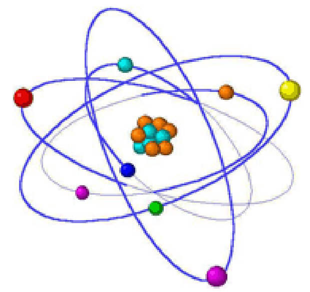
Radioisotope and Radiation Applications (FS2013)



Origin of the Nuclides (Week 1c, Seminar)

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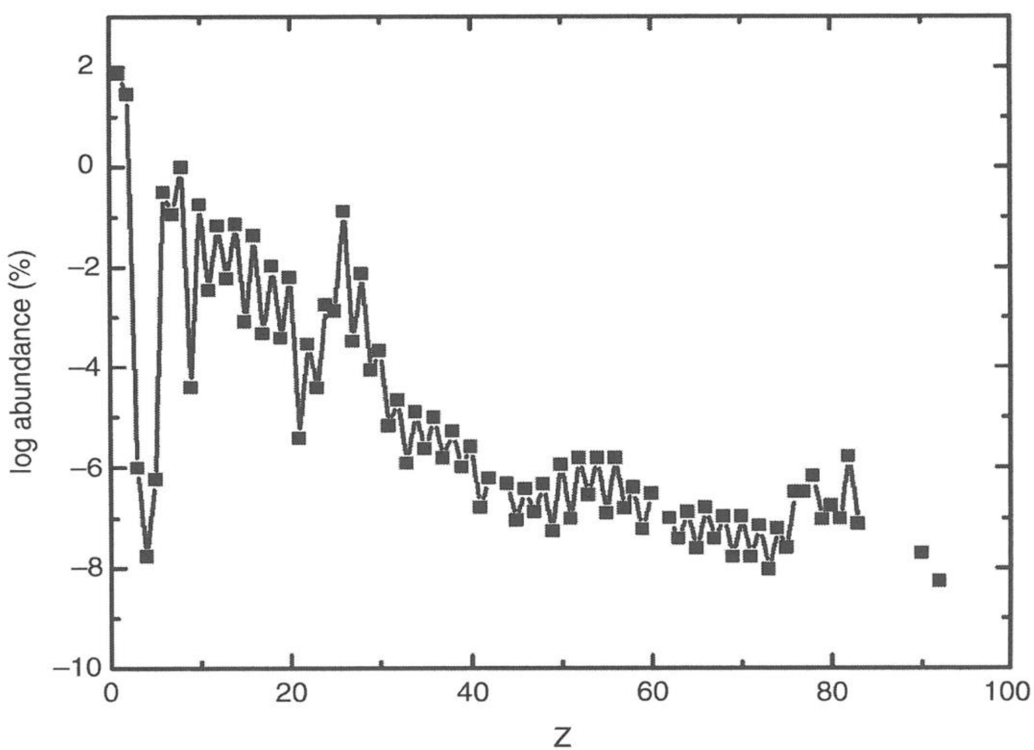
Origin of the Nuclides: Table of Contents

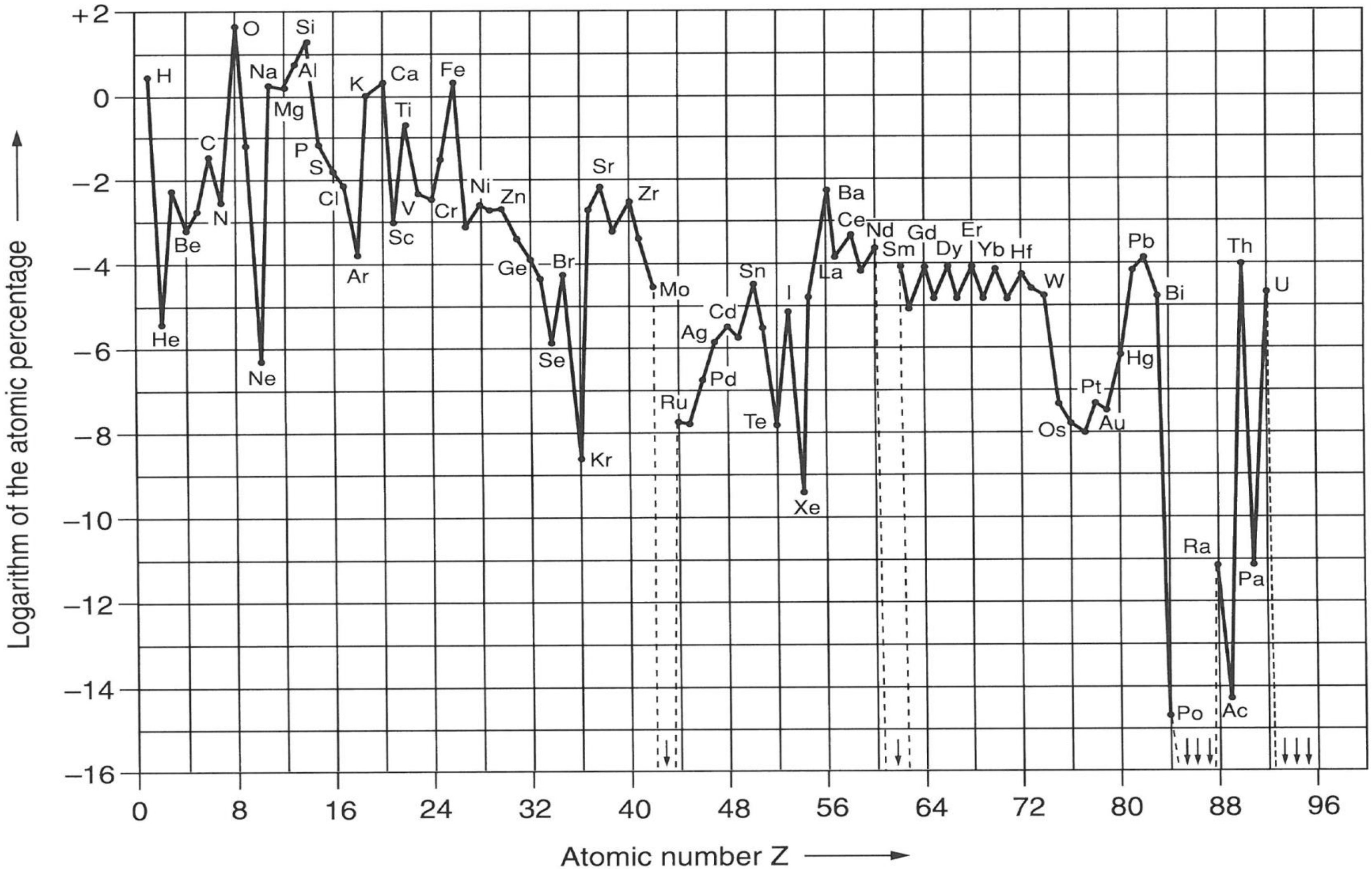
- Introduction: Nuclear Astrophysics
- Big-Bang and Big-Bang Nucleosynthesis
- Stellar Evolution and Burning Phases
  - Hertzsprung-Russell Diagram
  - Hydrogen Burning
  - Helium Burning and Higher Burning Stages
- Death of Stars: White Dwarfs and Supernovas
  - s-process
  - r-process
  - other processes (p-process, rp-process, ν-nucleosynthesis, νp-process)
- Radionuclides in the Environment
- Summary

