Lecture 22 Origin of the Elements

MODEL: Origin of the Elements or Nucleosynthesis

Fundamental Particles
quarks, gluons, leptons,
photons, neutrinos
+
Basic Forces
gravity, electromagnetic, nuclear

} Interactions ⟹ Conservation Laws

Universe:

Elemental Abundances
Sea of Stability

OUTLINE:

Primary Sources of the Elements

(1) Big Bang – Creation
(2) Stellar Nucleosynthesis } Evolution
(3) Cosmic-Ray Interactions } Evolution

I. Cosmological Nucleosynthesis: The Big Bang (Gamow)

A. Evidence

1. Red Shift: Doppler Effect

   Light from all distant galaxies is shifted to the RED

   $\Delta\lambda$ is proportional to distance (Hubble)

   Implication: Everything is moving away from us ; $\therefore$

   a. Universe is EXPANDING

   b. Matter has a COMMON ORIGIN

   Age = $13 \pm 2 \times 10^9$ years

2. Universal Black-Body Radiation – Remnant of primordial Explosion

   $T_{present} = 2.7\ ^\circ K \Rightarrow \rho \approx 10^{-31}\ g/cm^2$ (Penzias & Wilson)

   This radiation is isotropic in space ; i.e., it's not from our galaxy

3. Abundances of the Light Elements – esp. in old halo stars

^1H dominates the universe ; ^2H, ^3He, ^4He (little variation) ; ^7Li

Conclusion: Universe must have formed from the simplest particles.

4. STANDARD MODEL: Universe originated in a hot, dense explosion involving the simplest particles:

THE BIG BANG

B. Basic Assumptions of Standard Model (small subset)

1. Only the known particles and forces are allowed

   GUTS = Grand Unification Theories – Origin of Forces

2. Matter vs. Energy Dominance: Energy drives expansion; gravity (mass) constrains expansion

   $E = Mc^2$

3. T = f (density)

   Universe cools as it expands: $\langle E \rangle = (3/2)\,kT$; $k = 0.86 \times 10^{-10}$ MeV/K

C. Chronology of the Big Bang

1. Elementary Particle Phase: [time $< 10^{-6}$ s; $T > 10^{13}$ K $> M_n$]

   a. Most of mass-energy of the Universe in the form of ENERGY.
   b. Only fundamental particles present ; complex particles dissolved in heat bath (including nucleons).

2. Hadron Phase: [10^{-6} s $\lesssim$ time $\lesssim$ 1 sec; 10^{13} K $> T > 10^{10}$ K]

   a. quarks and gluons condense to form hadrons (p, n, π, …)
   b. No complex nuclei exist ; ^2H is simplest and binding energy is 2.2 MeV ($\sim 2 \times 10^{10}$ K) ; ∴ Universe is too hot for ^2H to form.
   c. Equilibria: $\left\{ \begin{array}{l} p + e \rightarrow n + \nu \\ n + e^+ \rightarrow p + \bar{\nu} \end{array} \right\}$ reaction rates determine p/n ratio: needs to be ~ 1:1 for ^2H

3. Nucleosynthesis Phase: [time ~ 3 minutes ; T ~ 10^9K, p ~0.1 g/cm^3

a. First step in nucleosynthesis now possible

$$\boxed{{}^1_1\mathrm{H}} + {}^1_0\mathrm{n} \rightarrow \boxed{{}^2_1\mathrm{H}} + \gamma$$

$${}^2_1\mathrm{H} + {}^1_0\mathrm{n} \rightarrow {}^3_1\mathrm{H} \Rightarrow {}^3_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow \boxed{{}^4_2\mathrm{He}}$$

$${}^2_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow \boxed{{}^3_2\mathrm{He}} \Rightarrow {}^3_2\mathrm{He} + {}^1_0\mathrm{n} \rightarrow \boxed{{}^4_2\mathrm{He}}$$

$${}^3_1\mathrm{H} + {}^4_2\mathrm{He} \rightarrow \boxed{{}^7_3\mathrm{Li}}$$

$${}^3_2\mathrm{He} + {}^4_2\mathrm{He} \rightarrow {}^7\mathrm{Be} \xrightarrow{\text{EC } 52\text{d}} {}^7_3\mathrm{Li}$$

b. Chain stops at ^{4}He, although a little ^{7}Li sneaks through (–10^{-11})

Synthesis of heavier elements is inhibited due to nuclear shell structure and very short lifetimes for nuclei just beyond doubly-magic ^{4}He

c. Theory predicts abundances of ^{1}H, ^{2}H, ^{3}He, ^{4}He and ^{7}Li well.

