Nucleosynthesis *

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Goals
Where and how were H and He created? How were the rest of the elements created (i.e., what the astronomers call "metals"!) ?

Cosmological nucleosynthesis: *Big Bang (production of H, He, and small amounts of ^{7}Li)*
Sequence of events:

1. Initial condition - *singularity: due to extrapolation of the expansion of the universe back in space/time (indistinguishable)* - Inflation followed by baryogenesis (10^{-37} s) where the quark soup cools to ionized plasma containing (predominance of matter over antimatter): creation of quarks and leptons, which then leads to the production of photons (γ), e^-, positrons (e^+), neutrinos (ν), protons, neutrons
2. Extreme temperatures allow protons to combine with e^- to make neutrons, ultimately leading to a neutron to proton ratio of $\sim$1
3. Cooling down to 10^{10}K – neutrons production attenuated. Note: half-life of free neutron in vacuum is 611 sec (i.e., a mean lifetime of 881.5±1.5 s) – otherwise a neutron decays to a proton by emitting a nuclear electron: β^- decay
4. At 10^9K (when neutron/proton ratio is 1:10), initial state is cooled to where neutrons combine with protons to form D (^{2}H)
5. Deuterium is reactive – collisions between H and D give rise to ^{3}He and then ^{4}He nucleui (He production in big bang)
6. Further cooling allows protons to combine with e^- to form neutral atoms at 3000K
7. Rotation and gravitational collapse of ISM, cloud fragments cause them to centrally build up mass, frictionally heat up, and eventually ignite their deep, high pressure cores into nuclear fusion fires and a star is born.

The remaining elements (i.e., He and heavier elements) are created in stars of varying masses and states of evolution. The Big Bang theory is based on two major assumptions: (1) that physical laws are universally applicable in time and space and (2) the cosmological principle, which states that the universe is homogeneous and isotropic on large scales. The universe is 13.77 ± 0.06 Ga old based on the background radiation left over from the Big Bang.

Stellar Evolution: Hertzsprung-Russell diagram
The HR (Hertzsprung-Russell) diagram provides a guide and a classification scheme of

**lecture 1 for "Rock and Mineral Science III" or "Advanced Earth Science I"* star types, showing the relationship between a stars' absolute magnitude or luminosity versus its Spectral class (stellar classifications) or effective temperatures. A star's brightness is plotted against its temperature (color); our own Sun plots along the main sequence of stars. Most stars are main sequence stars and are fusing hydrogen in their cores. After burning through their hydrogen budget, stars move off of the main sequence to become a giant moving along the red giant branch. It is at this stage that begins fusion in a hydrogen shell that surrounds a helium core. Solar luminosity is proportional to a stars' mass, which reflects the balance between gravitational (collapse) and thermal (expansion) forces. Betelgeuse, the ninth-brightest star in the night sky (Orion constellation) is a red supergiant and if it were at the center of the Solar System, its surface would extend past the asteroid belt.

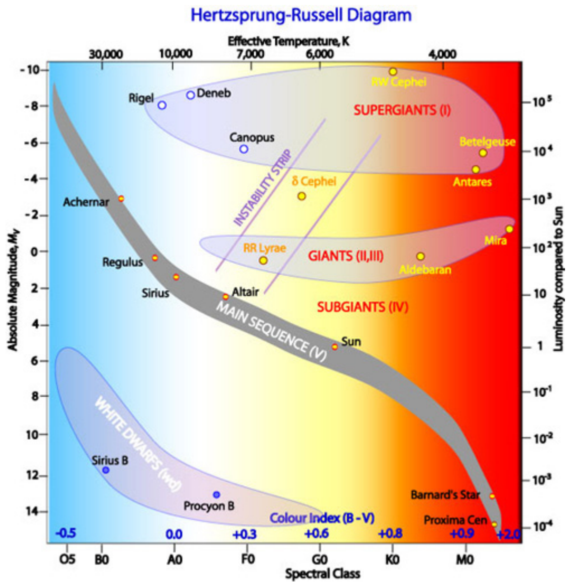

Figure 1: Hertzsprung-Russell diagram

Observations:
- Many stars lie on a linear "Main sequence" trend (i.e., the more massive, the bigger)
- Path and timing of star's evolution depends on its luminosity (mass)
- Stars eventually leave the main sequence and evolve to Red Giants
- Red Giants may evolve further to supernova stage
- Inside Red giants and supernovae: neutron capture occurs synthesizing elements Z > Fe