(Nuclear) Astrophysics

- Is the offspring of the marriage of (nuclear) physics and astronomy.
- Topics in Astrophysics are: Astronomy (radio, infrared, optical, ultraviolet, X-ray, γ-ray), stellar dynamics and evolution, galaxy formation, large-scale structure of matter in the universe, origin of cosmic rays, black holes, gravitational waves (general relativity), physical cosmology, astroparticle physics.
- Nuclear Astrophysics strives to answer the following questions:
  - How did the chemical elements that we have on Earth come into existence?
  - Where in space were they formed?
  - How does stellar energy production work (How does the sun shine?)
- Diagram shows the abundances of the elements in the solar system (mass-%).



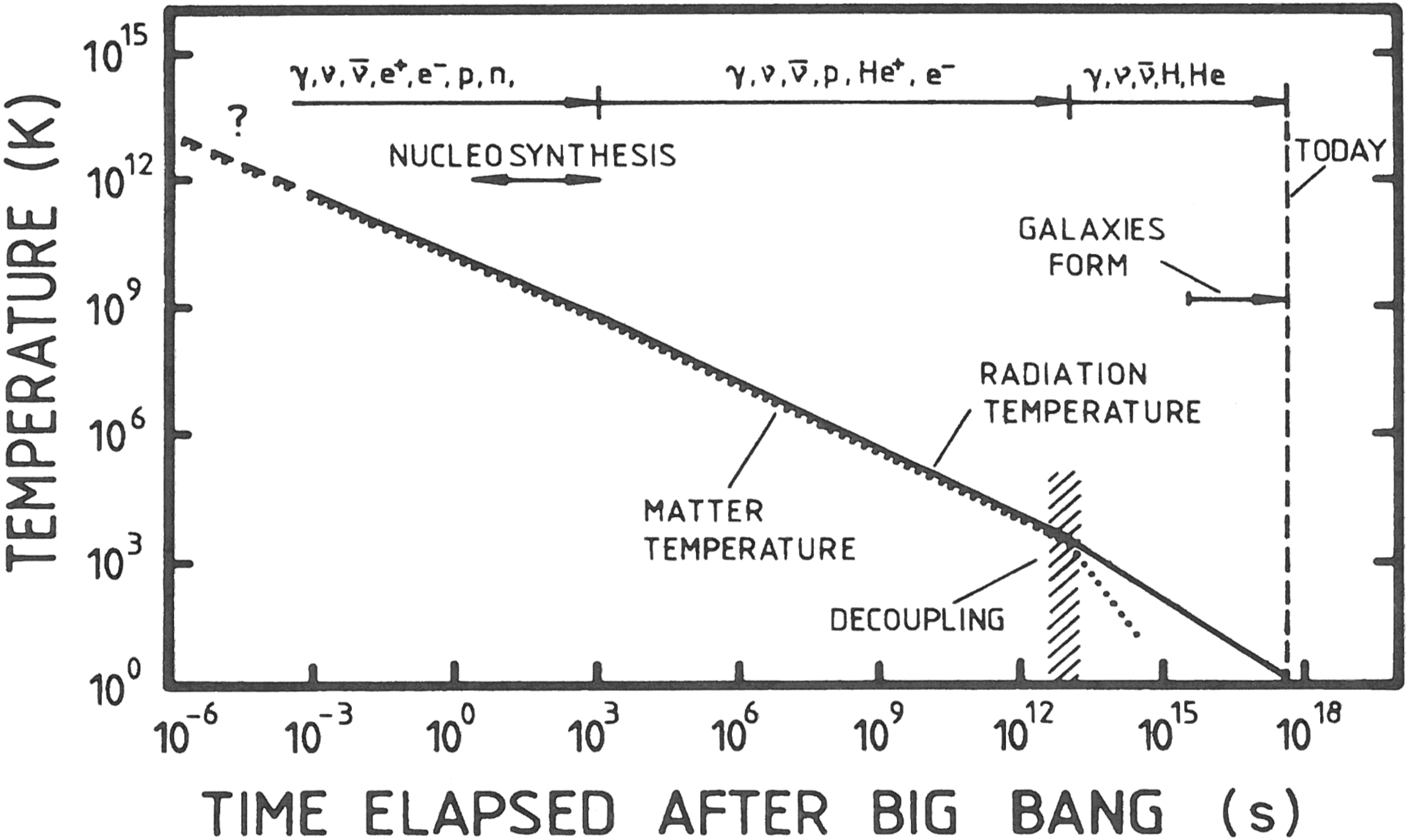
Astrophysics: Explain abundances of the elements and isotope variations



Abundance of the elements on the surface of the earth (lithosphere, hydrosphere and atmosphere).

Big Bang

- The universe is thought to have begun with a cataclysmic explosion. Pieces of evidence for this "Big Bang" are:
  - Astronomical observations show that the universe is isotropically expanding (red shift).
  - There is a 2.7 K universal microwave background radiation, the thermal remnant of the Big Bang EM-radiation.

