Part 2

Fusion & Origin of Elements

Fusion involves 2 nuclei of very low A amalgamating to form a more stable nucleus. The increased stability arises because the A value of the nucleus formed is nearer the value $A \cong 60$ where the binding energy per nucleon maximizes.

Big Bang theory: cosmological model of the observable universe that starts at the earliest known period and through its subsequent large-scale, long-time evolution.

Fred Hoyle 1949

- initially proposed by Georges Lemaître in 1927 (Belgian priest)

-> consistent with the Hubble-Lemaître law (observations that the galaxies farther away are moving the fastest away from earth

-> extrapolating cosmic expansion backwards in time following the known laws of physics suggests a high density state preceded by a singularity where time & space are meaningless

- no evidence of any phenomena prior to the singularity

- estimated at ~13.8 billion years ago within a fraction of a second, ~10^{-20} sec, newborn quarks coalesced into protons that fused to also give some helium (~4%)

Gravitational forces amplified ripples in the primordial soup pulling the densest regions together into a giant cosmic mesh of galaxies & voids

initial gas density ~1 atom/cm^3

- Theory offers a comprehensive explanation for a broad range of observed phenomena including the abundance of light elements the cosmic microwave background (CMB) radiation, & large scale structure

Big bang / initial event:
electrically neutral universe started from a region containing neutrons compressed to an extremely high density

Fred Hoyle: 1949 advocate of steady state model, interested in nucleosynthesis used term to differentiate two models during interview -> pejorative or not?

- See Handout: Genesis of Elements

In first few minutes the following processes would have taken place:

11.3 minutes

I

$^{0}n^{1} \rightarrow {}^{1}H^{1} + e + \bar{\nu}$

$\bar{\nu} + {}^{1}H^{1} \rightarrow {}^{0}n^{1} + \bar{e}$

${}^{1}H^{1} + {}^{0}n^{1} \rightarrow {}^{1}H^{1} + {}^{0}n^{1} + \gamma$

$e + \bar{e} \rightarrow \gamma + \gamma$

$\gamma \rightarrow e + \bar{e}$

${}^{1}H^{1}$ proton charge +1, 1.007amu

γ gamma ray, zero rest mass

e electron charge -1 $\frac{1}{1823}$amu

$\bar{e}$ position charge +1 $\frac{1}{1823}$amu

ν neutrino, no charge v small mass

$\bar{\nu}$ antineutrino, no charge v small m

${}^{0}n^{1}$ neutron, no charge 1.009amu

equilibrium at v high T between neutrons, protons, electrons, positrons, antineutrinos, neutrinos + γ radiation

radiation "cooled" by repeated Doppler shifts in the subsequent expansion of the system, ultimately constituting the isotropic 3K blackbody radiation (experimental)

In the high-density equilibrium distribution that existed for a short time before the system blew itself apart, He would be formed by the rxns:

$$^1H^1 + {}^0n^1 \rightarrow {}^1H^2 + \gamma$$

$$^1H^2 + {}^1H^2 \rightarrow \left[\begin{array}{l} ^2He^3 + {}^0n^1 \\ ^1H^3 + {}^1H^1 \end{array}\right.$$

$$^2He^3 + {}^0n^1 \rightarrow {}^1H^3 + {}^1H^1$$

$$^1H^3 + {}^1H^2 \rightarrow {}^2He^4 + {}^0n^1$$

He formed to about 10% (now observed in interstellar space)

90% essentially $^1H^1$, mostly formed from β-decay of free $^0n^1$ that found themselves in open space as cloud expanded after big bang.

See Supplement : 3.5 Nuclear Rxn Energies

3.5 Nuclear Reaction Energies

$\Delta E = \Delta m c^2$ mass ⟷ energy

$\Downarrow$ Joules $\leftarrow$ $\Downarrow$ kg $\quad \downarrow$ $3.00 \times 10^8 \frac{m}{s}$

mass not conserved in nuclear rxns

Calculate energy change ΔE in the rxn

$${}^2_1H + {}^3_1H \longrightarrow {}^4_2He + {}^1_0n$$

that occurs in stars. What energy change occurs when 1.00 g of reactants undergo the reaction?

