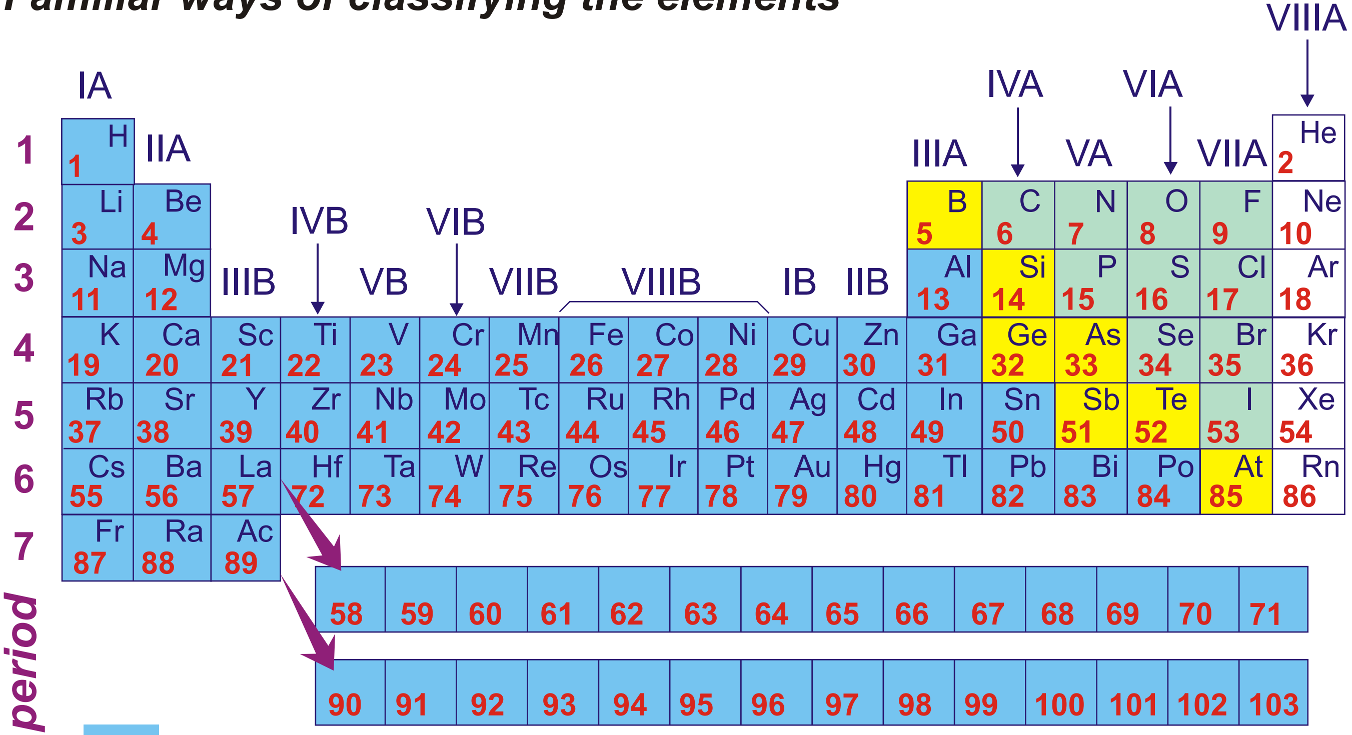
COSMIC ABUNDANCE of the ELEMENTS and NUCLEOSYNTHESIS

February 3, 2005

Familiar ways of classifying the elements



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

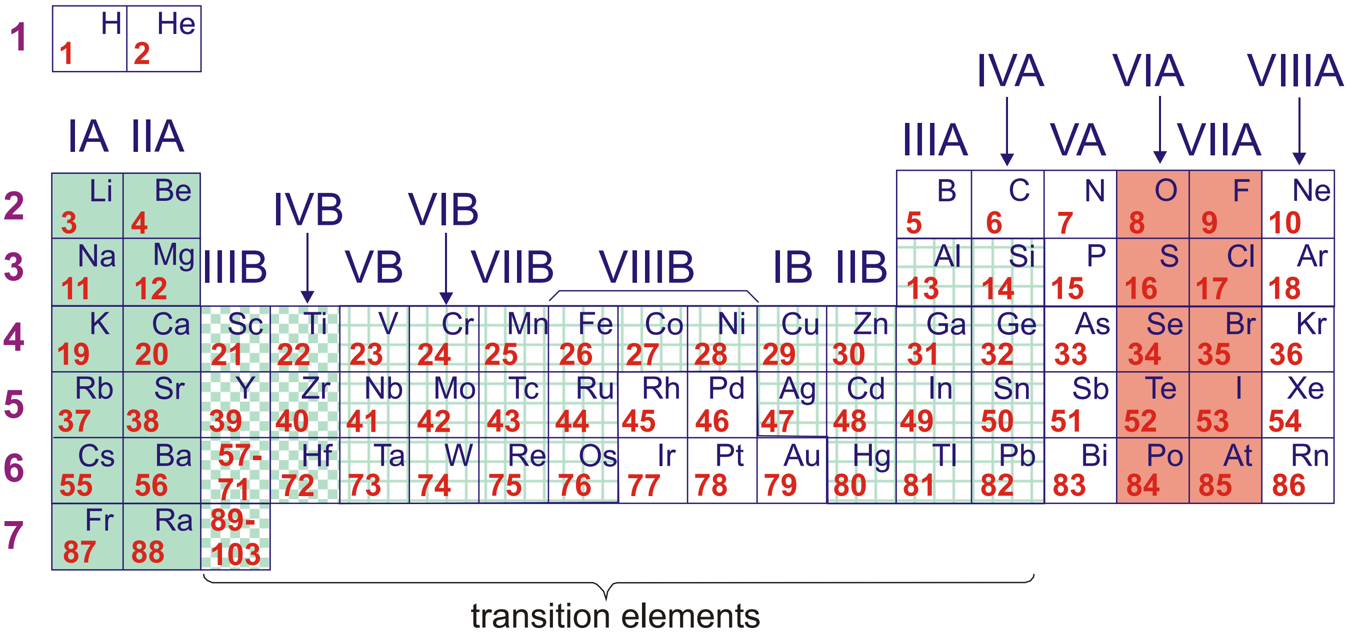
58	59	60	61	62	63	64	65	66	67	68	69	70	71
90	91	92	93	94	95	96	97	98	99	100	101	102	103

🟦 metals

🟩 non-metals

🟨 semi-conductors (semi-metals; metalloids)

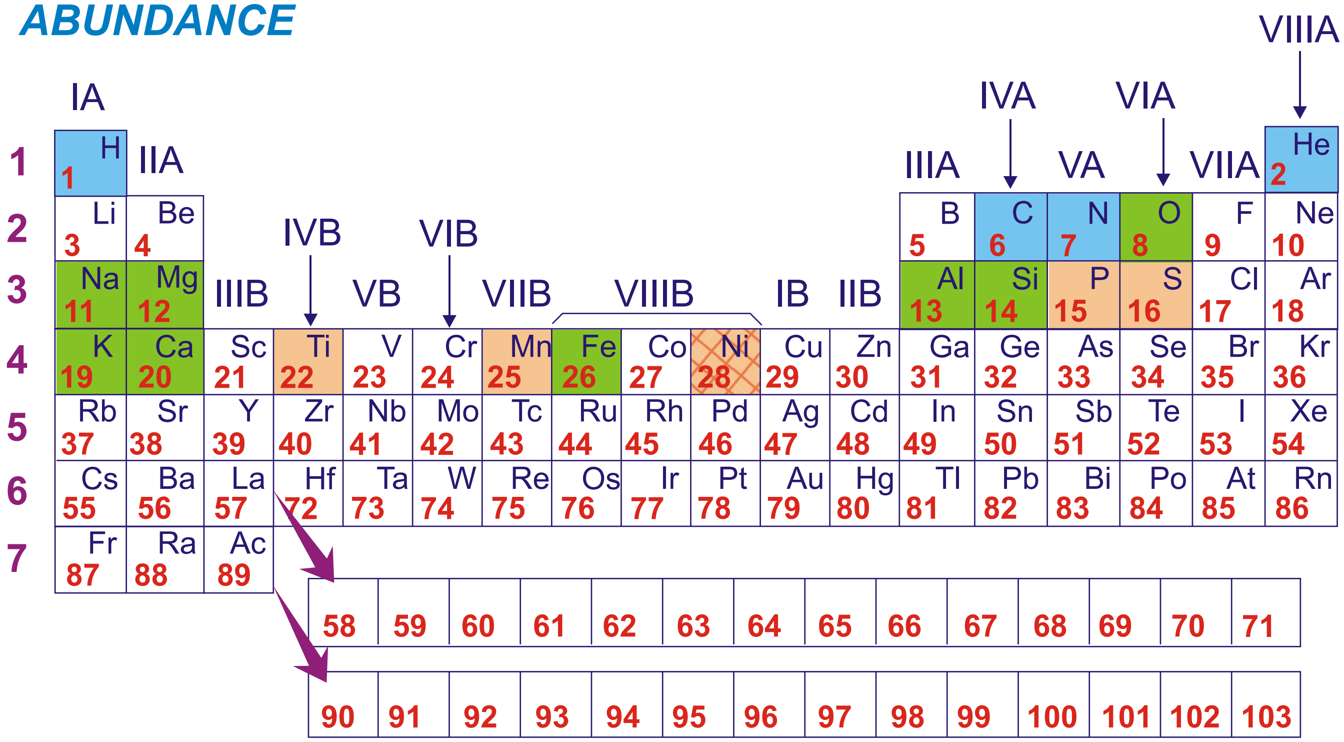
Alternatively...