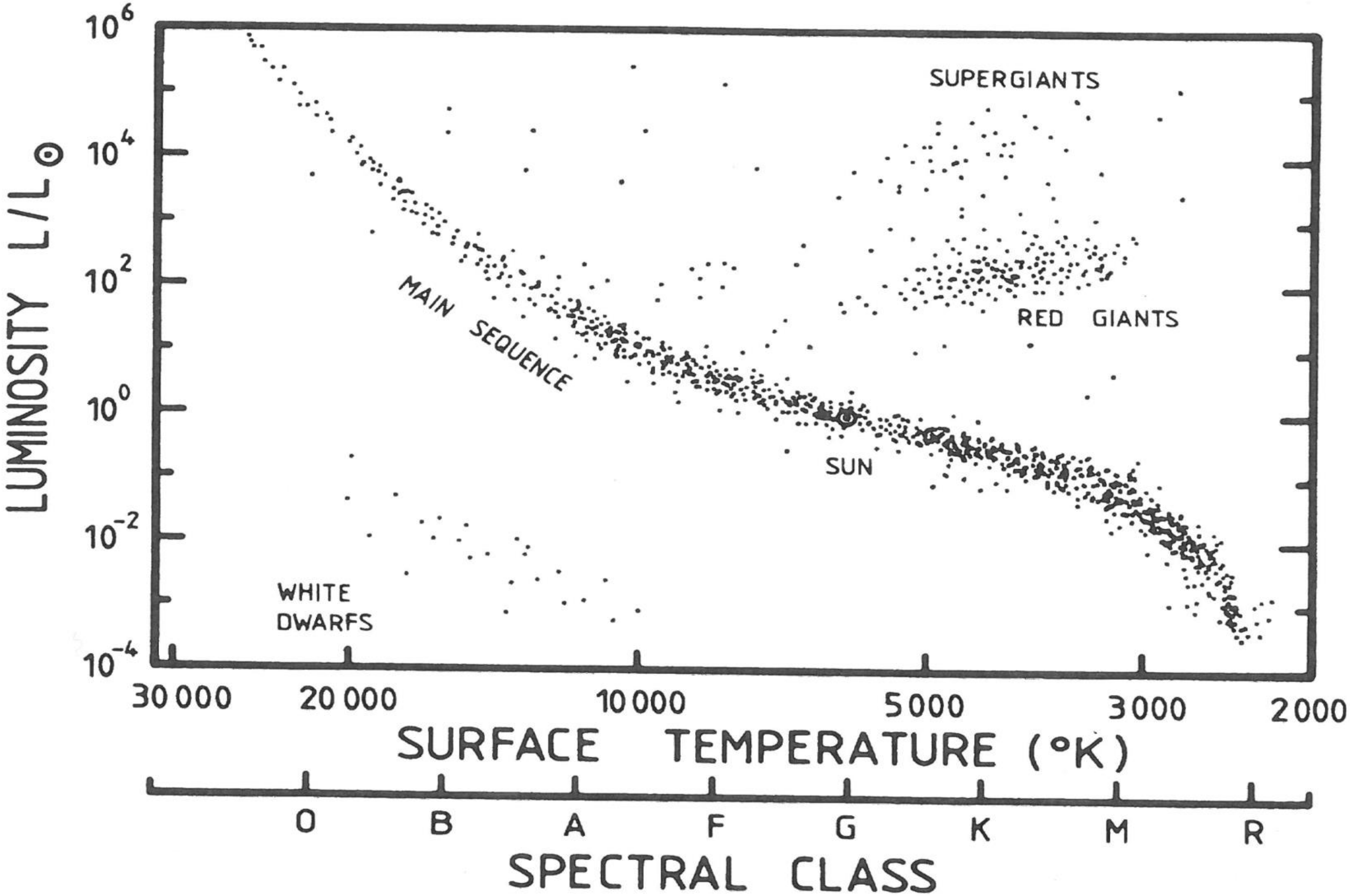


Big Bang Nucleosynthesis (BBN)

- After about 200 s and at a temperature of about 10^9 K primordial nucleosynthesis (or BBN) began with the reaction: $n + p \rightarrow d + \gamma$
- At this time the reverse reaction $d + \gamma \rightarrow n + p$ declined, such that the deuteron lived long enough to allow for the reactions:
  - $p + d \rightarrow {}^3He + \gamma$
  - $n + d \rightarrow {}^3H + \gamma$
- As ^{3}He and ^{3}H are more strongly bound, further reactions leading to the very stable α–particle can occur:
  - ${}^3H + p \rightarrow {}^4He + \gamma$
  - ${}^3He + n \rightarrow {}^4He + \gamma$
  - ${}^3H + d \rightarrow {}^4He + n$
  - $d + d \rightarrow {}^4He + \gamma$
- As stable nuclei with A=5 and A=8 do NOT exist, further (A=1 step) reactions cannot take place. Just some ^{7}Li is produced by:
  - ${}^4He + {}^3H \rightarrow {}^7Li + \gamma$
  - ${}^4He + {}^3He \rightarrow {}^7Be + \gamma$ and ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
- ^{7}Li is very weakly bound and rapidly destroyed. Thus the synthesis of larger nuclei was blocked. Further nucleosynthesis goes on in stars.

