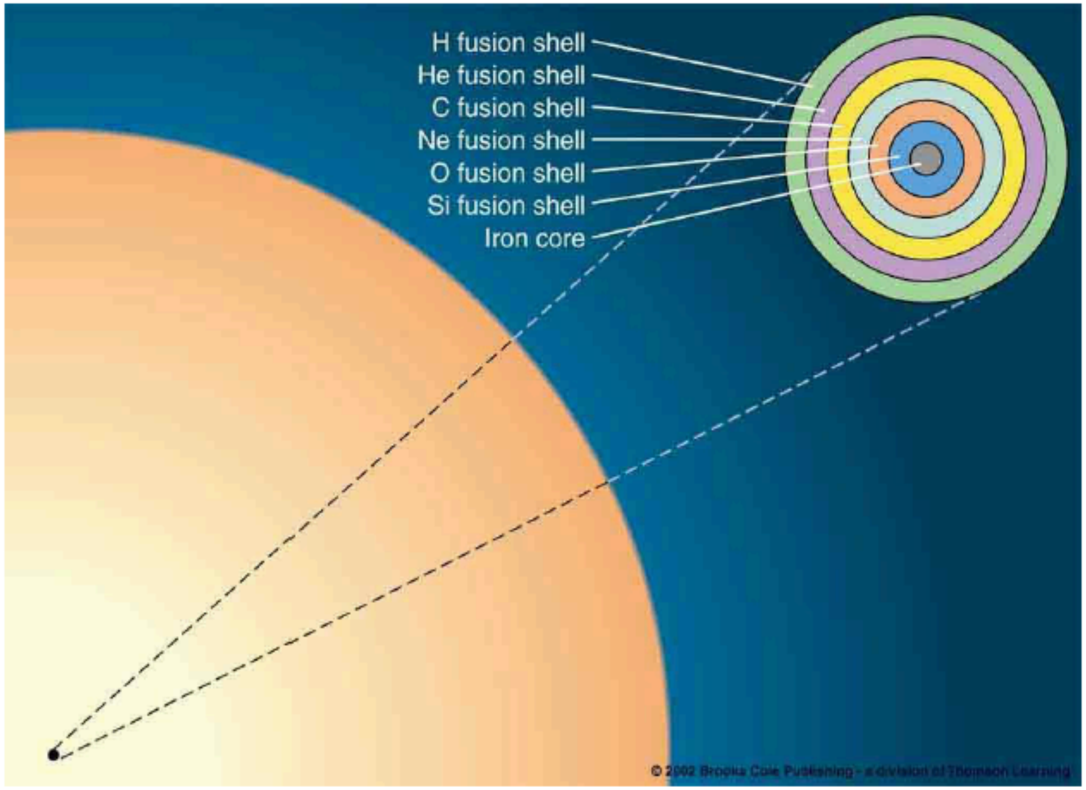
- Star exists as a violent balance between extreme heat making the Sun explode outward, and extreme gravity compressing its gases!
- If temperature drops, star compresses, which heats it up again; smaller diameter increases gravitational compression further ($1/r^2$)
- Contraction continues until some force replaces the energy being lost

- Once H starts to run out, He fuses to C
- Once He runs out, C starts to fuse
- If the star is much larger than the Sun, the core can fuse elements all the way up to 56Fe
- In a massive star, once no more fusion reactions are possible, the star may explode (supernova)