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

Geochemical variations on the periodic table...

ABUNDANCE



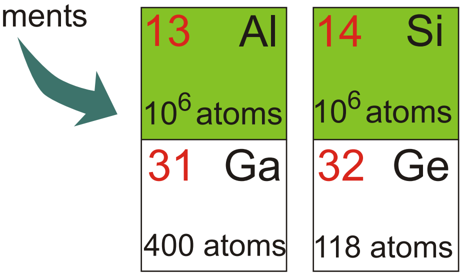
🟦 abundant in cosmos but not in(on) Earth

🟩 major elements in Earth (≳1 wt%)

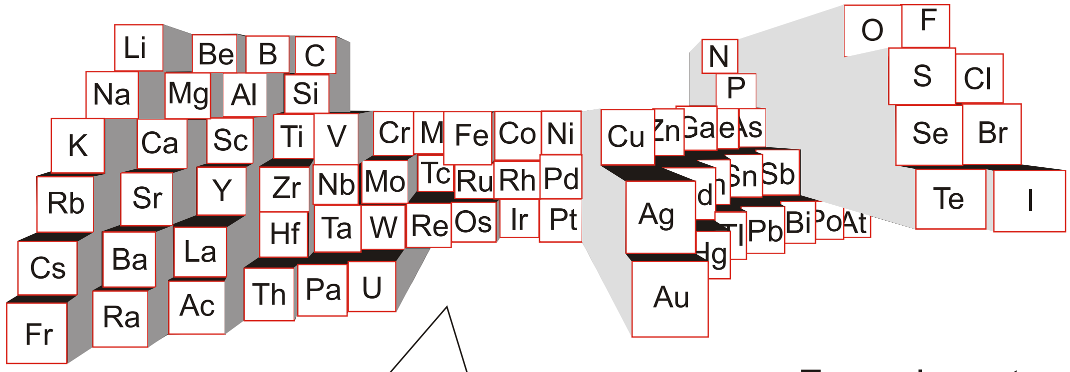
🟧 minor elements in Earth ($0.1 \lesssim$ conc $\lesssim 1\%$)

☐ trace elements (≲ 0.1%; some < 1 ppm)

relative abundances of chemically similar elements



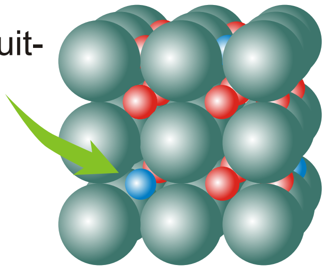
SIZES OF ATOMS (IONIC RADII)

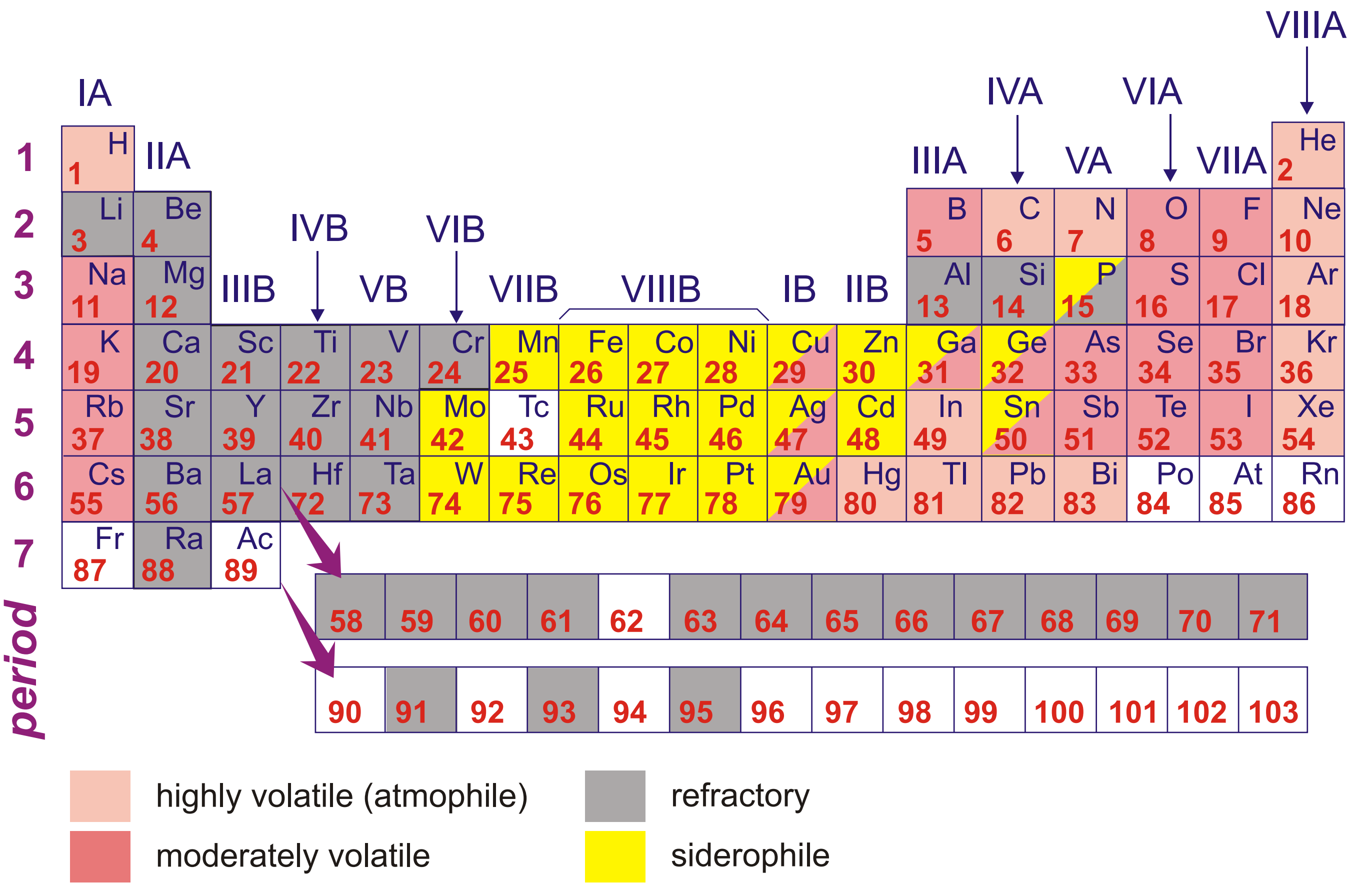


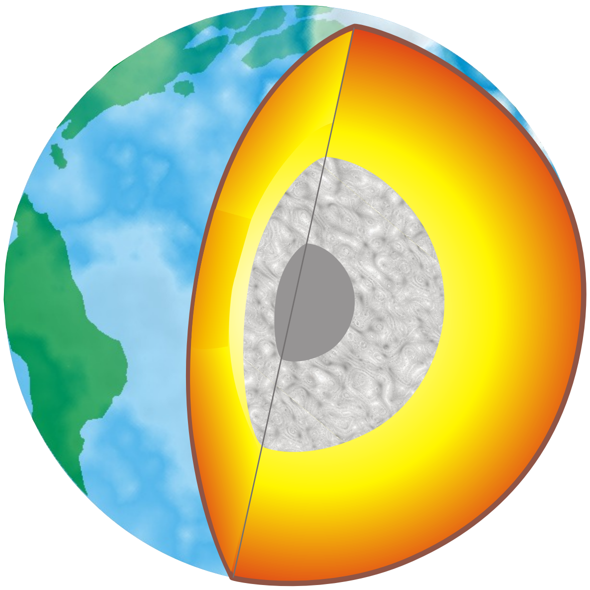
Ionic radius increases coming out of the figure. Sizes apply to the valence state that is most common in natural systems.