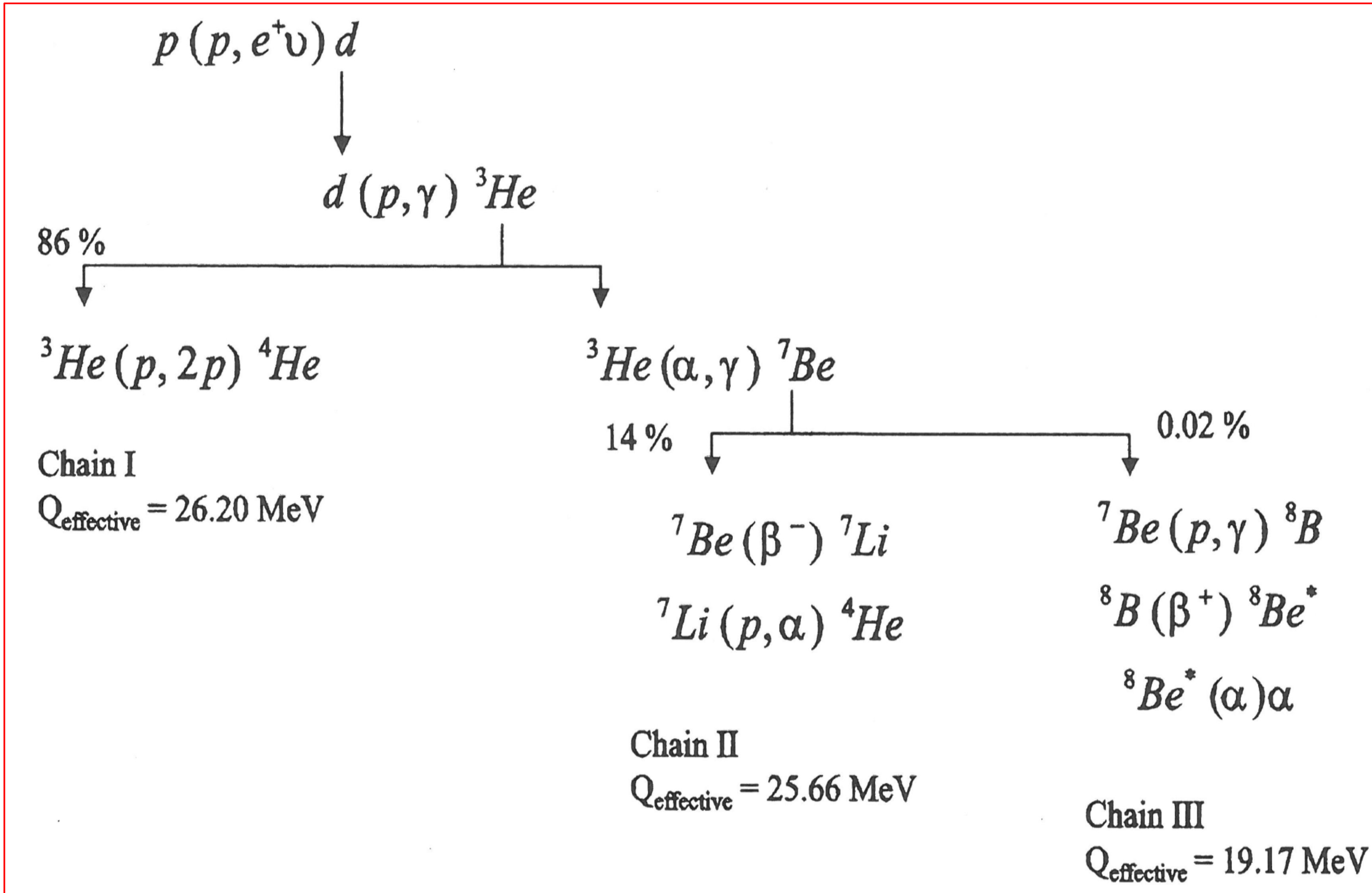
Stellar Evolution: Hertzsprung-Russell diagram

- A well defined correlation between luminosity and surface temperature of stars was observed by Hertzsprung and Russell. Most stars (like our sun) fall in a narrow band called the main sequence.



Hydrogen Burning

- Three chains of nuclear reactions that constitute hydrogen burning and convert protons into ^4He. The rate-limiting step in all reactions is the first reaction to create the deuterium. (CNO-cycle not discussed.)



Helium Burning and Higher Burning Stages

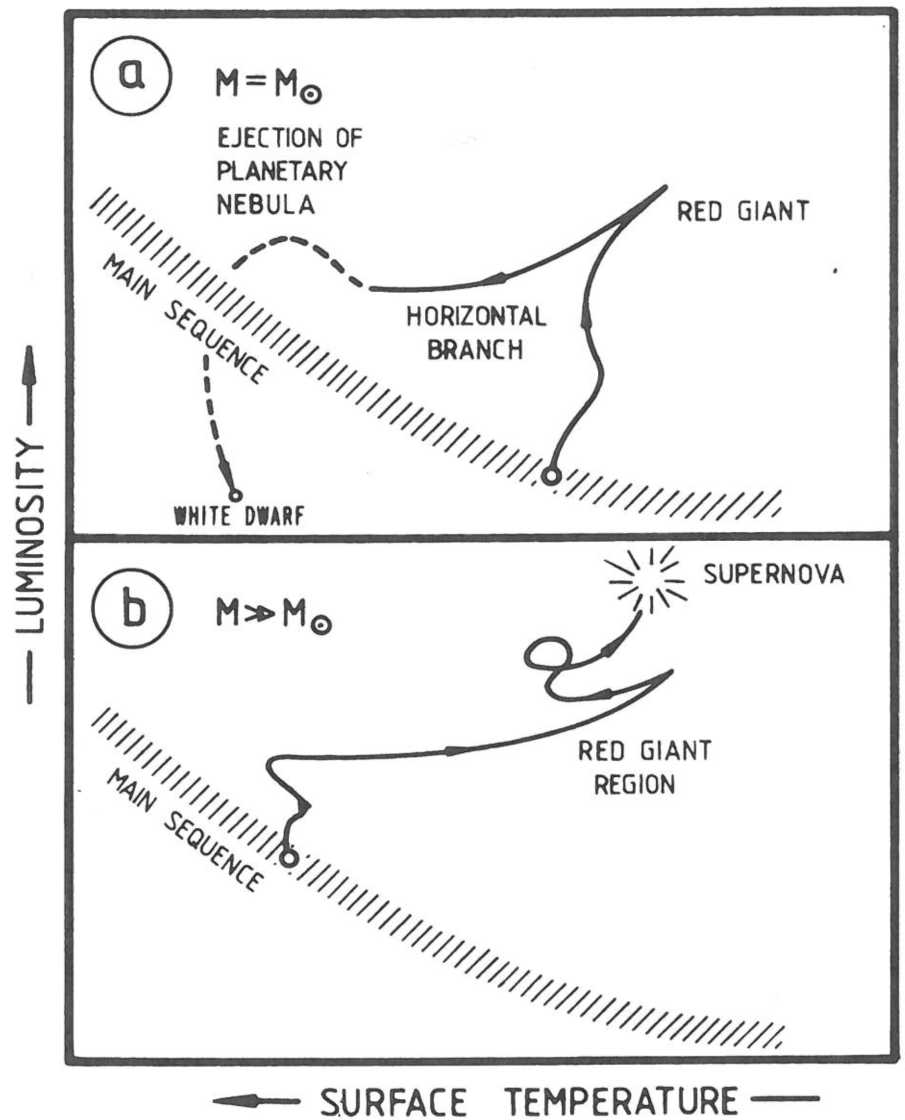
- When the hydrogen fuel of a star is exhausted a further gravitational collapse will occur leading to temperatures up to 1-2 x 10^8K. In this red giant helium burning will start by the triple-α-process:
  - $3\,{}^4He \rightarrow {}^{12}C + \gamma$ (through a resonance in ^{12}C)
- After some amount of ^{12}C has been formed the following reactions can take place:
  - ${}^4He + {}^{12}C \rightarrow {}^{16}O + \gamma$
  - ${}^4He + {}^{16}O \rightarrow {}^{20}Ne + \gamma$
- And nucleosynthesis may continue with neon-burning:
  - ${}^4He + {}^{20}Ne \rightarrow {}^{24}Mg + \gamma$
- … and carbon and oxygen burning:
  - ${}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^4He$; ${}^{23}Na + p$; ${}^{23}Mg + n$; ${}^{24}Mg + \gamma$
  - ${}^{16}O + {}^{16}O \rightarrow {}^{24}Mg + 2\,{}^4He$; ${}^{28}Si + {}^4He$; ${}^{31}P + p$; ${}^{31}S + n$; ${}^{32}S + \gamma$
- … and silicon burning up to nuclei with A~60:
  - ${}^{28}Si + {}^4He \leftrightarrow {}^{32}S + \gamma$
  - ${}^{32}S + {}^4He \leftrightarrow {}^{36}Ar + \gamma$
  - …
  - ${}^{52}Fe + {}^4He \leftrightarrow {}^{56}Ni + \gamma$

