Element abundances in the Universe

Abundances in the solar system

Photospheric and meteroic abundances

Cosmic abundances

What from where?

a) Primordial Nucleosysnthesis

b) Stellar Nucleosynthesis up to Iron

c) Nucleosynthesis beyond Iron

Definitions

- **Abundance in number** of an atomic species Z is the ratio between the number of atoms of this species and that of another species, X, chosen as a reference

$$n_Z = N(Z)/N(X)$$

- In the study of stellar photospheres one refers generally to Hydrogen, as this is the most abundant element. The quantity $n_Z = N(Z)/N(H)$ is directly derived by comparing intensities of the lines of element Z with those of Hydrogen.

- Another commonly used reference species is Sylicon (Si), which accounts for a large parte of Earth crust and of meteorites. In this case, $n'_Z = N(Z)/N(Si)$

- **The mass abundance** of an atomic species Z, (a_Z) is the fraction in mass of that elements in a sample

$$a_Z = m_z N(Z)/ \Sigma m_i N(i)$$

- Mass abundances are indicated in % o in "g/g", i.e. the quantity of that element contained in a gram of a substance.

Element abundances in the solar system

Abundances of the elements in the Solar System

- The figure shows number abundances, with respect to hydrogen

- Hydrogen is the most abundant element.

- Most of it is in the form ^1_1H, with Deuterium at the level of 10^{-5}.

- Next comes Helium, with number of atoms of about 1/12 with respect to Hydrogen

- Relative abundances decrease while Z increases
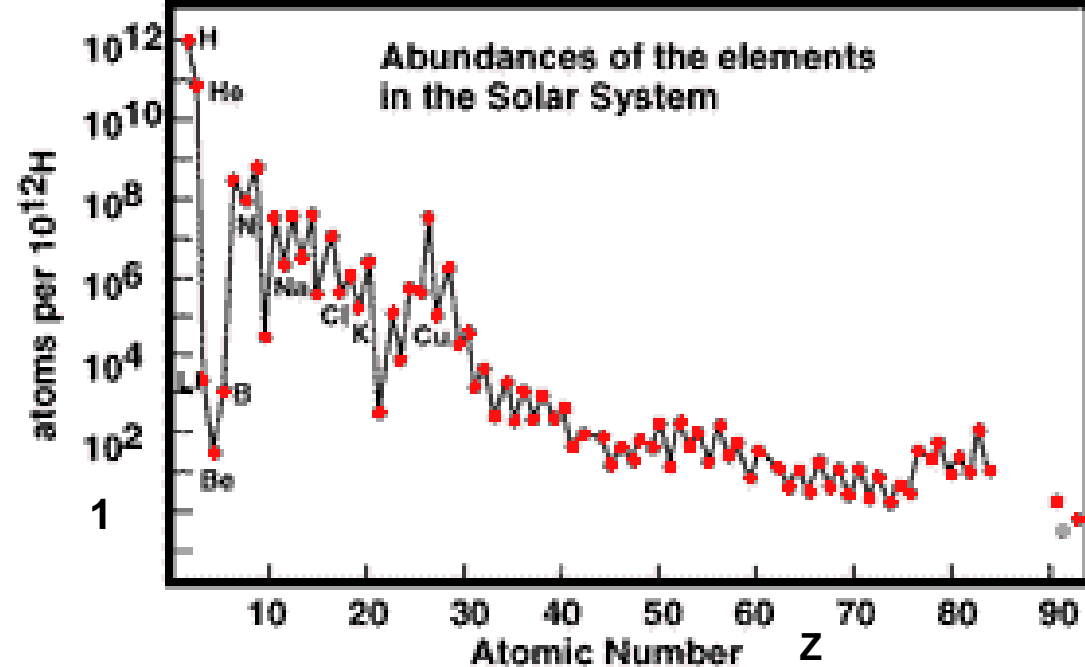
- Heaviest elements, as Uranium, have abundances as low as 10^{-12} with respect to Hydrogen