"Host" mineral (made of major elements)

Trace elements substitute into suitable lattice sites

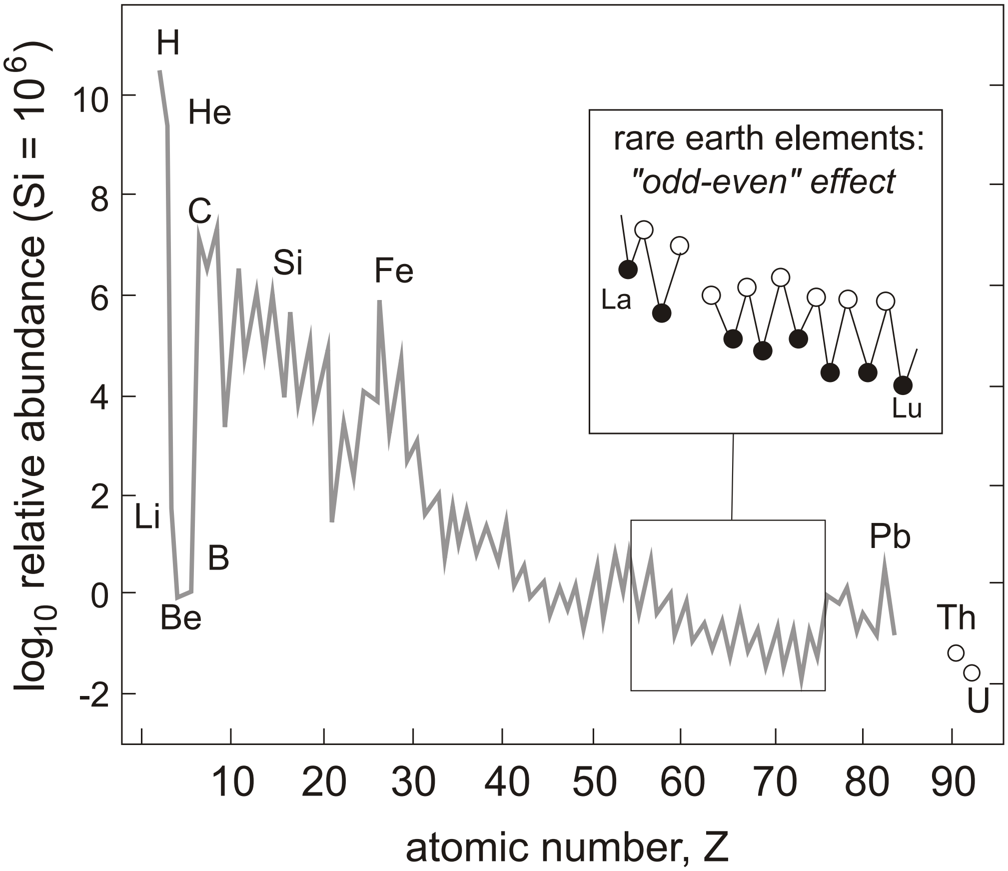






These geochemical tendencies largely determine where in the Earth many elements are sequestered – e.g., siderophile elements are concentrated in the core; volatile elements were partially lost from the Earth during its hot early history.

COSMIC ABUNDANCES of the elements



Some general features of cosmic abundance curve

>75% of the mass of the universe is hydrogen
>99% is H + He
(*note:* These statements *do not* apply to the Earth)

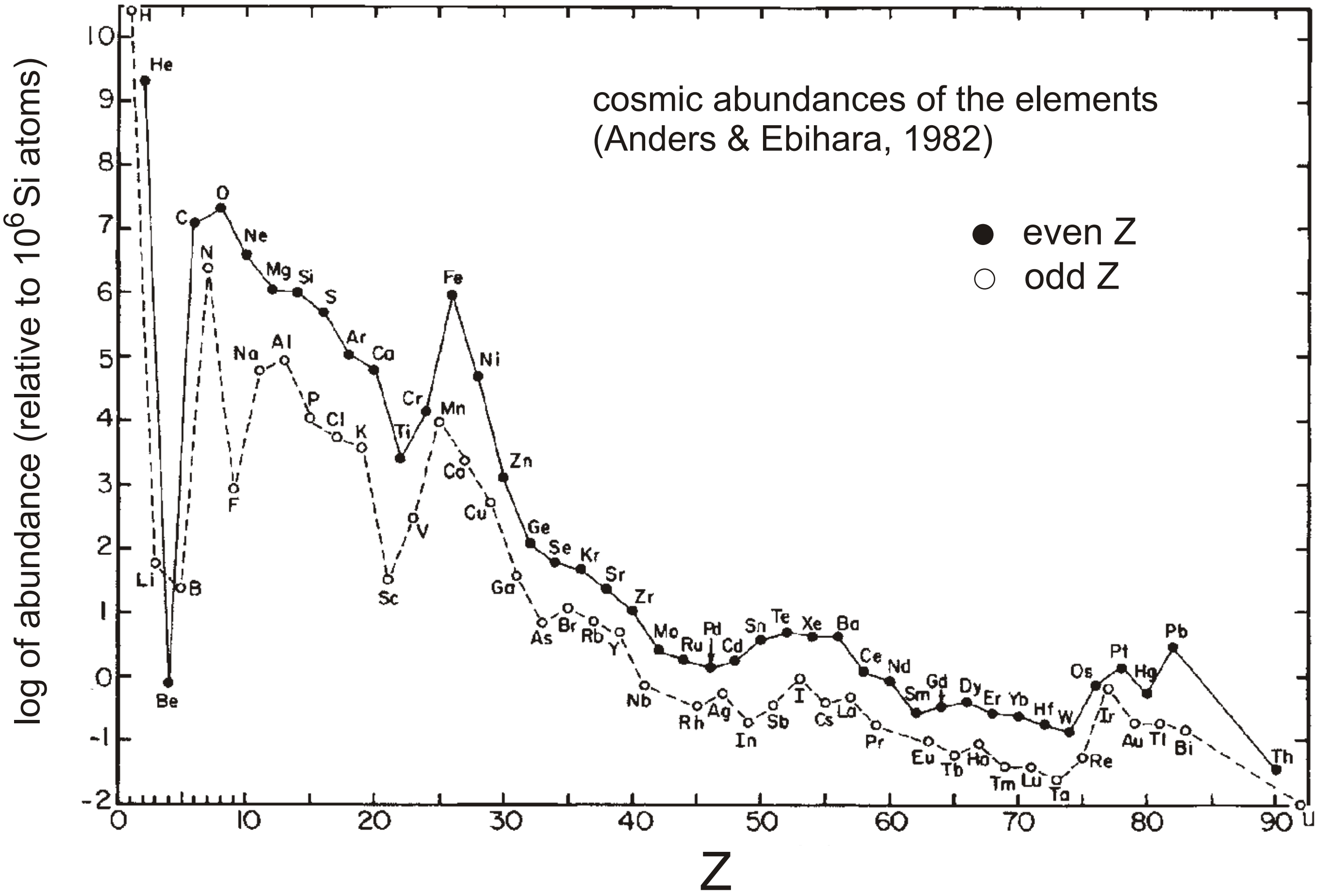
Elemental abundances drop off exponentially with increasing atomic number (Z) up to Z ~ 60; therafter remain ~constant