Time Scales of Nucleosynthetic Reactions in a 1 Solar Mass Star

Reaction	Time
H burning	6×10^9 y
He burning	0.5×10^6 y
C burning	200 y
Ne burning	1 y
O burning	Few months
Si burning	Days

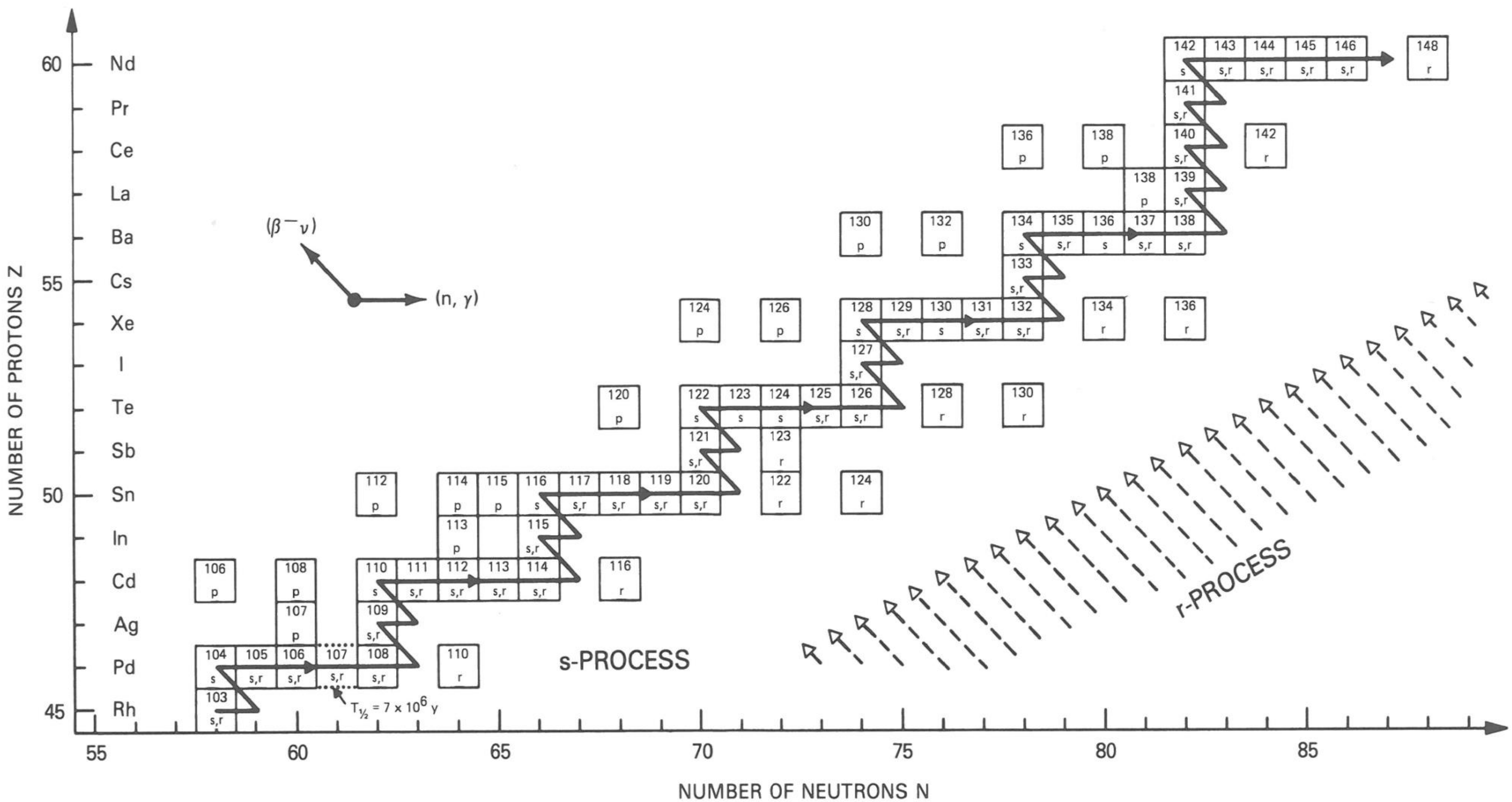
Death of Stars: White Dwarfs and Supernovas

- How the life of a star ends depends to a large extent on the mass of the star:
  - Stars with masses ~ M_{solar} do not reach the temperatures in their center to complete all burning stages. They extinguish and end as white dwarfs.
  - Stars with masses > 8 M_{solar} complete all stellar burning stages and can have an explosive end (supernova). The brightness of the star increases by a factor of $10^6 - 10^9$ releasing ~10^{51} ergs on a time scale of seconds. During the stellar explosion a lot of neutrons can be released leading to (n, γ)-reactions on iron-seed nuclei in the core.