${}^2_1H$	+	${}^3_1H$	$\longrightarrow$	${}^4_2He$	+	${}^1_0n$
2.01400 amu		3.01605 amu		4.00260 amu		1.008665 amu

$$\Delta m = [\underbrace{(4.00260 + 1.008665)}_{\text{products}} - \underbrace{(2.01400 + 3.01605)}_{\text{reactants}}] \text{amu}$$

$= -0.01924$ amu

amu $= 1.66054 \times 10^{-27}$ kg

$\Delta m = -3.20340 \times 10^{-29}$ kg

$$\Delta E = \Delta m c^2 = (-3.20340 \times 10^{-29} \text{kg})(3.00 \times 10^8 \tfrac{m}{s})^2$$
$$= -2.87 \times 10^{-12} \text{ J}$$

(reactants)

$5.03005 \text{ amu} \times \frac{1.66054 \times 10^{-27} \text{ kg}}{\text{amu}} = 8.35260 \times 10^{-27} \text{ kg}$

8.35260×10^{-27} kg reactants $\Rightarrow -2.87 \times 10^{-12}$ J

1 gm reactant $= 0.00100 \text{ kg} \left(\frac{-2.87 \times 10^{-12} \text{ J}}{8.35260 \times 10^{-27} \text{ kg}} \right)$

$= -3.43 \times 10^{11}$ J

~ -343 billion Joules

vaporize ~ 130 metric tons water

$\Downarrow$

equiv. weight entire freshman BU class in water

Nuclear & chemical rxns

1 g reactants: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

$\Delta E \sim -56$ kJ/g

${}^{235}_{92}U \rightarrow {}^{90}_{38}Sr + {}^{143}_{54}Xe + 2\,{}^{1}_{0}n$

$\Delta E \sim -7.0 \times 10^{7}$ J/g

nuclear fission

heavier nuclei into two lighter nuclei + neutrons tenuous gaseous material of interstellar space: fluctuations in density over v. large region. In such fluctuations, the gas collects into a cluster (gravity). If large enough, it stabilizes itself because of gravitational attractions between atoms it contains, & begins to grow by attracting more atoms. As cluster grows, increasing strength of gravitational attractions cause interior pressure (& therefore the interior temperature) to build up.

When T in core > $\sim 10^5$ °K, the H atoms in region are completely ionized into a plasma of protons & electrons.

When T in core > 10^7 K, $^1H^1$ have sufficient KE due to their thermal motion to have small probability of penetrating the repulsive Coulomb barriers that tend to keep them apart. (10% He does not participate: T too low for penetration owing to higher Coulomb barriers surrounding these nuclei)

$^1H^1$-burn

$^1H^1 + {}^1H^1 \to {}^1H^2 + \bar{e} + \nu + 0.42$ MeV   2 $^1H^1$ free

III

energy is liberated in the process – v low rate owing to process that requires both barrier penetration & weak β-decay interaction.

He is formed in a star cycle of rxns, called the proton-proton cycle, consisting of the proceeding rxns followed by

(H/He-burn)

$_1H^2 + {_1H^1} \rightarrow {_2He^3} + \gamma + 5.49\ MeV$ and

IV $_2He^3 + {_2He^3} \rightarrow {_2He^4} + {_1H^1} + {_1H^1} + 12.86\ MeV$

$_1H^1/{_1H^1}$ core shrinks & heats as more nuclei are locked up in each He nucleus

Counting 1.02 MeV liberated by each process: $\bar{e} + e$, total energy liberated in one cycle is 26.72 MeV

about 1% energy carried away from star by 2 ν

the remainder, plus gravitational contraction, continues to heat the core.

(He burn => C)

Density of He in core of cluster becomes high enough, Can form.

V $_2He^4 + {_2He^4} \rightarrow {_4Be^8} + \gamma$ — not stable, reverse $\sim 10^{-15}$ sec

$_2He^4 + {_4Be^8} \rightarrow {_6C^{12}} + \gamma$ — if it does not capture another $_2He^4$

rate would be zero, except that $_6C^{12}$ excited state at 7.65 MeV when $T \sim 10^8 K$, resonance rxn which makes cross section reasonably large.

Straightforward processes involving the successive addition of nucleons of $_2He^4$ cannot be used to form elements with A greater than 4 because such processes are blocked by complete instability of nuclei with A=5.