Li, Be & B show marked depletion relative to both higher and lower-Z elements

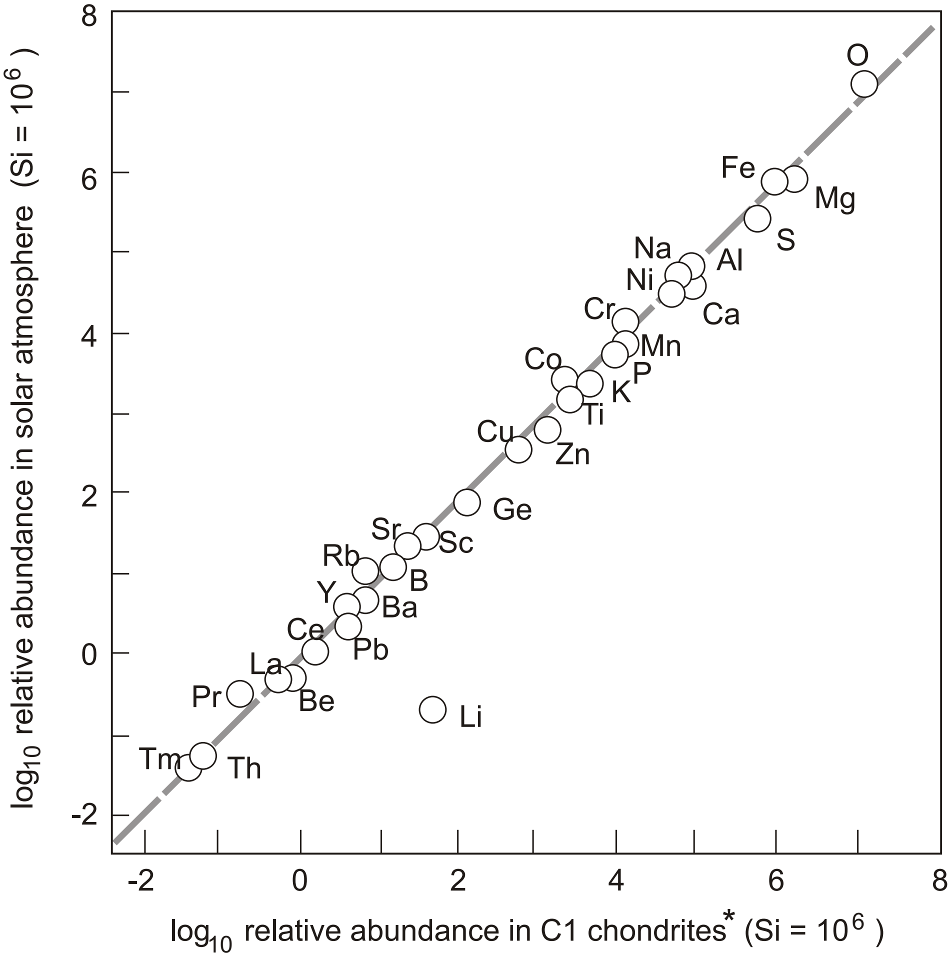
There is a pronounced abundance peak in the vicinity of Fe, as well as a few less obvious peaks at higher Z

Even-Z elements are more abundant than their odd-Z neighbors

A	Z	N	no. of stable isotopes
odd	odd	even	50
odd	even	odd	55
even	odd	odd	4
even	even	even	165!


cosmic abundances of the elements
(Anders & Ebihara, 1982)
● even Z
○ odd Z
log of abundance (relative to 10^6 Si atoms)
Z
10
9
8
7
6
5
4
3
2
1
0
-1
-2
0
10
20
30
40
50
60
70
80
90
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

similarilty in composition of chondrites and solar atmosphere...



* Chondrites are the most "primitive" of meteorites -- i.e., ones we believe represent the original, overall composition of the solar system. Five distinct types of chondrites are recognized.

Note: This diagram is a useful illustration, but bear in mind that:

1) it is a log-log plot (and just about anything can appear to be linear on such a plot!)

2) the chondrites represented are actually metamorphic rocks, so their composition may not be "primitive" in all respects

The elements as we know them are created in the interiors of stars...

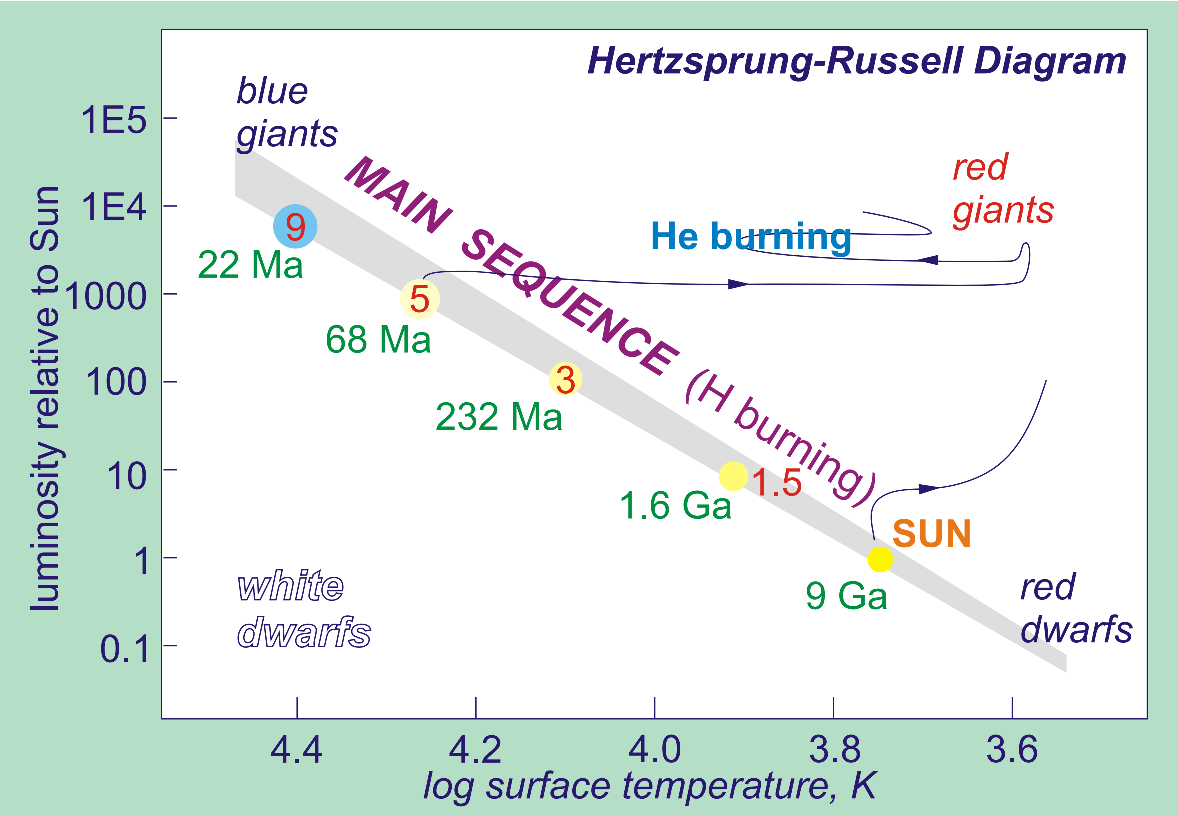
"Burning" of hydrogen and helium in first-generation stars

First-generation stars are ones that have come together from an "original" hydrogen-helium cloud – that is, they do not represent "re-processed" stellar material from a previous supernova explosion (*the Sun is actually a second-generation star*). In first-generation stars, hydrogen "burning" to produce helium occurs by these reactions:

$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + \text{energy}$$

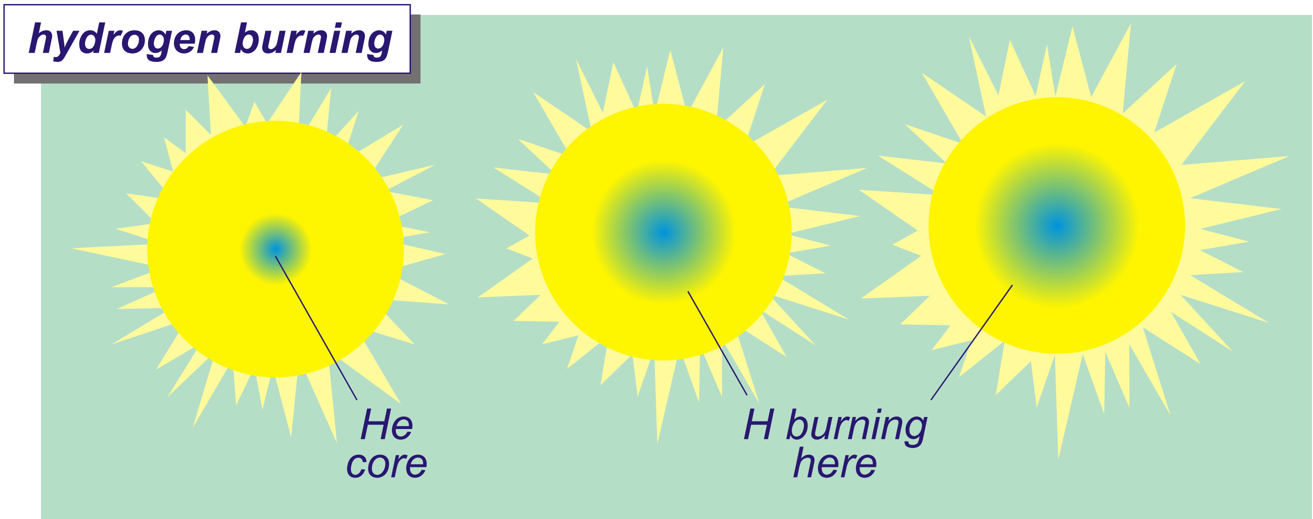
$$^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \text{energy}$$

$$^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + \text{energy}$$



red numbers: number of solar masses
green numbers: time on main sequence

On the main sequence, helium is the main product of hydrogen burning. A gravitationally stable core of helium is produced in the star, and hydrogen burning continues on the surface of the core. As H-burning migrates outward, the luminosity of the star increases slightly:



If the star is massive enough to achieve the required temperature and density in the core, ***helium burning*** is initiated and heavier elements can be synthesized

$$^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} \rightarrow ^{8}_{4}\mathrm{Be}$$ ***(endothermic!)***

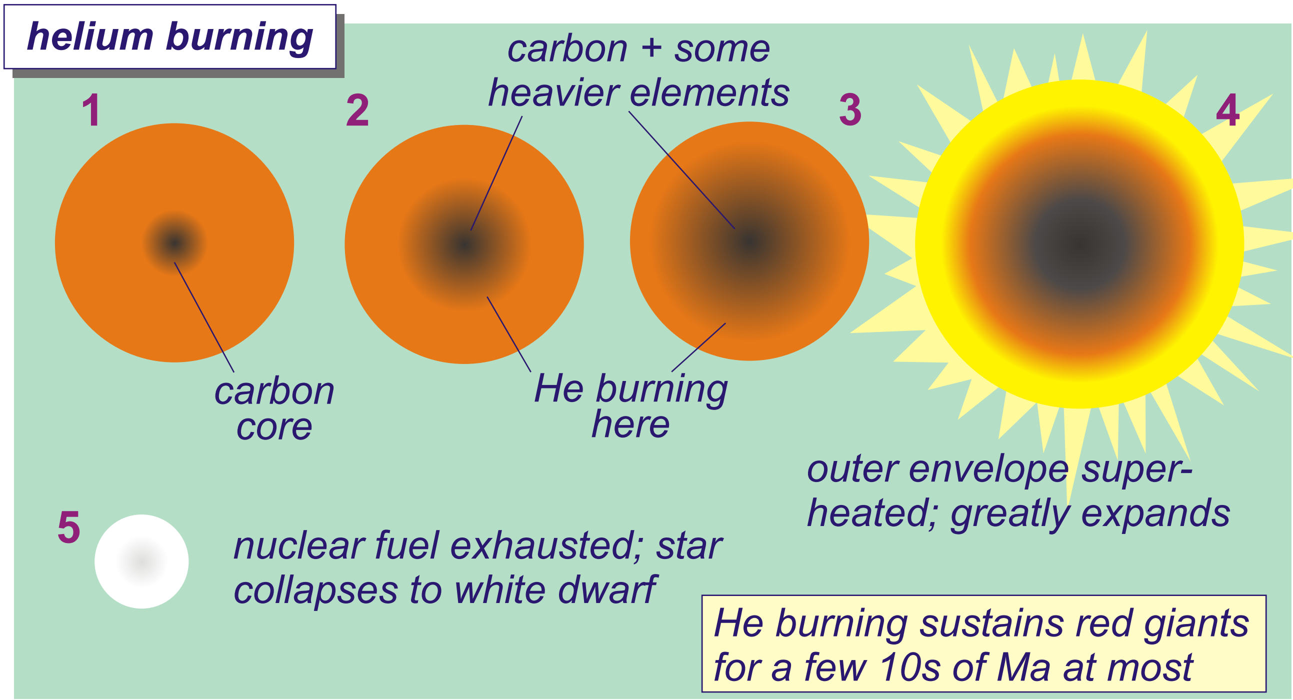
This process is exceedingly inefficient because $^{8}_{4}\mathrm{Be}$ is unstable and decays with a half-life of only 10^{-16} s. What probably happens is that another helium nucleus is immediately absorbed to make a carbon nucleus:

$$^{8}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \rightarrow ^{12}_{6}\mathrm{C}$$

or

$$^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} \rightarrow ^{12}_{6}\mathrm{C}$$

Note: These helium nuclei are actually positively-charged alpha particles and repel each other strongly (remember Mr. Coulomb?). Extreme temperatures and pressures are required to get them to fuse: He burning can occur only in stars having masses of 80% or more of our Sun. ***This "triple-alpha" process is the key to making heavier elements...***



Somewhat heavier elements...

If a red giant is sufficiently massive, successively heavier elements can be synthesized by addition of alpha particles (He nuclei) to carbon...

$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O}$$

$$^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{20}_{10}\mathrm{Ne}$$

etc.

This "alpha-process" can continue up to ^{56}Ni (which decays to ^{56}Fe), but elements heavier than Fe cannot be made by this process because the repulsion between large, positively-charged nuclei and particles is too strong.

Note that the nuclei forming by this process are all even-Z. Smaller abundances of odd-Z nuclei are produced by reactions among the fusion products, such as:

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{23}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}$$

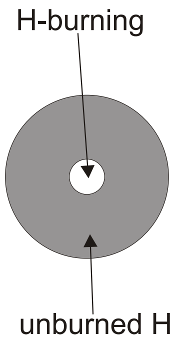
and $$^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{31}_{15}\mathrm{P} + {}^{1}_{1}\mathrm{H}$$

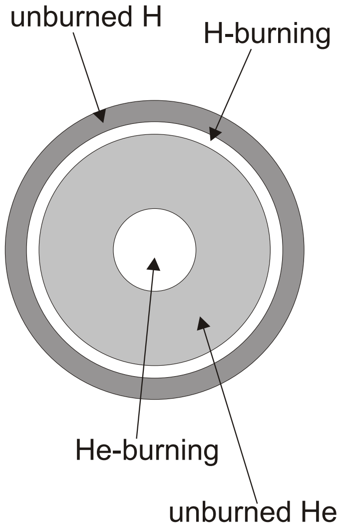
This creates further possibilities, e.g...