- In the solar system, mass abundances are $X=a_H=73\%$, $Y=a_{He}=25\%$, whereas elements with Z>2, generically indicated as "metals" total to about 2% ($Z=\Sigma_{Z>2}a_Z=2\%$)

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Photospheric abundances

- The main source of information about abundances in the solar system comes from the spectroscopy of the photosphere

- The diffusion time of elements in the sun is of order 10^{14} year (see next transparency)

- The photosphere is thus representative of the originary solar material, since there was not enough time to mix it with the inner part of the sun, where nuclear reactions occurs and element abundances change.

Z
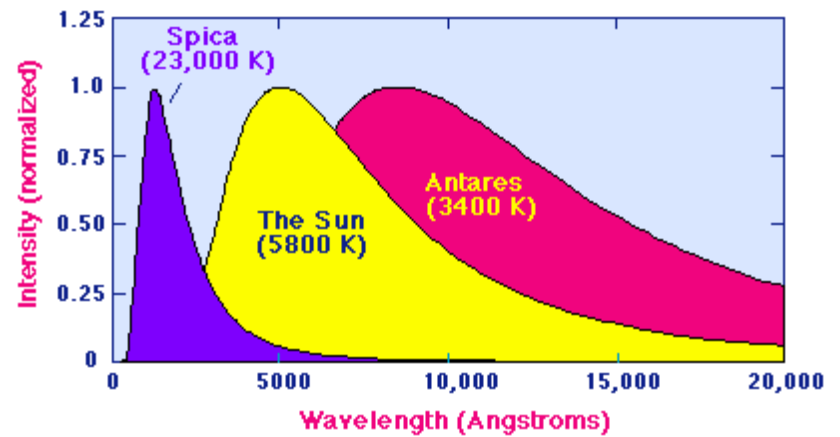
- Sun emits with the spectrum of a black body at temperature of 5800 ^{o}K, superimposed with the absorption lines specific of elements. From the line intensitites one decudes the abundances of elements, with respect to hydrogen..

- Helium has been discovered in the solar corona, but due to the position of its atomic levels one cannot determine its abundance in the photosphere with spectroscopic methods

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Time scale for diffusion in the Sun

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- The Sun has average density $n \approx 10^{24}$ cm^{-3} A single atom will make many collisions with the surrounding atoms. . The mean distance between two collisions is
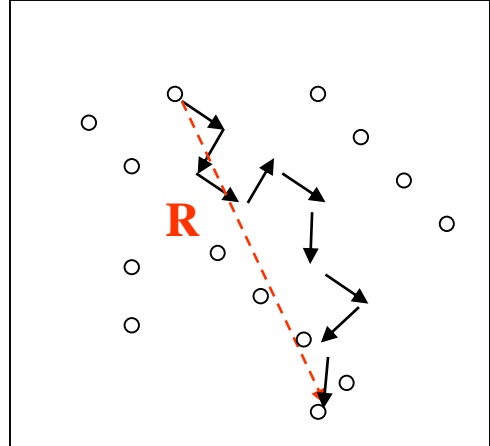
  $\lambda = 1/n\sigma \approx 1/[(10^{24}$ cm$^{-3})(10^{-16}$ cm^2 $)] \approx 10^{-8}$ cm.

- The speed will be of the order of the thermal movement. Taking m=10GeV e kT=1keV si ha
  $v \approx (kT/m)^{1/2} \approx c(1keV/10^7 keV)^{1/2} \approx 10^7$ cm/s

- After N collisions, the atom will have made a path: $\mathbf{R} = \Sigma_i \boldsymbol{\lambda}_i$ where $\boldsymbol{\lambda}_i$ are vectors with average length λ and arbitrary orientation

- By squaring $\mathbf{R}$ one has:

  $$R^2 = \mathbf{R} \cdot \mathbf{R} = \Sigma_i \boldsymbol{\lambda}_i{}^2 + \Sigma_{i \neq j} \boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j$$

