6.3 Element evolution and star formation

6.3.1 How did these elements evolve-NUCLEOSYTHESIS

Astrophysicists and theoretical physicists have done lots of work on this question. We won't discuss any of the details but its worth summarizing results very sloppily! (with apologies to astronomy classes)

The basic idea is that all elements are produced by reactions in stars. The material in our sun (and solar system) has been cycled through at least several stars.

Reasonable-since age of universe is substantially greater than that of our solar system.

solar system = 4.6 billion

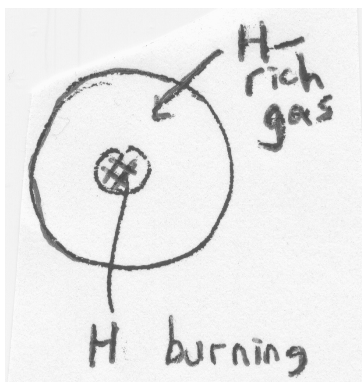
universe = 10-20 billion (lots of modern discussion)

6.3.2 Formation of stars

Stars aren't permanent fixtures-they are born, mature and die.

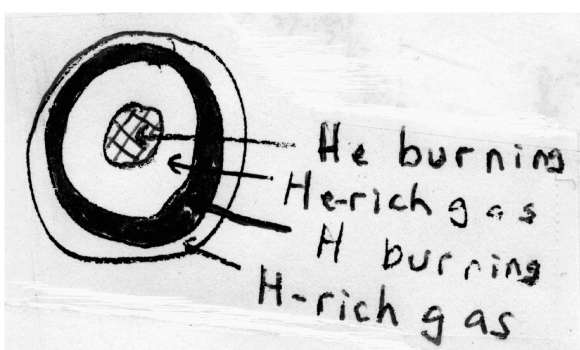
1) A turbulent cold gas of H atoms contracts gravitationally and heats up into a protostar.

2) When it gets hot enough-hydrogen burning stars. We're here!



What happens next?

3) As H in the core is burned to helium, hydrogen burning moves outward, while the helium core contracts and heats up.



4) When temperatures hit $\approx 2 \times 10^8$ °K - *helium burning* begins. This produces new elements

$^4He_2 + {}^4He_2 \rightarrow {}^8Be_4$

$^4He_2 + {}^8Be_4 \rightarrow {}^{12}C_6$

$^4He_2 + {}^{12}C_6 \rightarrow {}^{16}O_8$

Eventually-run out of helium and He-burning stops.

5) At this point two things can happen-hard to visualize intuitively

a) For small stars - less than 2-4 solar masses - the star contracts but cannot restart burning. Instead contracts, cools and becomes a WHITE DWARF: density $10^6 gm/cm^3$ (degenerate electron gas in center)