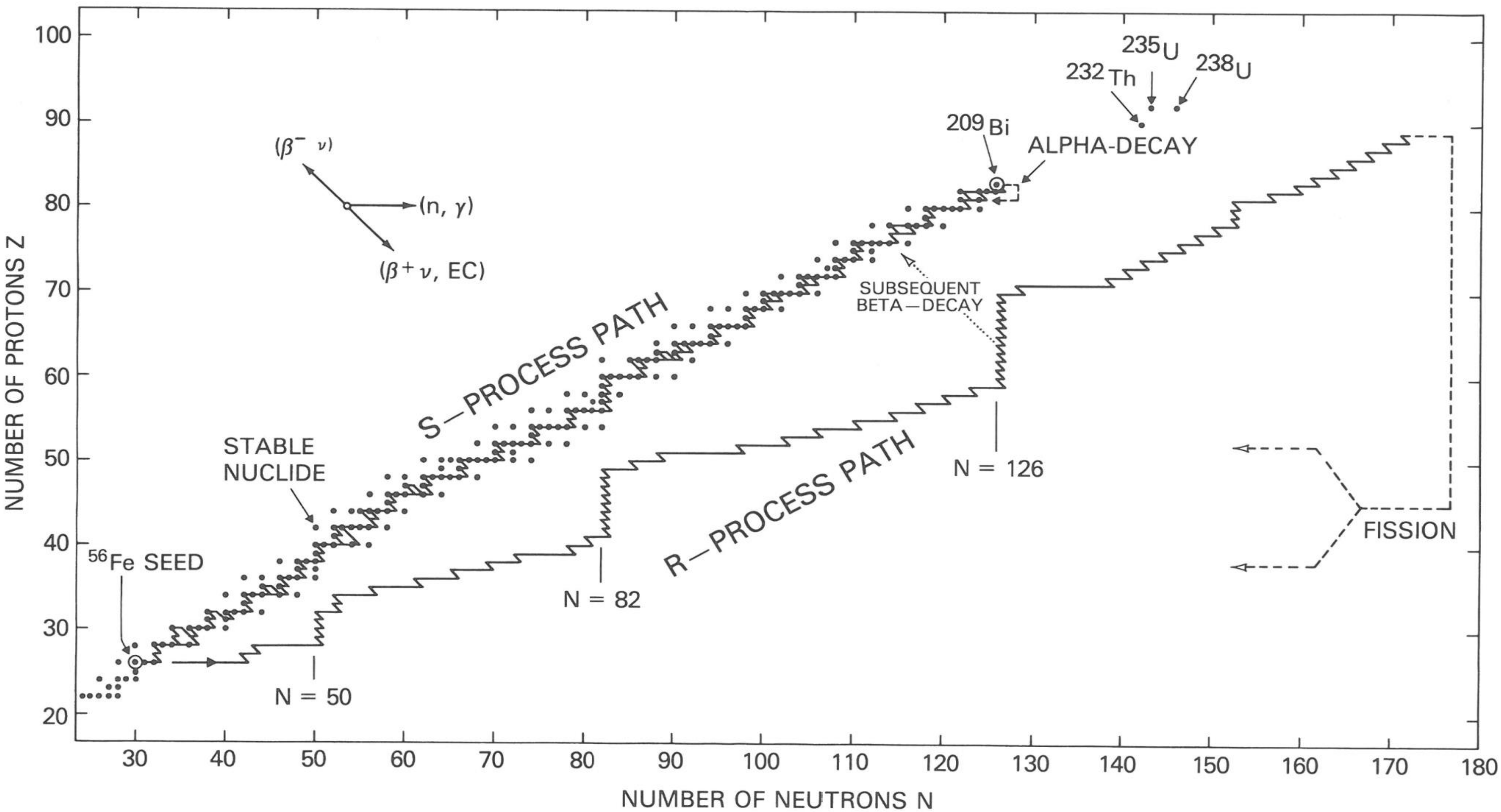


s-process: Buildup of A>60 nuclei by slow n-capture

- $^{56}Fe+n \rightarrow ^{57}Fe$(stable)$+\gamma$; $^{57}Fe+n \rightarrow ^{58}Fe$(stable)$+ \gamma$; $^{58}Fe+n \rightarrow ^{59}Fe(t_{½}=44.5d)+ \gamma$; $^{59}Fe(\beta^-)^{59}Co$(stable)…
- The s-process terminates at ^{209}Bi: $^{209}Bi(n, \gamma)^{210}Bi(\beta^-)^{210}Po(\alpha)^{206}Pb(n, \gamma)(n, \gamma)(n, \gamma)^{209}Pb(\beta^-)\ ^{209}Bi$



r-process: Buildup of A>60 nuclei by rapid n-capture



Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The *s*-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (*N*, *Z*)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm^{-3}.