- For large N the first term grows like λ^2 N, whereas the second term has contributions of varying signs, with null average. Thus on the average:

  (1) $<R^2> = N \lambda^2$

- The mean time between two collisions is $\Delta t = \lambda/v$, so that after time t

  (2) $N = t/\Delta t = tv/\lambda$

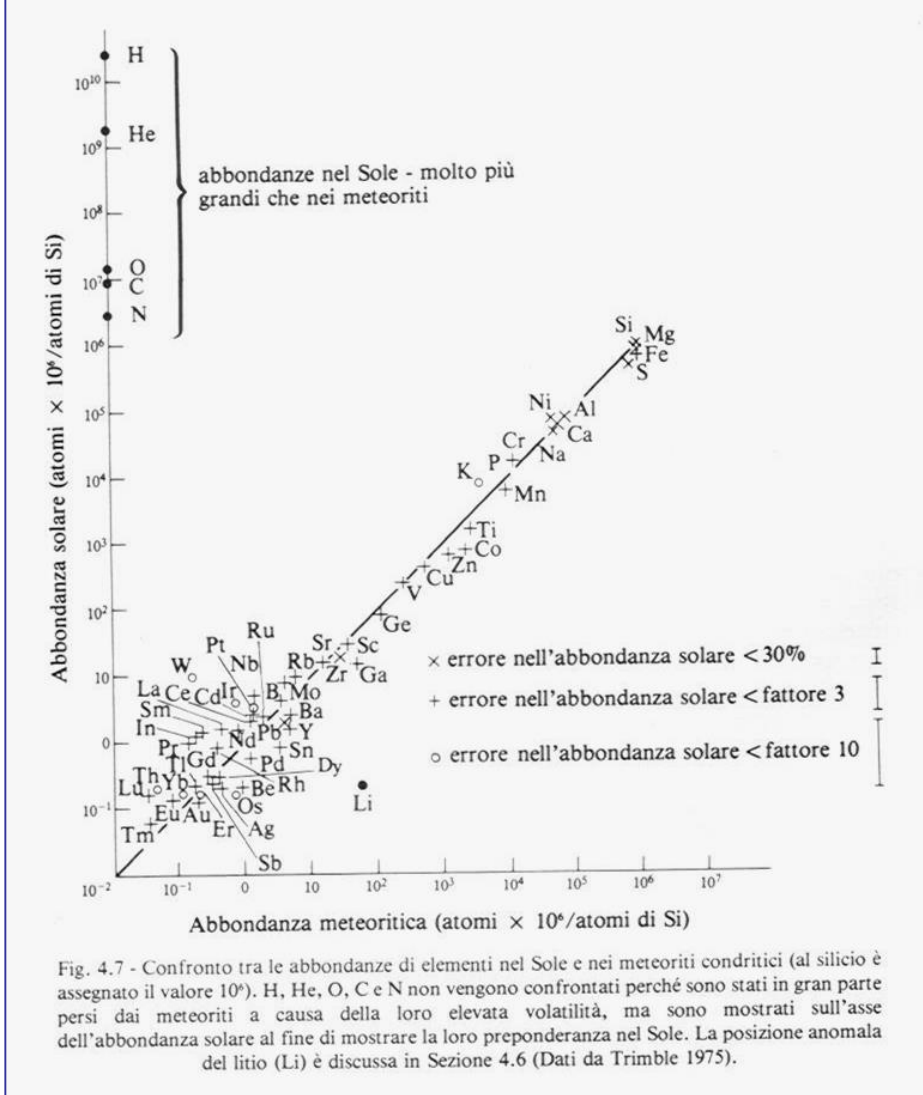- By combining (1) and (2) one has the law of Brownian motion