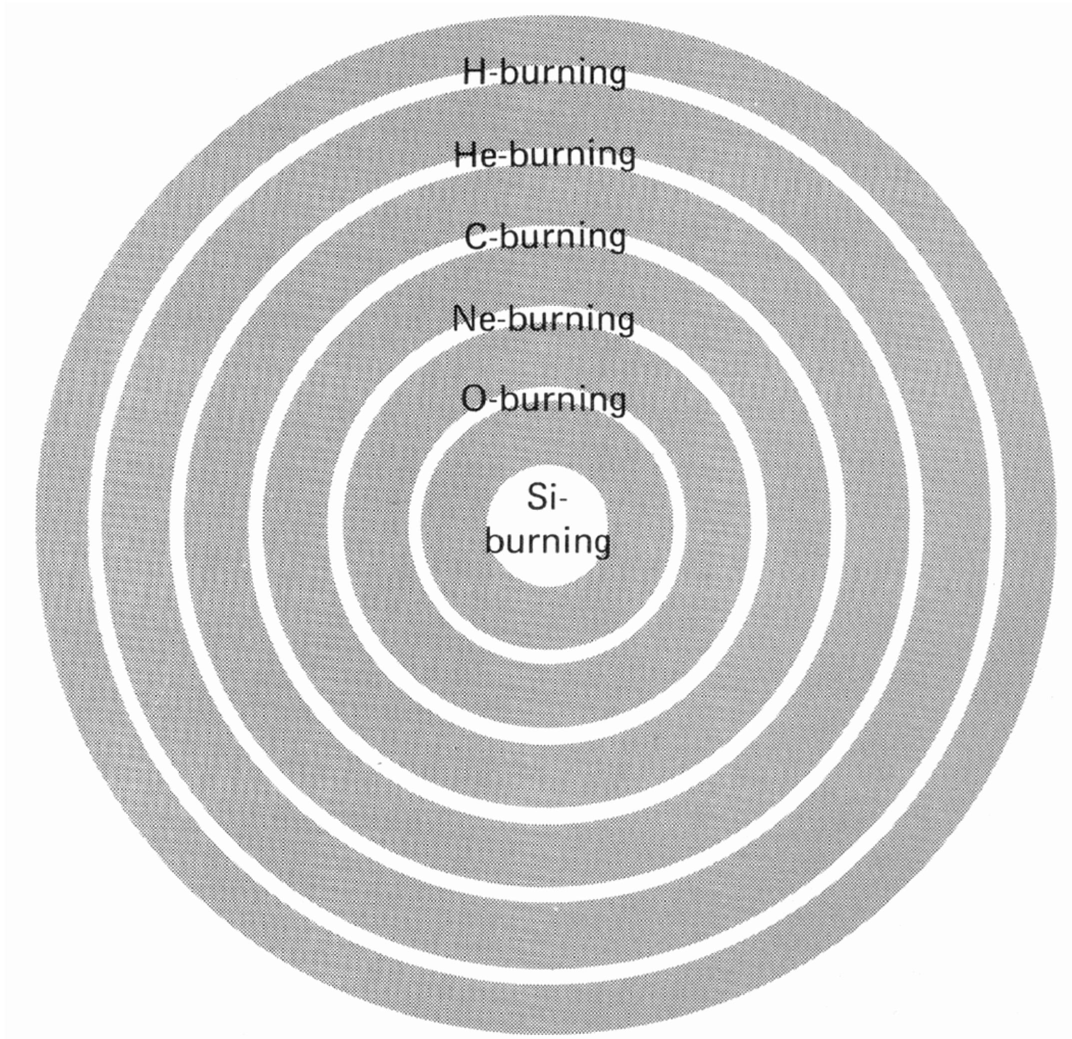
b) For large stars - greater than about 4 solar masses - go into further sucessive burning stages:
-carbon burning (8×10^8 °K) produces O, $^{20}Ne_{10,}$ $^{24}Mg_{12}$
-neon burning (1.5×10^9 °K)
-oxygen burning (2×10^9 °K) produces Mg to ^{32}S
-silicon burning (3×10^9 °K) produced elements up top $^{56}Fe_{26}$

Table 6-1 Stages of Nuclear Energy Generation

Name of Process	Fuel	Products	Approximate Temperature (°K)
HYDROGEN-BURNING	H	He	$1\text{–}3 \times 10^7$
HELIUM-BURNING	He	C, O	2×10^8
CARBON-BURNING	C	O, Ne, Na, Mg	8×10^8
NEON-BURNING	Ne	O, Mg	1.5×10^9
OXYGEN-BURNING	O	Mg to S	2×10^9
SILICON-BURNING	Mg to S	Elements near Fe	3×10^9

From A. G. W. Cameron, 1976, in Frontiers of Astrophysics, *E. H. Avrett ed.* (*Harvard University Press*), *554 pp.*

During this period the star is a SUPERGIANT



6) Beyond Fe, further burning won't produce higher mass elements, since the BF/nucleon is less, so they're less stable.

At this point contraction forces stellear core density to 10^8 gm/cm^3, and the core collapses (degenerate electron gas collapses as electrons + protons $\longrightarrow$ neutrons - a massive SUPERNOVA explosion occurs. Most material is blown away into space.