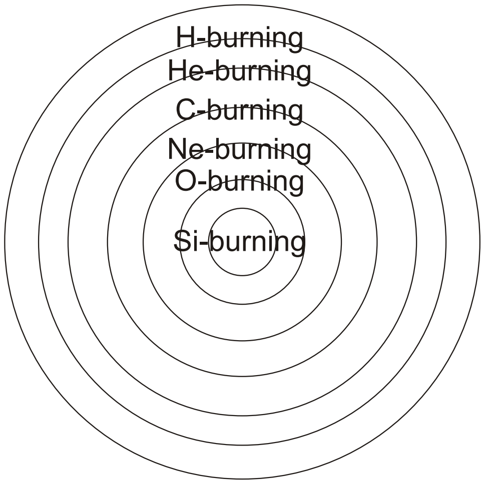
$$^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{13}_{7}\mathrm{N} + \quad \text{then} \quad {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{+} +$$

and $$^{13}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \mathrm{n}$$

This type of reaction is crucial because neutrons are a product! (more soon)







process	fuel	products	temperature (K)
H-burning	H	He	6E7
He-burning	He	C, O	2E8
C-burning	C	O, Ne, Na, Mg	8E8
Ne-burning	Ne	O, Mg	15E8
O-burning	O	Mg to S	2E9
Si-burning	Mg to S	elements near Fe	3E9

Later generations of stars and the CNO cycle

That's about as much as we need to know about first-generation stars. The key thing to remember is that when these explode, they contribute elements heavier than H and He to the interstellar gas, so the next generation of stars can begin with a different, more "versatile" fuel. Subsequent stars *can burn hydrogen in the* ***CNO cycle***, in which hydrogen nuclei are added to carbon to produce first nitrogen and then oxygen. This mode of H burning requires less extreme conditions than the proton-proton fusion reactions on p. 6. ***The Sun is now burning H in the CNO cycle***:

$$^{12}_{6}\mathrm{C} + ^{1}_{1}\mathrm{H} \rightarrow ^{13}_{7}\mathrm{N}$$

$$^{13}_{7}\mathrm{N} \xrightarrow{\textit{decays}} ^{13}_{6}\mathrm{C}$$

$$^{13}_{6}\mathrm{C} + ^{1}_{1}\mathrm{H} \rightarrow ^{14}_{7}\mathrm{N}$$

$$^{14}_{7}\mathrm{N} + ^{1}_{1}\mathrm{H} \rightarrow ^{15}_{8}\mathrm{O}$$

$$^{15}_{8}\mathrm{O} \xrightarrow{\textit{decays}} ^{15}_{7}\mathrm{N}$$

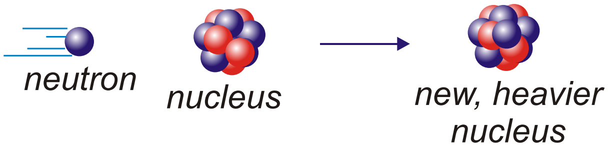
$$^{15}_{7}\mathrm{N} + ^{1}_{1}\mathrm{H} \rightarrow \boxed{^{12}_{6}\mathrm{C} + ^{4}_{2}\mathrm{He}}$$

end result: 4 protons fused to make ^{4}He; ^{12}C "released" for future use

Elements heavier than Fe: NEUTRON CAPTURE

If there is a source of neutrons, the following type of reaction can occur

$$^{A}_{Z}X \; + \; neutron \; = \; ^{A+1}_{Z}X$$



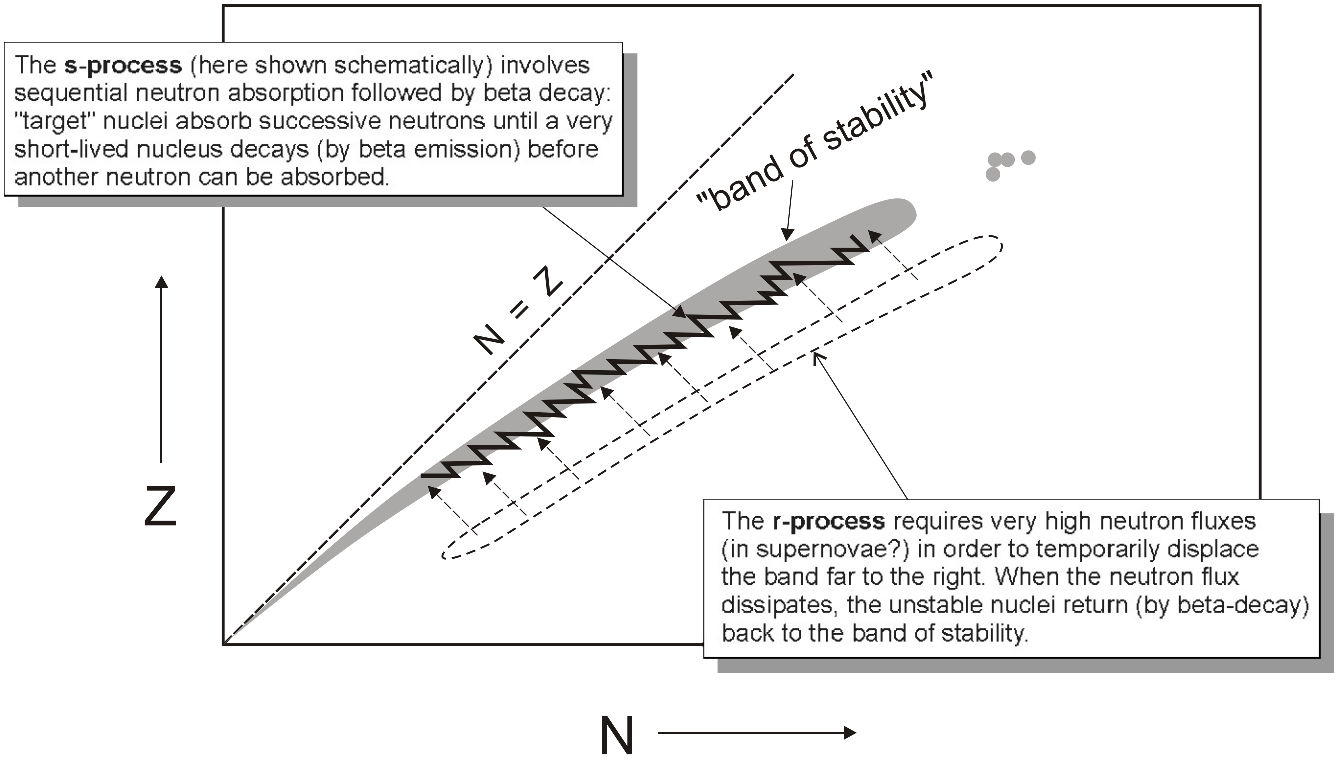
If a nucleus absorbs *too many* neutrons, it will eventually become too neutron-rich to be stable and decay by beta decay. Through neutron-capture reactions, it is possible to work up through most of the periodic table.

We recognize two distinct types of neutron-capture processes, which differ in terms of the neutron flux required:

s-process: moderate neutron fluxes in the late red-giant stage

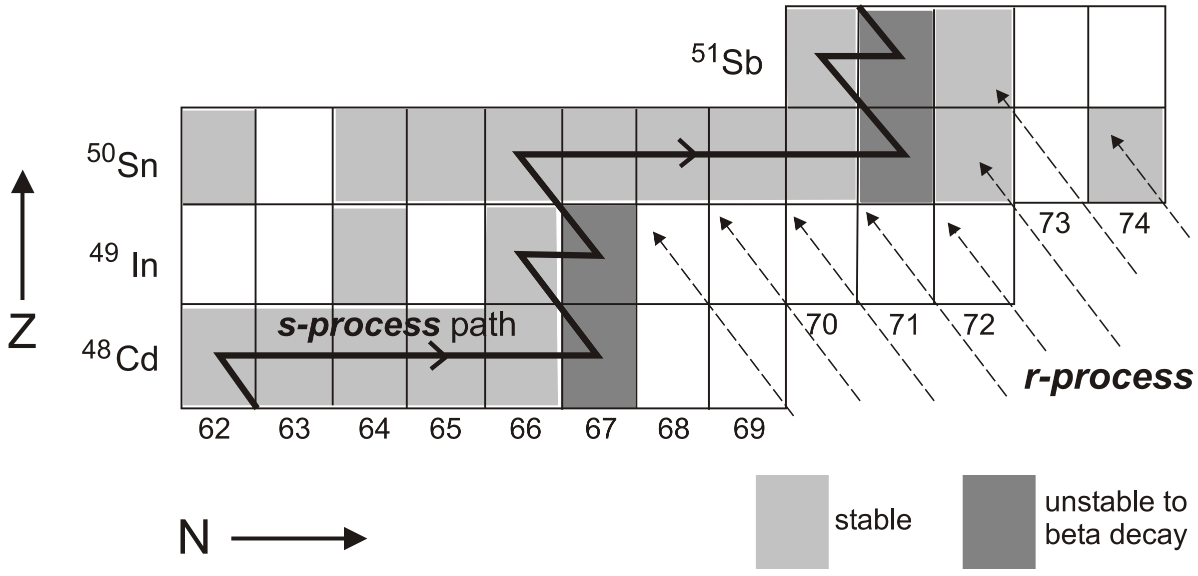
r-process: very high neutron fluxes in supernovae

Synthesis of heavy nuclei by neutron capture: the *s-* and *r-processes* in second-generation stars



The **s-process** (here shown schematically) involves sequential neutron absorption followed by beta decay: "target" nuclei absorb successive neutrons until a very short-lived nucleus decays (by beta emission) before another neutron can be absorbed.