  (3) $<R^2> = vt \lambda$

- By requiring $<R^2> = (10^{10}$ cm$)^2$, i.e. a fraction of the solar dimension, one has

  $$t \approx 10^{14} \text{ yr}$$

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Meteroic abundances

- They are derived from the study of the composition of meteorites which had little chemical differentiation, i.e. with abundances similar to those of the pre-solar nebula.
- In this respect the so called "chondritic carbonaceous CI" meteorites are of particular interest
- It is natural that, with respect to the photosphere, in meteorites are rare Hydrogen, Helium and noble gaes , i.e. the most volatile elements which need a strong gravitational attraction for being trapped
- Generally, photospheric and meteroic abundances, when normalized to a common element (Sylicon) are concordant as a testimony of a substantially homogeneous composition of the solar system

Fig. 4.7 - Confronto tra le abbondanze di elementi nel Sole e nei meteoriti condritici (al silicio è assegnato il valore 10^6). H, He, O, C e N non vengono confrontati perché sono stati in gran parte persi dai meteoriti a causa della loro elevata volatilità, ma sono mostrati sull'asse dell'abbondanza solare al fine di mostrare la loro preponderanza nel Sole. La posizione anomala del litio (Li) è discussa in Sezione 4.6 (Dati da Trimble 1975).

- *There is a single exception, not yet understood: in the Sun Li is depleted by a factor 100 with respect to meteoites*

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Cosmic abundances

- The main features of the abundances in the solar system are also found in other stars and galaxies
- Hydrogen and Helium abundances ($a_H \approx 75\%$; $a_{He} \approx 25\%$) are universal.
- Elements beyond He and preceding Carbon(Li, Be, B) are particularly depleted
- There is a peak in the C-O region
- Another peak is present close to Iron and a next one around Lead.

Abundances of the elements in the Solar System
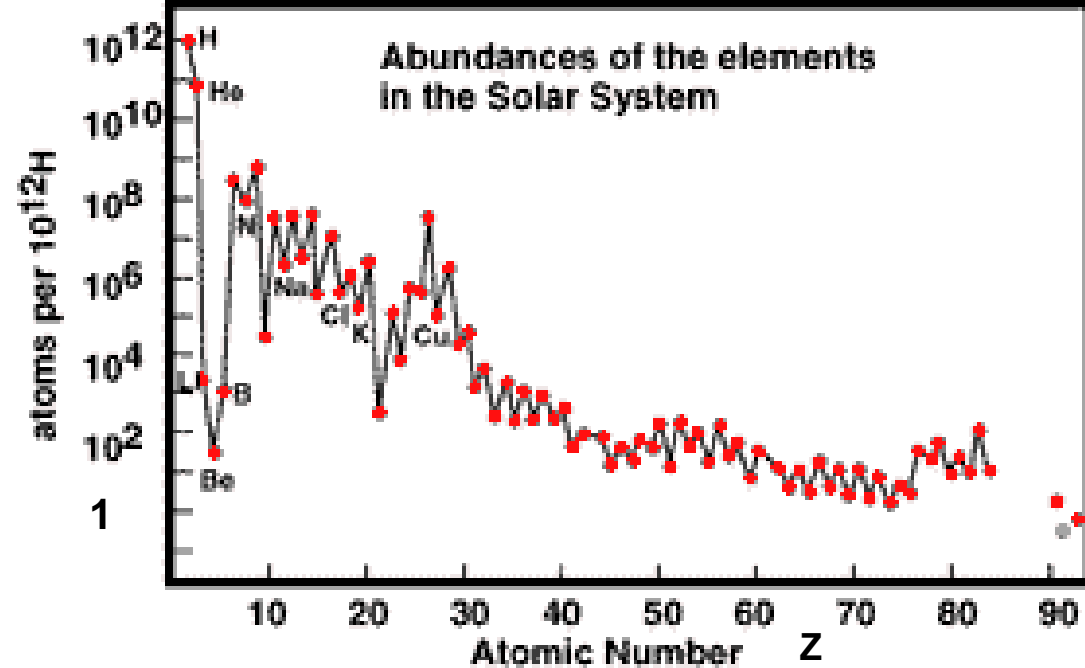
- Metal abundances are variable, from Z=2% (population I stars *) down to Z=0.01 % (population II stars).