Structure of “evolved” stars



Shell structure of a “young” red giant



From Horizons, by Seeds

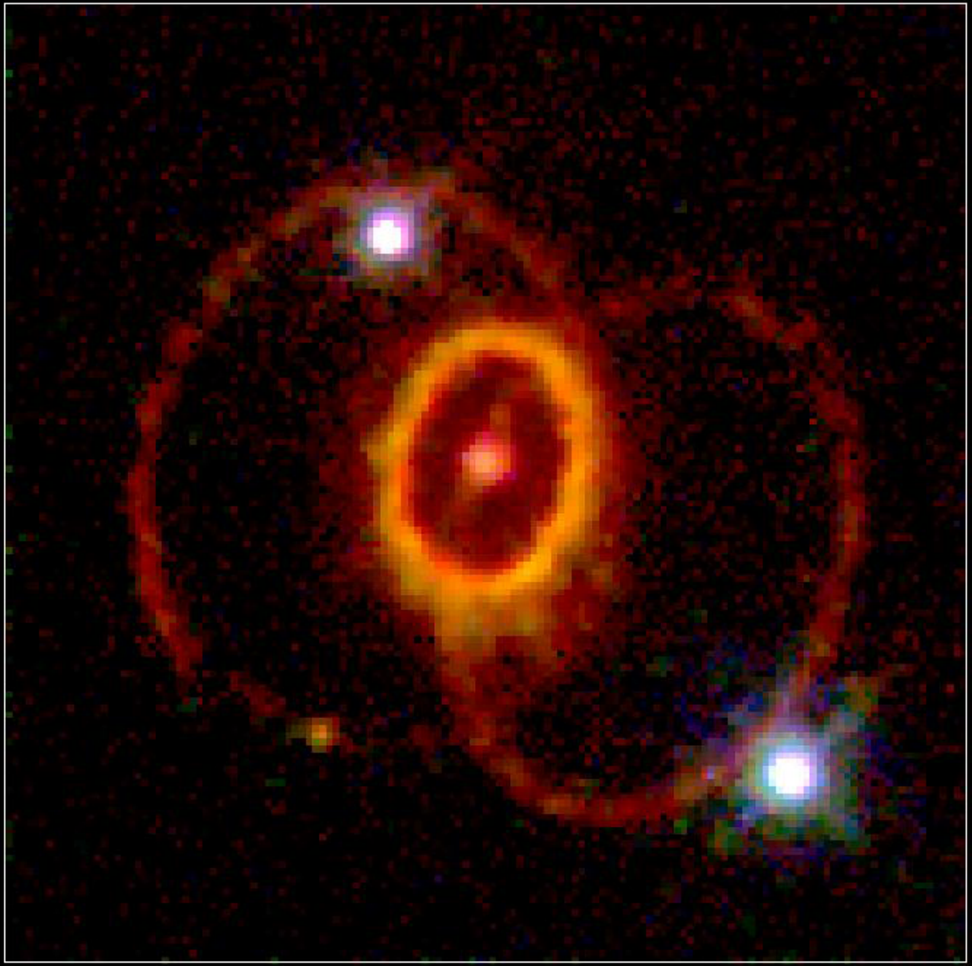
Shell structure of an “old” massive giant

- The sun is ~ 5 billion years old.
- When it reaches ~10 billion years the H will run out in the core and it will become a red giant somewhat like the one on the left.
As its core contracts its outer layers will expand enough to envelop the earth..

Neutron Capture

- ^{56}Fe + n → ^{57}Fe, ^{57}Fe + n → ^{58}Fe, ^{58}Fe + n → ^{59}Fe
- ^{59}Fe is unstable and decays to ^{59}Co, Co captures a neutron to become ^{60}Co, which decays to ^{60}Ni, and so forth – you're on the way to heavier elements.