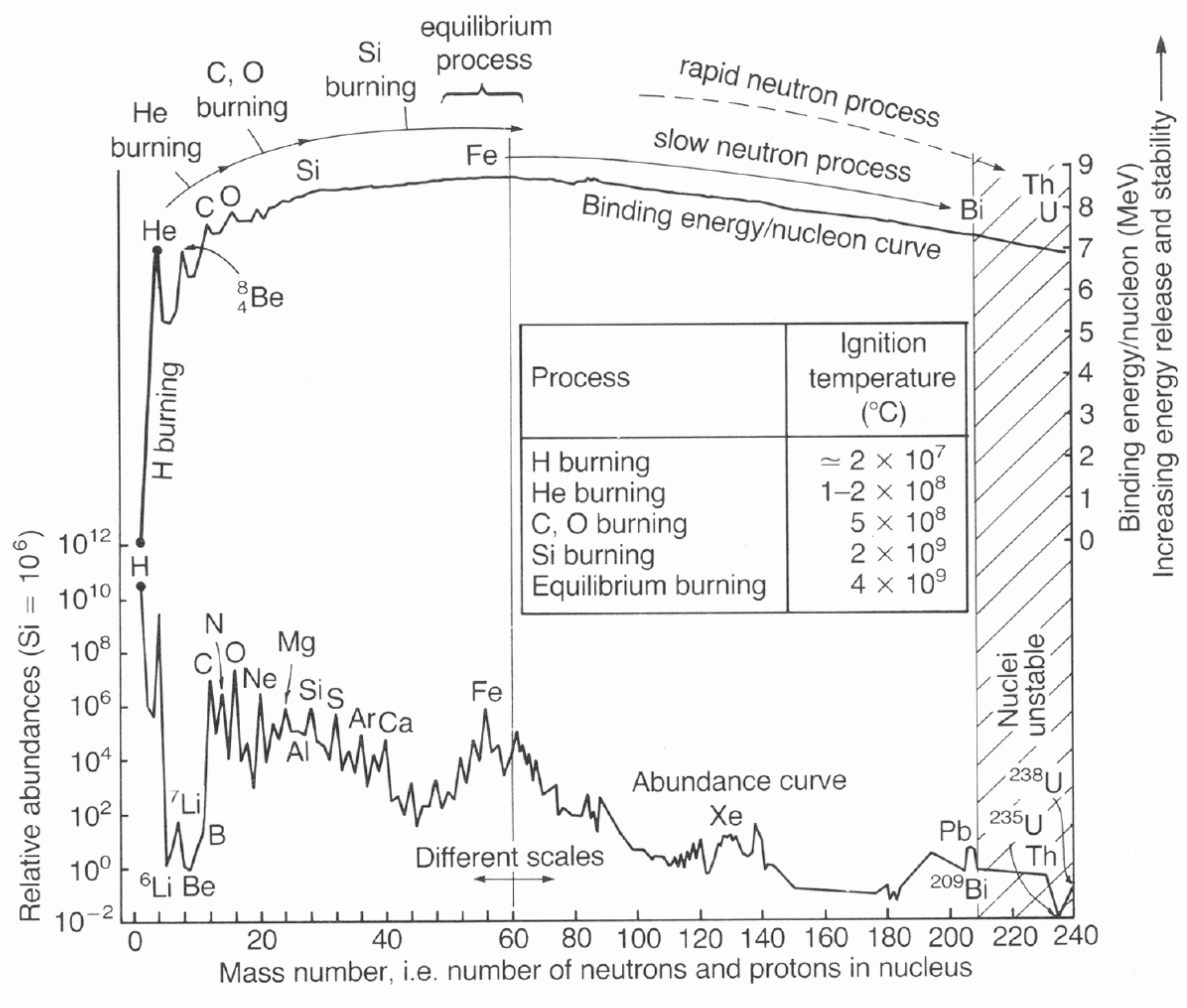
7) As result - the higher atomic mass elements (beyond Fe) can be made by two basic processes

a) r-processes - *rapid neutron* capture during the supernova explosion (1-100 sec) forms elements including many of the naturally radioactive decaying ones ^{235}U, ^{238}U, ^{232}Th (long lived) as well as shorter lived ones.

b) S-process - after a supernova explosion there are elements like Fe floating around. When these are incorporated into a later generation star, slow neutron capture can form other elements

6.3.3 Net effect of nucleosythesis seen in element abundances

Notice (figure) what's happening at each stage elements with higher binding energy/nucleon were made, up to Fe.



Process	Ignition temperature (°C)
H burning	$\simeq 2 \times 10^7$
He burning	$1\text{–}2 \times 10^8$
C, O burning	5×10^8
Si burning	2×10^9
Equilibrium burning	4×10^9

At each stage the elements produced most are those with masses multiples of 4 since they can be done by fusing with helium: some others produced.

Hence, Stars have a life cycle - they're born and die.