The Sun

Our Sun is a relatively small main sequence star, which will evolve to red giant in another 4-5 Ga (with a total time on main sequence of 10 Ga). It is powered by nuclear fusion in its core involving H burning to form He. The standard solar model (SSM), based on equation of hydrostatic equilibrium that are integrated numerically, assumes a spherical structure of symmetric shells, with the central core of high enough temperature and pressure to promote nuclear fusion. Reactions in the Sun's core convert hydrogen nuclei into helium nuclei by the proton-proton chain and to a lesser extent by the CNO cycle. All neutrinos from proton-proton chain (see figure above) have been detected except hep neutrinos. Super Kamiokande and other related neutrino experiments are presently measuring the flux of neutrinos created by the nuclear fusion processes ongoing in the core of our Sun.

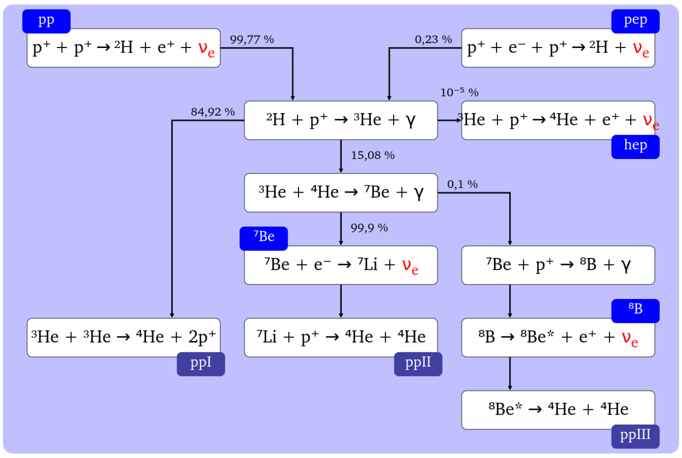

Figure 2: Solar neutrinos (proton-proton chain) in the Standard Solar Model

Red Giant Stars

1. H used up in core, star contracts, temperature rises and He fusion commences
2. Energy production shifts to exterior and star moves off main sequence (surface temperature

decreases while luminosity stays relatively constant

3. Results in synthesis of elements between mass 4 and 56 (Fe) through fusion

Nucleosynthetic Processes

In order to explain all the features of the cosmic abundance curve, 8 types of synthesizing processes are required (originally outlined in a famous paper by Burbidge, Burbidge, Fowler and Hoyle, 1957). These are nuclear reactions that occur at specific temperatures in the course of stellar evolution. Several may occur simultaneously and in different regions of the star. Thus, stars may be compositionally stratified.

Requirements:

1) high density of matter – allows collision of nuclei. [Note: Interstellar space is very low density ($\sim 10^{-27}$ kg/m^3). Thus, there are astronomically low chances for such collisions in space.]

2) very high temperatures (10^6 K) to overcome electrostatic repulsion of nucleii

Fusion reactions

Hydrogen fusion occurs in the Sun's core forming He by one of the following two reactions:

1) *proton-proton chain*: (note notation convention (atomic number, atomic mass).

$$^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + \beta^+ + \nu_e + 0.422\ MeV$$

where β^+= positron (e^+), ν_e = electron neutrino (proton $\rightarrow$ neutron with emission of a positron and neutrino)

$$^2_1\text{H} + ^1_1\text{H} \rightarrow ^3_2\text{He} + \gamma + 5.493\ MeV$$

$$^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + ^1_1\text{H} + ^1_1\text{H} + 12.859\ MeV$$