He burn: core smaller, outer layer 50 times previous radius

Carbon cycle:
When enough C has been formed in the core of the star, the principal source of energy production is through the carbon cycle. C is a catalyst (i.e., it reappears at the end of the cycle) to aid in the fusion of 4 $^1H^1$ into one $^2He^4$ plus $\bar{e}$, ν & γ.

VI

$$^6C^{12} + {}^1H^1 \rightarrow {}^7N^{13} + \gamma + 1.94\,MeV$$
$$^7N^{13} \rightarrow {}^6C^{13} + \bar{e} + \nu + 1.20\,MeV$$
$$^6C^{13} + {}^1H^1 \rightarrow {}^7N^{14} + \gamma + 7.55\,MeV$$
$$^7N^{14} + {}^1H^1 \rightarrow {}^8O^{15} + \gamma + 7.29\,MeV$$
$$^8O^{15} \rightarrow {}^7N^{15} + \bar{e} + \nu + 1.73\,MeV$$
$$^7N^{15} + {}^1H^1 \rightarrow {}^6C^{12} + {}^2He^4 + 4.96\,MeV$$

Counting energy liberated by annihilation of 2 $\bar{e}$, total energy liberated in one cycle is 26.72 MeV, just as in the ^1H-^1H cycle. In C cycle, ~5% energy lost by 2 ν. Rate of C cycle > ^1H-^1H cycle because no step in the C cycle is anywhere as near as slow as the 1st step in the ^1H-^1H cycle.

T ~ 10^8 K required for C formation & C cycle

$\gamma + {}^{14}Si^{28} \rightarrow {}^{12}Mg^{24} + {}^{2}He^{4}$

${}^{14}Si^{28} + {}^{2}He^{4} \rightarrow {}^{16}S^{32} + \gamma$

$\rightarrow$ ${}^{16}S^{32} + {}^{2}He^{4} \rightarrow {}^{18}Ar^{36} + \gamma \;\ldots\; {}^{26}Fe^{56}$

As concentration of stellar core continues, T ↑ & elements heavier than carbon are formed.

successive captures of ${}^{2}He^{4}$ by ${}^{6}C^{12}$:

VII

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

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

${}^{10}Ne^{20} + {}^{2}He^{4} \rightarrow {}^{12}Mg^{24}$

T ~ 10^{9} K, sufficient thermal energy to penetrate Coulomb barriers directly forming nuclei of even A through ${}^{26}Fe^{56}$

other rxns

${}^{6}C^{12} + {}^{6}C^{12} \rightarrow {}^{10}Ne^{20} + {}^{2}He^{4}$

${}^{8}O^{16} + {}^{8}O^{16} \rightarrow {}^{14}Si^{28} + {}^{2}He^{4}$

${}^{8}O^{16} + {}^{8}O^{16} \rightarrow {}^{16}S^{31} + {}^{1}n^{0}$

Nuclei of odd values of A can be formed, if even-A nuclei are forced by turbulence out of the stellar core into the surrounding cooler zone where ${}^{1}H$-${}^{1}H$ cycle is still going on:

${}^{10}Ne^{20} + {}^{1}H^{1} \rightarrow {}^{11}Na^{21} + \gamma$

${}^{11}Na^{21} \rightarrow {}^{10}Ne^{21} + \bar{e} + \nu$

Some of these odd A nuclei participate in rxns which lead to production of neutrons:

${}^{10}Ne^{21} + {}^{2}He^{4} \rightarrow {}^{12}Mg^{24} + {}^{0}n^{1}$

Abundance of Fe due to inherent stability of nucleus addition of neutrons occurs:

$_{26}Fe^{56} + 13\ {}_0n^1 \rightarrow {}_{26}Fe^{69} \rightarrow {}_{27}Co^{69} + e$

require large flux of $_0n^1$, not readily available in normal star.