Other Processes that can synthesize Elements

p-process:

- Consists of a series of photonuclear reactions (γ,p), (γ,α), (γ,n) on seed nuclei from the s- or r-process.
- Leads to the synthesis of some proton-rich nuclei with $70 < A < 200$.
- Contribution to the abundances of most elements is very small, but there are some nuclei (^{190}Pt, ^{168}Yb) that seem to have been exclusively made by it.

rp-process:

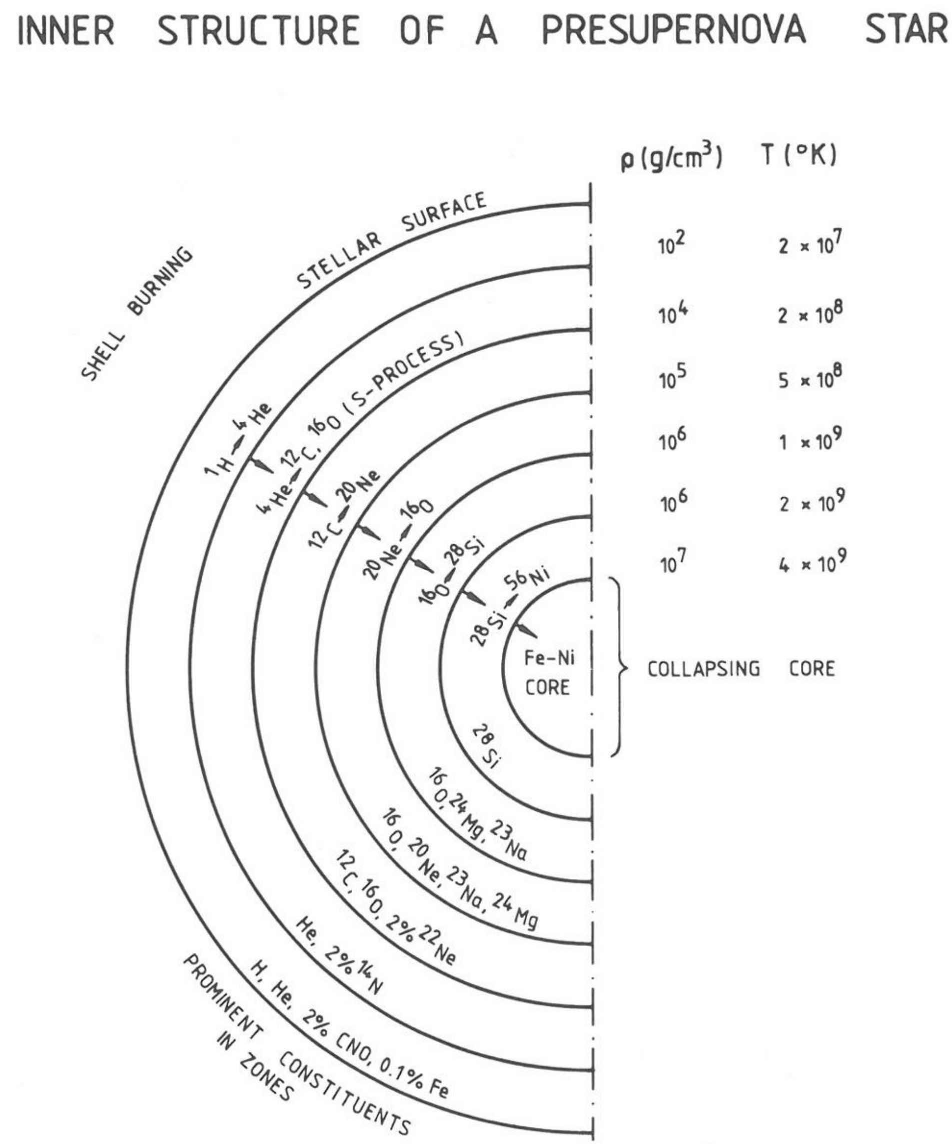
- Rapid proton capture process that makes proton-rich nuclei with $7 < Z < 27$ by (p, γ)-reactions and β^+-decays
- Creates p-rich nuclei like ^{21}Na, ^{19}Ne, and a small number of nuclei with $A < 100$.

ν-nucleosynthesis:

- In a type II supernova the intense neutrino flux of all flavors that passes through the onion layers of the PNS can cause a transmutation of nuclei via (ν, ν')- and (ν_e,e^-)-, ($\bar{\nu}_e$,e^+)-reactions on nuclei.
- Some rare isotopes that could be due to this process are ^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta.

νp-process:

- Occurs in supernovae when strong neutrino fluxes create proton-rich ejecta.
- In this process antineutrino absorptions produce neutrons that are immediately captured by proton rich nuclei.
- Nuclei with $A > 64$ can be produced, e.g., ^{92,94}Mo and ^{96,98}Ru.



Radionuclides in the Environment (1)

Stages of the evolution of the earth.

Time before present	Stage
$5 \cdot 10^9$ y	Solar nebula
$4.6 \cdot 10^9$ y	Formation of the solar system
$4.5 \cdot 10^9$ y	Formation of the earth, the moon and of meteorites
$4.3 \cdot 10^9$ y	First stages of the earth's crust, formation of the oldest minerals found on the earth, formation of hydrosphere and atmosphere
$3.9 \cdot 10^9$ y	End of major meteoritic impacts
$3.8 \cdot 10^9$ y	Beginning of formation of rocks
$(3.8\text{–}3.5) \cdot 10^9$ y	Formation of oldest rocks
$3.5 \cdot 10^9$ y	First traces of life (stromatolites)

Ratio of the activities of some long-lived radionuclides at the time of the birth of the earth to those present.

Radionuclide	Activity ratio A/A_0
^{40}K	11.4
^{87}Rb	1.07
^{232}Th	1.02
^{235}U	84.1
^{238}U	2.01

Radionuclides from natural decay series

Decay series	Decay mode of the mother nuclide	Half-life of the mother nuclide [y]	Range of dating [y]	Application
^{238}U ... ^{226}Ra ... ^{206}Pb	α	$4.468 \cdot 10^9$	10^6–10^{10}	Minerals, geology, geochemistry
^{235}U ... ^{207}Pb	α (sf: $3.7 \cdot 10^{-7}$%)	$7.038 \cdot 10^8$	10^6–10^{10}	Minerals, geology, geochemistry
^{232}Th ... ^{208}Pb	α	$1.405 \cdot 10^{10}$	10^6–10^{10}	Minerals, geology, geochemistry
^{210}Pb ... ^{206}Pb	β^-	22.3	20–150	Ice, exchange with the atmosphere

Radionuclides in the Environment (2)