The **r-process** requires very high neutron fluxes (in supernovae?) in order to temporarily displace the band far to the right. When the neutron flux dissipates, the unstable nuclei return (by beta-decay) back to the band of stability.



Creating heavy elements by neutron capture: An example...

$$^{56}\mathrm{Fe} + n \longrightarrow {}^{57}\mathrm{Fe} \quad \text{(stable)}$$
$$^{57}\mathrm{Fe} + n \longrightarrow {}^{58}\mathrm{Fe} \quad \text{(stable)}$$
$$^{58}\mathrm{Fe} + n \longrightarrow {}^{59}\mathrm{Fe} \quad (t_{1/2} = 45\ \mathrm{d})$$

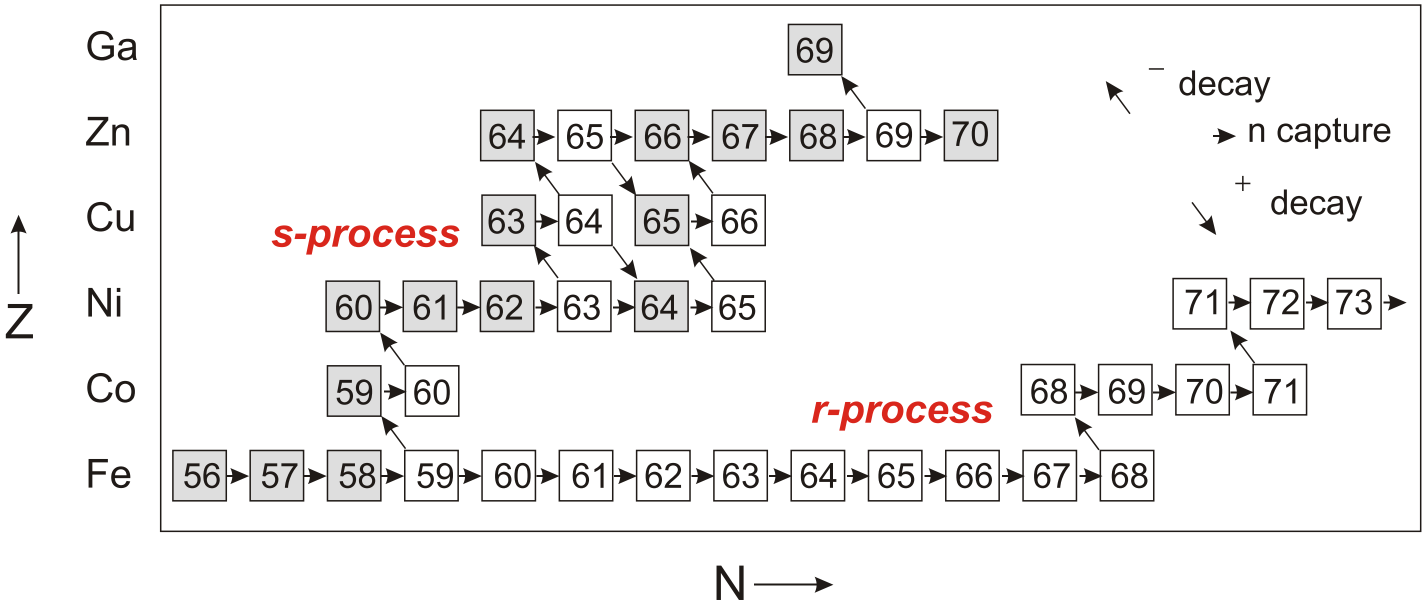
The way things proceed from here depends upon the neutron flux (no. of neutrons available). ***If the flux is limited***, the next step would be:

$$^{59}\mathrm{Fe} \longrightarrow {}^{59}\mathrm{Co} + e^- + {}^-$$
$$^{59}\mathrm{Co} + n \longrightarrow {}^{60}\mathrm{Co} \quad (t_{1/2} = 5\ \mathrm{y})$$
$$^{60}\mathrm{Co} \longrightarrow {}^{60}\mathrm{Ni} + e^- + {}^- \quad {}^{60}\mathrm{Ni}\ \text{is stable)}$$

However, ***if the neutron flux is large*** (lots of neutrons available), we can get past ^{59}Fe: instead of decaying to ^{59}Co, it absorbs another neutron...

$$^{59}\mathrm{Fe} + n \longrightarrow {}^{60}\mathrm{Fe} \quad (t_{1/2} = 3\mathrm{E}5\ \mathrm{y})$$
$$^{60}\mathrm{Fe} + n \longrightarrow {}^{61}\mathrm{Fe} \quad (t_{1/2} = 6\ \mathrm{m})$$
$$^{61}\mathrm{Fe} \longrightarrow {}^{61}\mathrm{Co} + e^- + {}^- \quad (t_{1/2} = 1.65\ \mathrm{h})$$
$$^{61}\mathrm{Co} \longrightarrow {}^{61}\mathrm{Ni} + e^- + {}^- \quad {}^{61}\mathrm{Ni}\ \text{is stable)}$$