End products: 4 p fused together to form 1 He nucleus, 3 γ, 2 e^+, and 2 ν_e and 19.749 MeV of energy. There are some issues worth consideration: (1) these reactions require extremely high temperatures (20×10^6 K), (2) the reaction cross section is small and thus it has a low probability of occurrence, and (3) ^{3}He is a rare nuclide (currently only 0.014% of total He)

An alternative mechanism has been proposed: H fusion by CNO cycle. There are problems with this hypothesis: (1) This mechanism requires elements more massive than He, (2) this process would not have occurred in 1st generation stars, (3) most stars are second generation (only smallest stars can be 1st generation), and (4) H fusion is believed to be the dominant process in stars today. This generation process is not favored. On Earth the fusion process is being explored as perhaps the best process for power generation. However, very high temperatures (20×10^6 K) are needed for it to proceed. Hence, the big fuss about the so-called "cold fusion" in the late 1980s.

2) *Helium Burning*: **Red Giant** Once significant amounts of H has been produced, the core contracts and its temperature rises. At $\sim10^8$ K, He fusion proceeds via the "triple α reaction":

Significantly, "double α reaction" are not tenable because ^{8}Be has very short half-life $\sim 7\times10^{-17}$ s. Since ^{8}Be is essentially joining two α, it has a large surface to volume ratio. Consequently, this configuration of ^{8}Be results in a large surface tension term requiring excess binding energy for a simple liquid drop model. The *semi-empirical mass formula* (SEMF) (or the Bethe - Weizsäcker's formula) is based on the liquid drop model for the nucleus. The nucleus (protons and neutrons) is held together by the nuclear force. The formula predicts the binding energy of a nucleus in terms of the numbers of protons and neutrons it contains based on five terms corresponding to (1) cohesive binding of all the nucleons by the nuclear force (volume term), (2) a surface energy term, (3) the electrostatic (Coulomb) mutual repulsion of the protons, (4) an asymmetry term (derivable from the protons and neutrons occupying independent quantum momentum states) and (5) a pairing term (partly derivable from the protons and neutrons occupying independent quantum spin states).

Also note that Li, Be or B are created in the He burning process, but are side products of the proton fusion process (see Figure 2). The "triple α reaction" bridges the element production gap in stability of Li, Be and B.

He burning sustains red giants for $\leq$10 Ma. As the core temperature rises, carbon fuses with He to form nuclei of higher Z (e.g., ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ...) producing elements up to mass ^{56}Fe, but not beyond because of Coulombic repulsion forces between nuclei. This cycle leads to the peak in abundance at Fe. Formation of heavier elements requires other processes, most importantly the neutron-capture reactions, "s-" and "r-processes". These latter processes produce elements with A $>$ 56 (and a few with A $<$ 56).

s-process: AGB stars For elements heavier than iron half are produced by a process of slow neutron captures (i.e., s-process) coupled with β^- decays. This process occurs mostly in AGB (Asymptotic Giant Branch) stars having low to intermediate masses (M<8 $M_\odot$) and in massive stars (M>8 $M_\odot$) during the helium burning phase.

- Neutron capture with emission of γ radiation
- occurs on timescales of 10^2 to 10^5 years for each capture
- this is slow rate to the β decay of the resultant nuclide, thus it is called the "**s-process**"
- occurs during red giant stage of stellar evolution.

β decay – 3 types:

1) beta-minus (β^-) decay $\quad {}^A_ZX \rightarrow {}_{Z+1}^{\;\;A}X' + e^- + \bar{\nu}_e$

2) beta-plus (β^+) decay $\quad {}^A_ZX \rightarrow {}_{Z-1}^{\;\;A}X' + e^- + \nu_e$

3) electron capture (EC) $\quad {}^A_ZX + e^- \rightarrow {}_{Z-1}^{\;\;A}X' + e^- + \nu_e$

These are all "isobaric": no change in mass, but change in Z. In all cases the atomic number changes (because the number of protons changes) but the mass remains constant.