Cosmogenic radionuclides

Radio-nuclide	Production	Decay mode and half-life [y]	Production rate [atoms per m^2 per y]	Range of dating [y]	Application
^{3}H (T)	$^{14}N(n, t)\ ^{12}C$	β^-, 12.323	$\approx 1.3 \cdot 10^{11}$	0.5–80	Water, ice
^{14}C	$^{14}N(n, p)\ ^{14}C$	β^-, 5730	$\approx 7 \cdot 10^{11}$	$2.5 \cdot 10^2$–$4 \cdot 10^4$	Archaeology, climatology, geology (carbon, wood, tissue, bones, carbonates)
^{10}Be	Interaction of p and n with ^{14}N and ^{16}O	β^-, $1.6 \cdot 10^6$	$\approx 1.3 \cdot 10^{10}$	$7 \cdot 10^4$–10^7	Sediments, glacial ice, meteorites
^{26}Al	Interaction of cosmic rays with ^{40}Ar	β^+, $7.16 \cdot 10^5$	$\approx 4.8 \cdot 10^7$	$5 \cdot 10^4$–$5 \cdot 10^6$	Sediments, meteorites
^{32}Si	Interaction of cosmic rays with ^{40}Ar	β^-, 172	$\approx 5.10^7$	10–10^3	Hydrology, ice
^{36}Cl	Interaction of cosmic rays with ^{40}Ar	β^-, $3.0 \cdot 10^5$	$(4.5$–$6.5) \cdot 10^8$	$3 \cdot 10^4$–$2 \cdot 10^6$	Hydrology, water, glacial ice
^{39}Ar	Interaction of cosmic rays with ^{40}Ar	β^-, 269	$\approx 4.2 \cdot 10^{11}$	10^2–10^4	–

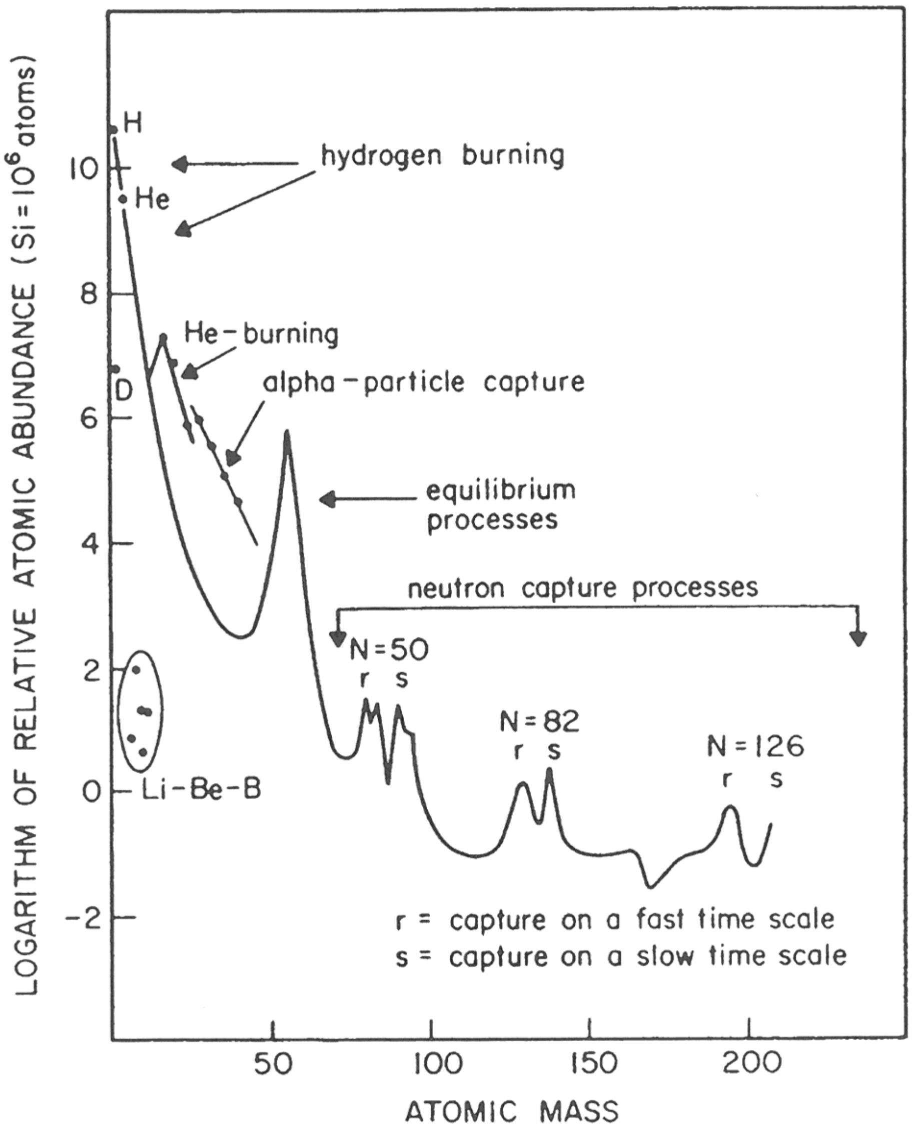
Radionuclides in the Environment (3)

Terrestrial radionuclides

Nuclide pair	Decay mode of the mother nuclide	Half-life of the mother nuclide [y]	Range of dating [y]	Application
$^{40}K/^{40}Ar$	β^- (89%) $\varepsilon + \beta^+$ (11%)	$1.28 \cdot 10^9$	10^3–10^{10}	Minerals
$^{87}Rb/^{87}Sr$	β^-	$4.8 \cdot 10^{10}$	$8 \cdot 10^6$–$3 \cdot 10^9$	Minerals, geochronology, geochemistry
$^{147}Sm/^{143}Nd$	α	$1.06 \cdot 10^{11}$	10^8–10^{10}	Minerals, geochronology, geochemistry
$^{176}Lu/^{176}Hf$	β^- (97%) ε (3%)	$3.8 \cdot 10^{10}$	10^7–10^9	Geochemistry
$^{187}Re/^{187}Os$	β^-	$5 \cdot 10^{10}$	10^6–10^{10}	Minerals

Summary

- Stars are Cauldrons in the Cosmos.
- The atomic abundances of the elements/isotopes in the solar system can largely be explained by astrophysical processes:
  - Big Bang Nucleosynthesis
  - Stellar burning phases
  - Explosive burning (s- and p-process)
- The radionuclides found in the lithosphere, hydrosphere and atmosphere are largely leftovers (decay-products) from supernova explosions.
- We consist of “star-dust”.
- **Radionuclides are a part of nature!**



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