- So far, no star has been observed without metals (population III)

- *The term "population I" might be misleading: actually these are believed to be most recent stars, formed with prestellar material which had been stronlgy recycled '

The 3 cosmic kitchens

Abundances of the elements in the Solar System

- Element abundances we are observing are the fruit of three distinct cosmic kitchens

A) Primordial nucleosynthesis

B) Stellar nucleosynthesis, up to Iron ,

C) Stellar nucleosynthesis beyond iron

- A) e B) correspond to exo-energetic nuclear fusion reactions

- C) corresponds to endo-energetic processes, where formation of heavier elements requires energy absorption.

- We need both A) che B) in order to :

  -account for the Helium abundance in the universe (A)

  -account for variable metal abundances
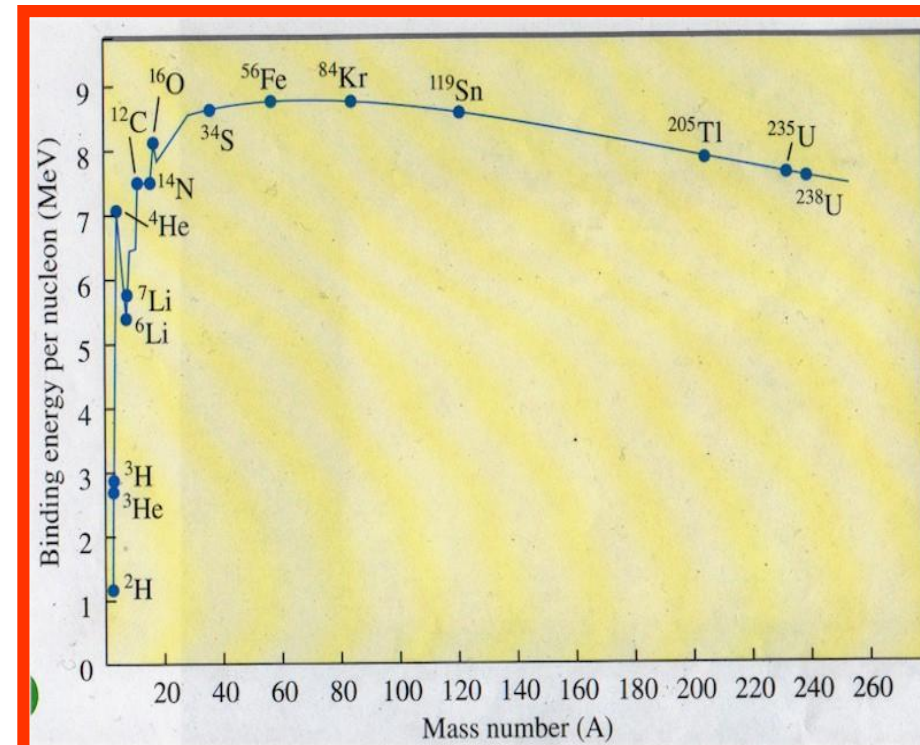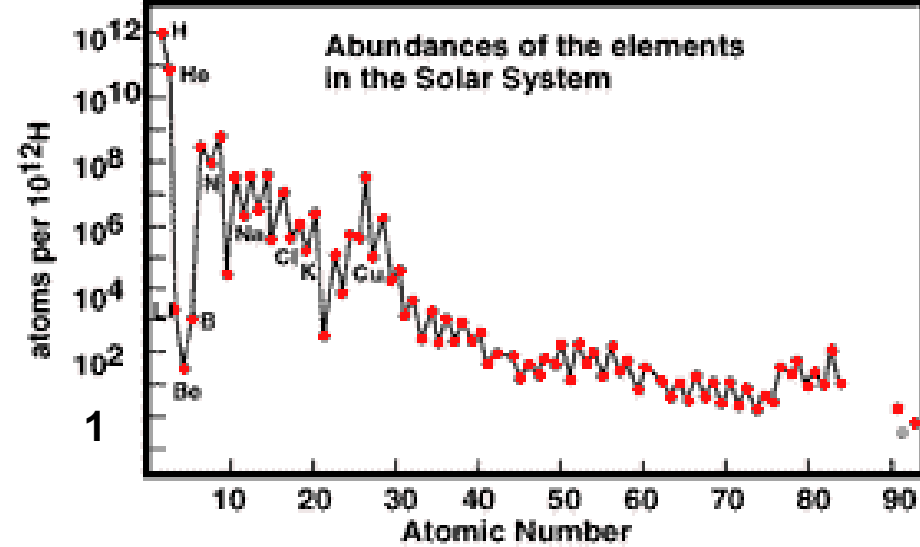
Notes about nuclear fusion and fission