- produces nuclides mostly in the range 23<A<46 (Ne-Ti, excluding those synthesized mainly by the α-process) and 63<A< 209 (Cu to Bi).
- produces abundance peaks at A = 90, 138 and 208.

Basic process: addition of neutron to nucleus to produce atom with same atomic number, but larger mass number.

r-process: Supernovae and/or Kilonovae
The other half of the elements heavier than iron are formed by rapid neutron captures, which requires an environment with a very high neutron flux. The actual site of the r-process production is debated. The source of these elements was dominantly considered to come from core collapse supernovae, with its accompanying neutrino driven wind that is expelled by the explosion of this proto-neutron star. However, recent stellar observations and the 2017 gravity wave observation now challenges this long standing belief. Neutron star merger models are becoming preferred source of these elements.

A supernova is the last stellar evolutionary stage of a massive star's life. A supernova expels much of its matter away from the star's core, with matter traveling at about 1/10 the speed of light. The shock wave expands into the surrounding interstellar medium and under the right conditions interacts with a gas-dust cloud to fragment the cloud by adding mass and momentum. If this fragment rotates and collapses it will ultimately lead to the generation of a new star, likely with a encircling solar system of planets. A kilonova event has some probability of a similar outcome.

- Neutron capture on a very short time-scale (0.01 -10 sec)
- Occurs only under extreme neutron flux conditions present in supernovae

By this method, nuclides can be synthesized before they have a chance to disintegrate via radioactive decay.
- Requires much more rapid neutron flux compared with s-process
- produces large number of isotopes in the range $70<A<209$ (Ga to Bi) and also Th and U and a few light elements.
- produces abundance peaks at 80, 130 and 194.
- production during the last few minutes of red giant evolution, when it explodes into supernova and — or during the cataclysmic merger of two neutron stars.
- Estimated frequency of supernovae: 1 per galaxy per 100 years; I do no know frequency of neutron star mergers

In general, any isotope with an exposed southeast corner (see chart of the nuclides) can be made by the r-process.

P-process: nuclides, lying to the left of the main trend cannot be produced by neutron capture (i.e., ^{74}Se). There are only a few of these proton-rich (or it could be considered neutron poor) nuclides, which are missed by the s- and r-processes. These originate from the p-process (or photo-disintegration process, γ) and are created by proton addition, or possibly by bombardment of photons, causing neutrons to convert to protons. The astrophysical site(s) has not been identified. Their origins are from isotopes produced during s- and r-processes seed that undergo photo-disintegration, at temperatures of a few 10^9 K.

X-process: *Also called cosmic ray spallation* The production of lithium, beryllium and boron (LiBeB) can be considered non-thermal nucleosynthesis and may be important locally and galactic-ally for isotopes not produced in stars. Production of LiBeB via fusion and spallation reactions involving cosmic ray (CR) protons and α particles with interstellar carbon, nitrogen, oxygen (CNO) and He.

Constituents of Atoms:
proton: 1.007276467 u = 1.67262178 × 10^{-27} kg = 938.2720 MeV/c^2
neutron 1.008664916 u
electron 0.0005485799 u = 9.10938291 x 10^{-31} kg = 0.5109989 MeV/c^2

Definitions
N: the number of neutrons
Z: the number of protons (dictates the chemical properties of the atom)
A: Mass number (N + Z)
M: Atomic Mass, I: Neutron excess number (I = N – Z)
Isotopes have the same number of protons but different numbers of neutrons
Isobars have the same mass number (N + Z), but N and Z are different
Isotones have the same number of neutrons but different number of protons

Fundamentals

$${}^{A}_{Z}X_{N}$$

Mass Defect: Mass defect is the mass difference between the mass of an isotope and the sum of the masses of its parts. Using a helium atom as an example, it contains 2 electrons and 4 nucleons (2 protons and 2 neutrons). [See calculation below.] The mass of any nuclide (normalizing to $^{12}C = 12.0000$) based on number of protons and neutrons is greater than the actual mass (determined from precise measurements). This mass defect is due to conversion of mass into energy at the time of the nuclear reactions that create the nuclide:

$E = mc^2$

So the binding energy, Δmc^2 per unit mass, can be calculated. A plot of mass normalized binding energy vs. mass number shows the greatest binding energy occurs at Z = 28 (Ni) and decreases on either side.