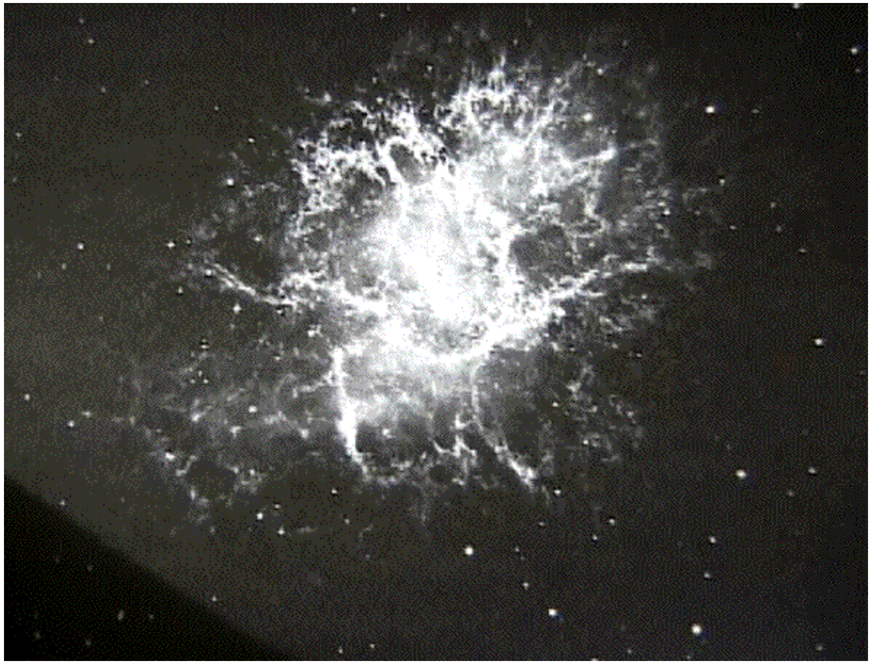
Supernova 1987A Rings



Hubble Space Telescope
Wide Field Planetary Camera 2

SPACE
TELESCOPE
SCIENCE
INSTITUTE

- Technitium (Tc) detected in supernova cloud
- Tc decays by radioactive decay in a few million years, so its presence means that it was recently made - in the supernova explosion



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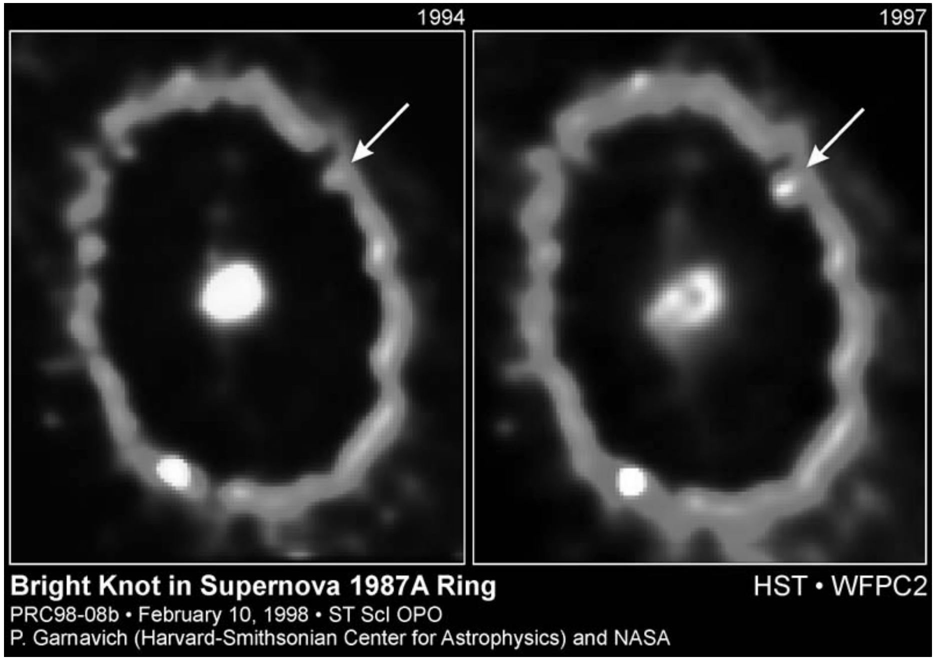