- Binding energy per nucleon ε grows with A for A<60, where it reaches a maximum (≈9 MeV), and then slowly decreases.
- This means that energy can be liberated by fusion of two nuclei A_1 e A_2 as long as A= A_1 + A_2 <60.
- Indeed the mass of A nucleus is
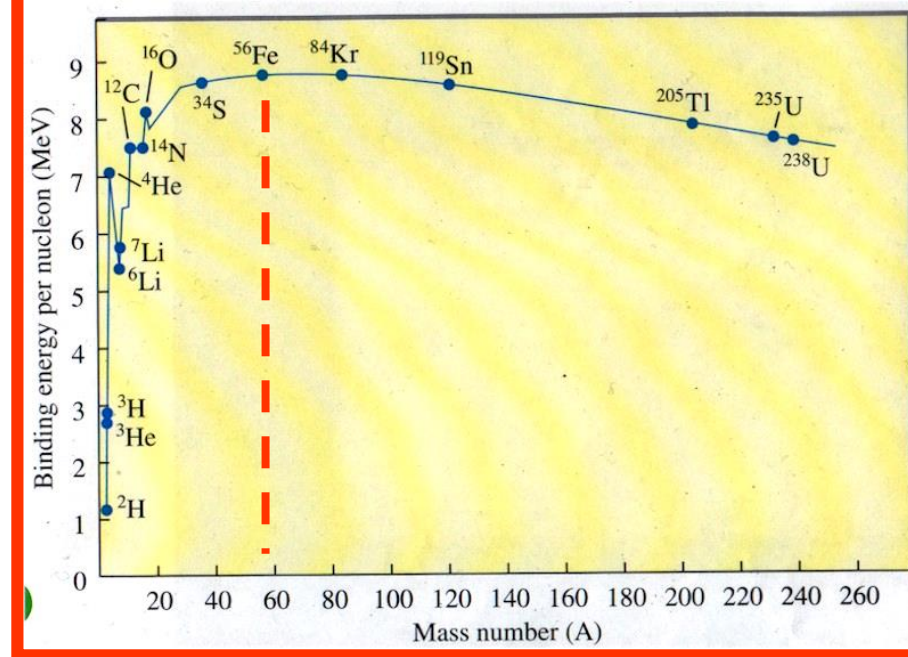
$$M(A)c^2 = (Z_1+Z_2)m_pc^2 + (N_1+N_2)m_nc^2 - E_b(A)$$

The binding energy of this nucleus is

$$E_b(A) = A\, \varepsilon(A) = A_1\, \varepsilon(A) + A_2\, \varepsilon(A) > A_1\, \varepsilon(A_1) + A_2\, \varepsilon(A_2)$$

so that

$$M(A)c^2 < (Z_1+Z_2)m_pc^2 + (N_1+N_2)m_nc^2 - A_1\, \varepsilon(A_1)\ A_2\, \varepsilon(A_2) = M(A_1)c^2 + M(A_2)c^2$$

Since $M(A) < M(A_1) + M(A_2)$ the reaction $A_1 + A_2 \rightarrow A$ liberates energy .