^{4}He atom
2 protons: 2 x 1.007276467 u
2 neutrons: 2 x 1.008664916 u
2 electrons: 2 x 0.0005485799 u
Total: **W** = 4.03298u
Actual Mass: **M** = 4.002603u
This is a deficit, Δ = **W-M**, of 0.0306767 u

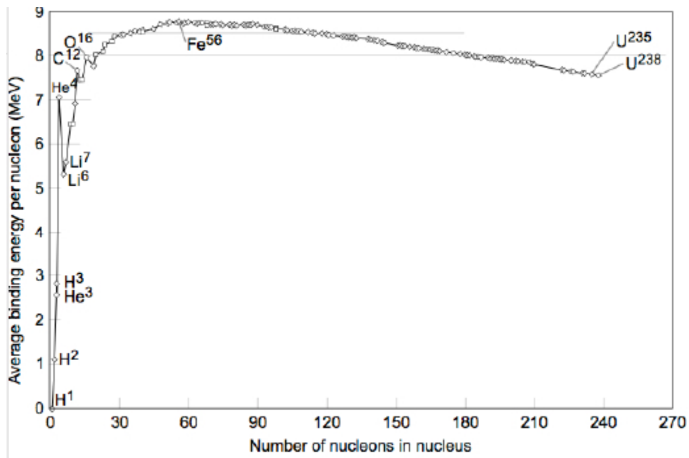

Figure 3: Binding Energy curve

Chart of the Nuclides

The first 20 elements (up to Ca) have approximately equal number of protons and neutrons (see chart on the next page). Heavier elements deviate a 1:1 relationship of N to Z having more neutrons than protons. This shift is because of Coulombic forces in the nucleus that requires additions neutrons to offset the space charge effects of the protons.

Enhanced abundances of even (E) elements

- Isobars with lower mass are more stable – more strongly bonded together. *Even isobars*: can be E-E (e.g., ${}^{12}_{6}C_{6}$) or O-O (e.g., ${}^{14}_{7}N_{7}$). There are only 5 stable O-O pairs, ${}^{2}_{1}H_{1}$, ${}^{6}_{3}Li_{3}$, ${}^{10}_{5}B_{5}$, ${}^{14}_{7}N_{7}$, and ${}^{180m}_{73}N_{73}$, with the last one being most unusual as it the only primordial nuclear isomer, which has never been observed to decay. There are also 4 long-lived, and well known to geochronology, radioactive O-O nuclides, including ${}^{40}_{19}K_{19}$, ${}^{50}_{23}V_{23}$, ${}^{138}_{57}La_{57}$, and ${}^{176}_{71}Lu_{71}$. Some odd Z elements completely lacking from Earth: ^{43}Tc, ^{61}Pm, ^{85}At, and ^{87}Fr. Techecium (Tc) has been detected recently in debris disks from supernovas. There are 21 known isotopes of Tc – all are radioactive with the longest half life (the time it takes for 1/2 of atoms to decay) being 4 Ma. Thus there is no Tc naturally occurring on Earth, but it has been observed in recent supernovas.