So...
We got to a different place because we had more neutrons available


Ga
Zn
Cu
Ni
Co
Fe
Z
N
s-process
r-process
− decay
n capture
+ decay
69
64
65
66
67
68
69
70
63
64
65
66
60
61
62
63
64
65
71
72
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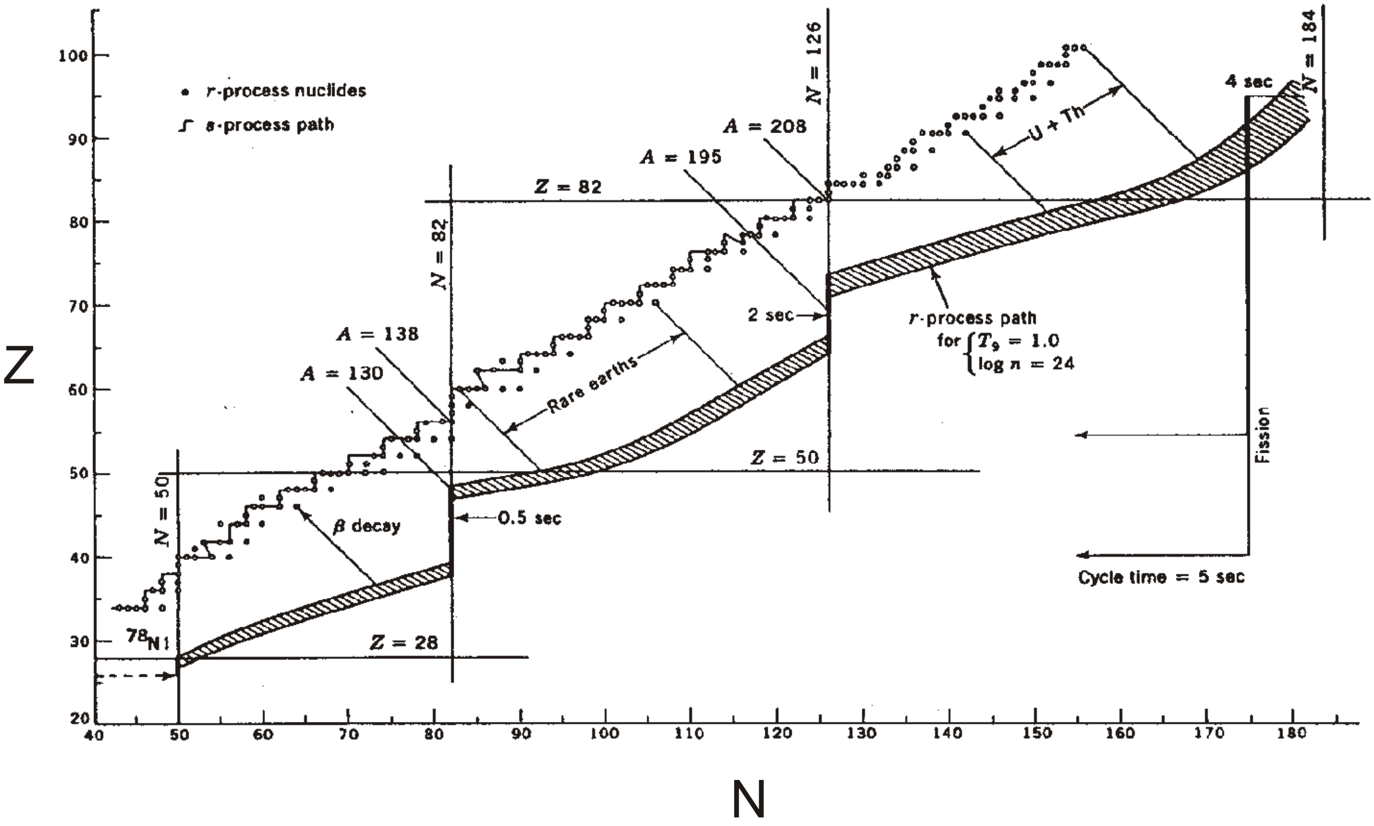
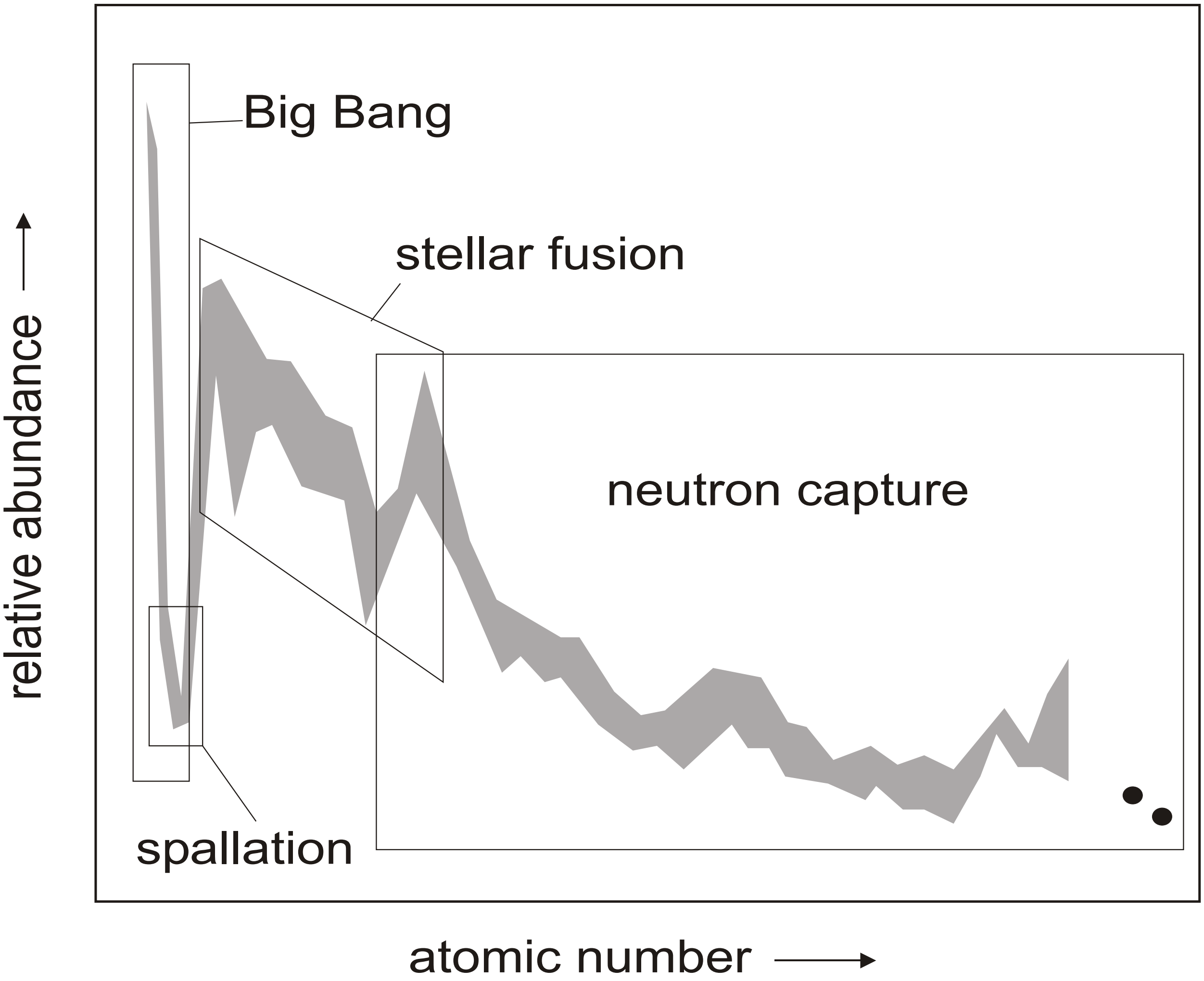
68


Z
N
r-process nuclides
s-process path
A = 208
A = 195
A = 138
A = 130
Z = 82
Z = 50
Z = 28
N = 50
N = 82
N = 126
N = 184
4 sec
2 sec
0.5 sec
U + Th
Rare earths
β decay
r-process path
for T₉ = 1.0
log n = 24
Fission
Cycle time = 5 sec
78Ni
100
90
80
70
60
50
40
30
20
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

SUMMARY


Big Bang
stellar fusion
neutron capture
spallation
relative abundance
atomic number

Neutron Activation: *“artificial” nucleosynthesis*

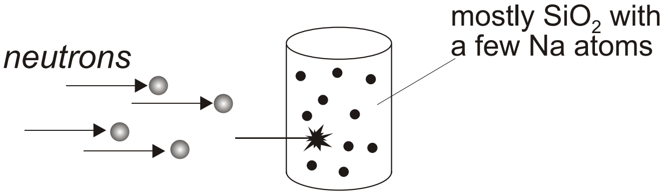
An example of neutron capture followed by beta decay (as in the s-process)...

Neutron activation is an analytical technique used extensively in the bio-, geo- and materials sciences for measurement of trace concentrations (e.g. 1-100 ppm) of elements in a wide variety of materials. As the name suggests, it involves the use of a neutron flux in a research reactor to “activate” the element of interest. This really means that the element (nucleus) of interest is “transmuted” -- by absorbing a neutron -- into a heavier nucleus that is radioactive. This “activated” nucleus is then detected by recording the gamma ray emitted when it disintegrates by beta decay.

The sequence just described (neutron absorption followed by beta-decay) *is analogous to a step along the **s-process path*** (see class hand-out). The only difference in the case of neutron activation is that the source of neutrons is a man-made reactor (and the target nuclei are different).

Here’s an example: Analysis of SiO_2 glass for sodium impurities...

Step 1 Place glass sample in reactor



^{23}Na is “activated” by conversion to ^{24}Na: $^{23}\text{Na} + \text{N} \rightarrow {}^{24}\text{Na}$
(^{24}Na is radioactive)

Step 2 Detect ^{24}Na decay events by counting rays produced by the reaction

$$^{24}\text{Na}\ (\ ^{-}, \ ) \ ^{24}\text{Mg}$$