- Conversely, the fission of a nucleus with large A, is energetically favored, i.e. the fission fragments are more bound and the fission process liberates energy

First elements about primordial nucleosynthesis

- In the first minutes after the Big Bang neutrons bind to protons through nuclear capture reactions, as example:
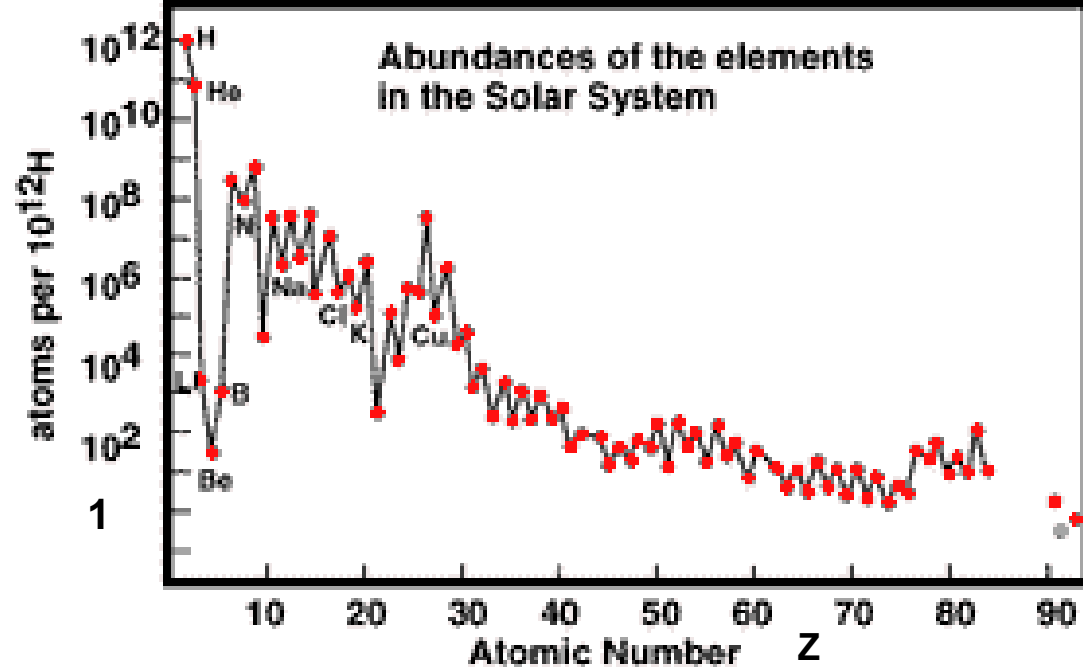
$$p + n \rightarrow d + \gamma$$

$$d + p \rightarrow {}^3He + \gamma$$

$${}^3He + n \rightarrow {}^4He + \gamma$$
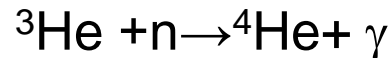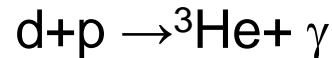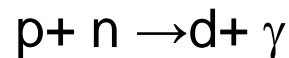
The net result is the transformation:

$$2p + 2n \rightarrow {}^4He + energy$$

In the intermediate stages stable* nuclei, are formed, which can wait for the arrival of another particle to be captured.

- *same if unstable, however with half lives larger than a few minutes…*

Abundances of the elements in the Solar System

- The series of reactions ends with ^4He since for A=5 there are no stable systems
- Elements heavier than ^4He are formed by means of 3α reactions

$${}^4He + {}^4He + {}^4He \rightarrow {}^{12}C + energia$$
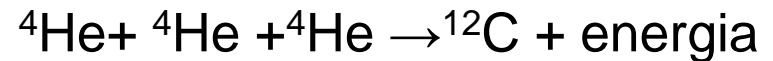
- This occurs for densities large enough to allow for a 3 body reaction .
- The produced elements are immitted in the interstellar gas through the final explosion of stars.