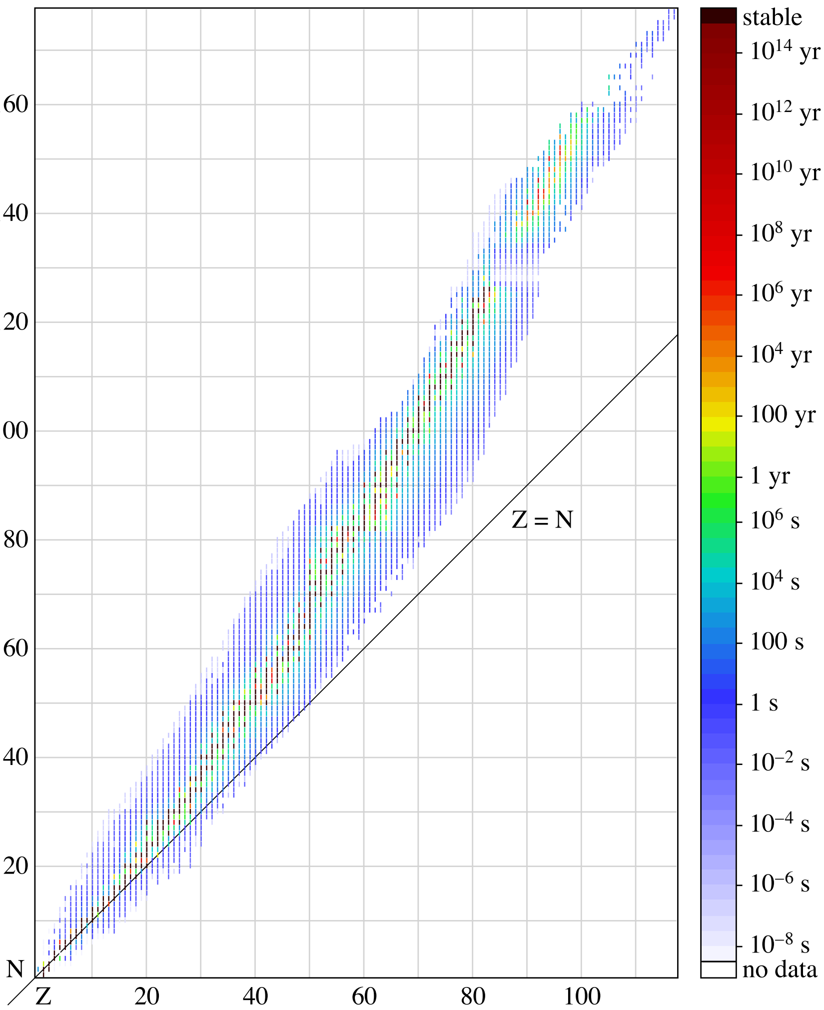

Figure 4: chart of the nuclides from `https://en.wikipedia.org/wiki/Table_of_nuclides`

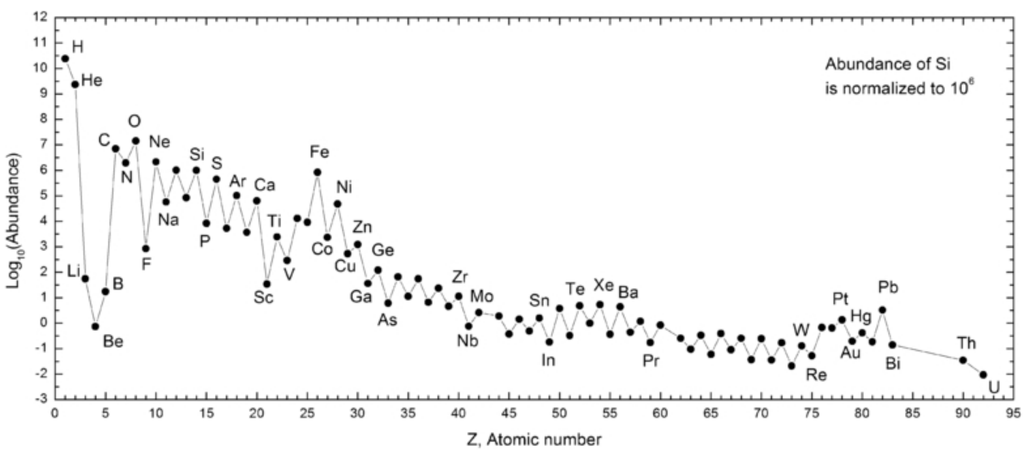

Figure 5: Element Abundance curve