Bright Knot in Supernova 1987A Ring

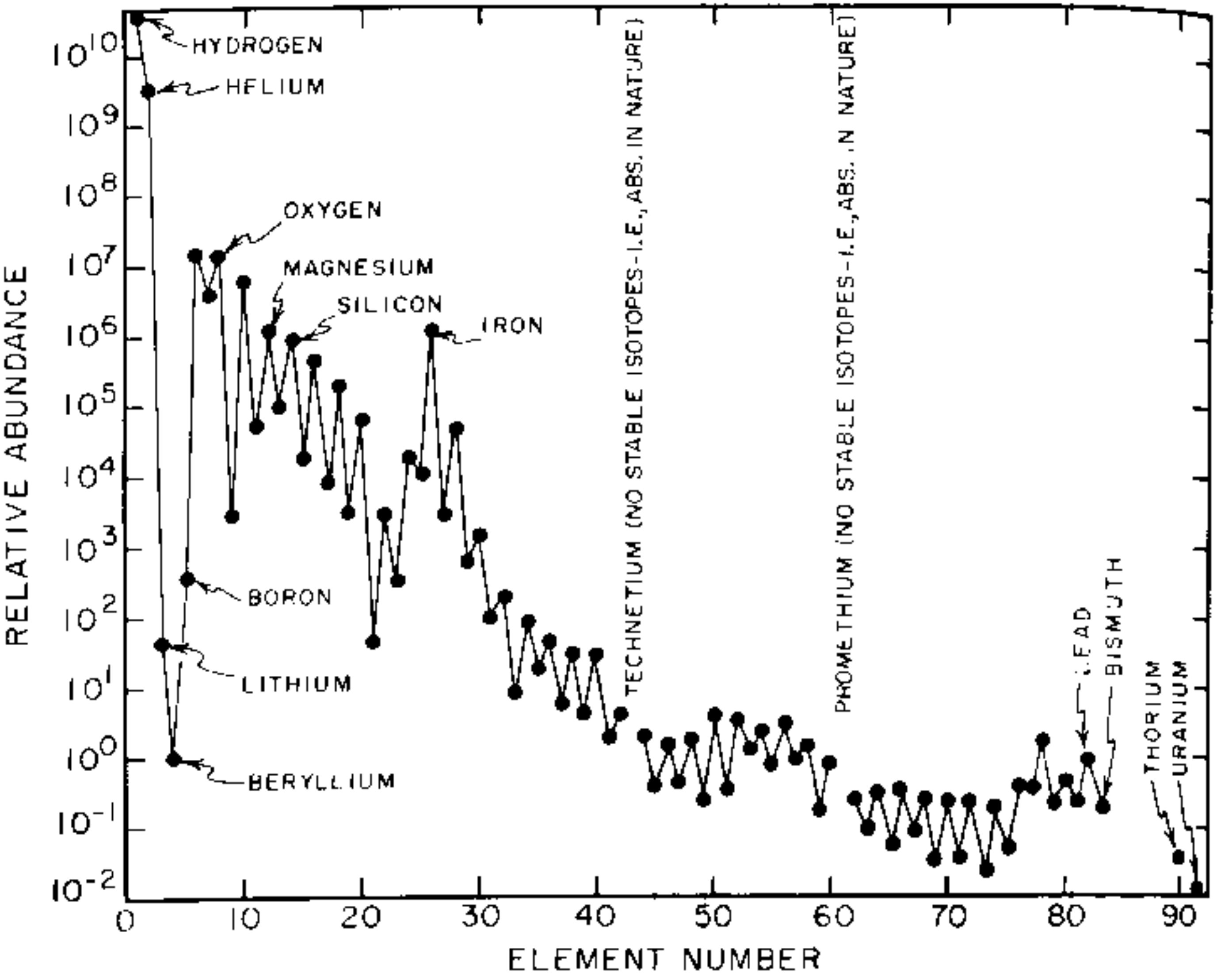
HST • WFPC2

PRC98-08b • February 10, 1998 • ST ScI OPO

P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA

1987

Elemental Abundances



Some elemental attributes