1) as fusion occurs $_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + e + \nu$

$_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma$

$_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + {}_1H^1$

4 nucleons locked up in each He nucleus

T & ρ of core ↑ to maintain pressure balance

→ less homogeneous; core smaller, outer layers swell up to 50× previous radius

our Sun: $^1H/^1H$ burn, some He burn

will burn ~ 10 billion years, in about 4.5 billion years from now, C-burn - red giant (cool) (earth within surface*)

last several million years then outer layers pushed off, shell of gas, planetary nebula - unstable

⇒ white dwarf (QM free electrons, exclusion principle keeps it from total collapse)

2) Star more massive than our sun (~ 20 solar masses)

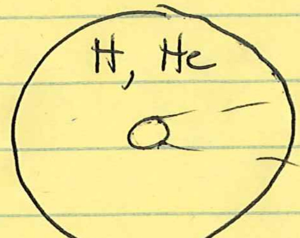
20,000 times as luminous

^1H fusion 10^3 faster, swells to red giant

10 million yrs, not 10 billion years

Cosmic onion: pre-supernova

a)



~60-fold
expansion
core

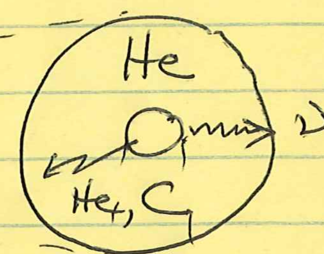
18 solar masses
30 million km
(~18 million miles)

earth → sun 93,000,000
miles

light takes 8.3 minutes

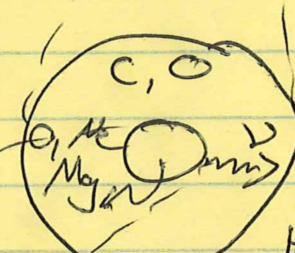
Your sun ~1,400,000 km
diameter (1.4×10^6 km)
(840,000 mile) → 3× distance
earth - moon

earth ~1.3×10^4 km
(~10^7 difference in V)



b) 500,000 km
20 million K
1 gm/cm^3
6.1 solar masses
He/C core 3-4×
diameter of Jupiter
(140,000 km)

c)



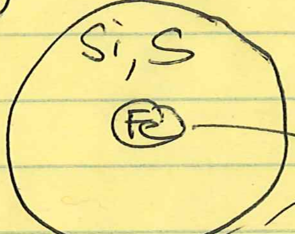
10×
expansion
core

ash from
He burn

50,000 km
250 million K
1,000 g/cm^3
(2.2 lbs/mL)
3.9 solar masses

1.9 solar
masses

d)



10×
expansion
core

→ size of mars
3,500 km radius
(7,000 km diameter)

density:
Pb 11.34 $\frac{g}{cm^3}$
Au 19.3 $\frac{g}{cm^3}$
Os 22.59 $\frac{g}{cm^3}$

5000 km
3 billion K
1 million g/cm^3
1000 $\frac{kg}{mL}$, 2,200 $\frac{lbs}{mL}$
or $\frac{1 \text{ ton}}{cm^3}$

collapses

ρ 10^{10} $\frac{g}{cm^3}$
T 10^{10} K

$1\times10^7 \frac{kg}{cm^3}$ 22,000,000 $\frac{lbs}{cm^3}$ 22,000 $\frac{tons}{cm^3}$

- core collapses generates a shock wave which moves out through the outer layers of star

- initial shock travels at high energy & heats inner layers of star to high temperatures. These high temperatures lead to nuclear re-processing of inner layers of material into elements ranging from Mg to Fe

- as shock wave moves outward (losing energy all the time) eventually a point is reached where T generated by shock cannot ignite nuclear rxns

- shock then pushes the outer layers away & these layers reflect the normal evolution of star. Transition occurs around the Ne/O layer.

burst is a v strong source of neutrons. Since there is no electrical barrier for the addition of neutrons to nuclei, can build up v massive elements if sufficient #'s neutrons. SN have high neutron fluxes

$$n + (A,Z) \rightarrow (A+1, Z) \rightarrow (A+1, Z+1) + e^- + \nu$$

β-decay

$$n + (A+1, Z+1) \rightarrow (A+2, Z+1) \rightarrow (A+2, Z+2) + e + \nu$$

result is a neutron star or if massive enough, a black hole

10 second burst releases more energy than 100 times more than the sun will radiate in its entire 10-billion year lifetime

Gold => lead => uranium
Au -> Pb -> U

for every 100 billion H atoms you get 1 U atom

On Earth, ~6,000,000 tons U (6×10^6 tons)
~4,200 moles per ton
~6.02×10^{23} atoms/mol

In our bodies, Fe, Co, Zn, Cu, Mo arise from these events

=> this course will examine the consequences of this process, namely the chemistry of the periodic table elements and how they behave in different phases or states of matter