4. Cooling Phase: [t > 3 min, T < 10^9 K]

Expansion continues

a. Neutron Decay: ${}^1_0\mathrm{n} \rightarrow {}^1_1\mathrm{H} + {}^{0}_{-1}\beta^- + \bar{\nu}$; $t_{1/2}$ = 10.8 min

b. Nuclear reactions cease ; T too low to exceed Coulomb barrier for charged particles and neutrons are gone.

c. Matter now dominates the Universe

5. Chemistry Phase: [t ~ 10^5 y ; T $\lesssim 10^5$ °K]

Electrons now attach to H, He and Li ions to form neutral atoms

FLASH ! photon burst → microwave background

$${}^1\mathrm{H}^+ + e^- \rightarrow {}^1\mathrm{H} + \gamma$$

II. Stellar Nucleosynthesis

Neutral gas expands

Local inhomogenities develop (consequence of Inflation at ~ 10^{-30} s)

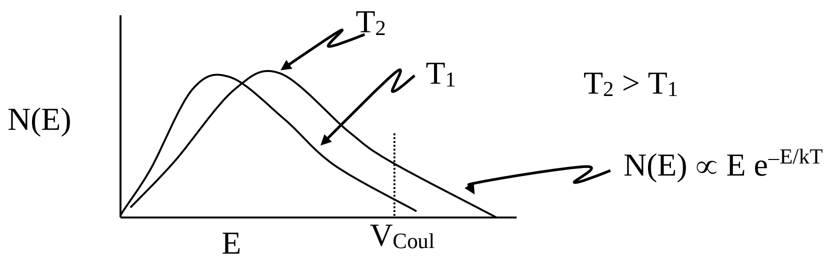
Once matter is inhomogeneous, localized gravitational fields are created that set the stage for galaxy formation

Result: { (1) Density increases and reheats matter; esp. in core of field. (2) Stars form }

A. Main Sequence Stars (~ 90% of stars)

Sun: $M_{\odot} = 2 \times 10^{33}$ g

1. Primordial Proton (+ He & Li) Gas: conditions
   a. Gravitational pressure heats core; ionizes medium.
   b. Electrostatic repulsion inhibits nuclear reactions and contraction
   c. IF $M_{star} \gtrsim 0.5 M_{\odot}$, gravity dominates and T increases
   d. At $T_{core} \sim 10^7$ K, proton burning begins to occur in high energy tail of Maxwell-Boltzmann distribution:



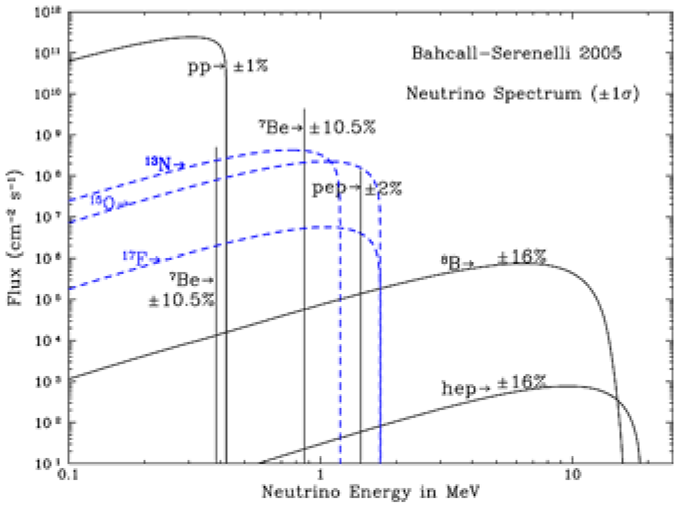
2. Hydrogen Burning

   a. Core conditions { $T \approx 1\text{-}2 \times 10^7$ K, $\rho \approx 100$ g/cm^3 } Universe: $\rho \sim 10^{-31}$ g/cm^3; Nucleus: $\rho \sim 10^{14}$ g/cm^3; H_2 @ STP: $\rho \sim 1 \times 10^{-4}$ g/cm^3

b. Fundamental Reaction

$$^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{-1}\beta^{+} + \nu$$ WEAK INTERACTION SLOW } rate-determining step *

c. Solar Neutrino Experiment



Spectrum of solar neutrinos

- Homestake, SD: $^{37}_{17}Cl + \nu \rightarrow {}^{37}_{18}Ar + {}^{0}_{-1}e^{-} \rightarrow$; $^{37}_{18}Ar + e^{-} \rightarrow {}^{37}_{17}Cl + \nu$

- GALLEX (Italy)
- SAGE (Russia) } $^{71}_{31}Ga + \nu \rightarrow {}^{71}_{32}Ge + e^{-}$

- Kamiokande (Japan) $\nu + e^{-} \rightarrow \nu' + e'$

- SNO (Canada/US) $\nu + {}^{2}_{1}H \rightarrow n + p + \nu'$ (10^3 tons of D_2O)

See also: http://www.hep.anl.gov/ndk/hypertext/solar_experiments.html

GALLEX: http://www.mpi-hd.mpg.de/nuastro/gallex/detector.htm

The experimental procedure for GALLEX is as follows: 30.3 tons of gallium in form of a concentrated $GaCl_3$-HCl solution are exposed to solar neutrinos. In $GaCl_3$-HCl solution, the neutrino induced ^{71}Ge atoms (as well as the inactive Ge carrier atoms added to the solution at the beginning of a run) form the volatile compound $GeCl_4$, which at the end of an exposure is swept out of the solution by means of a gas stream (nitrogen). The nitrogen is then passed through a gas scrubber where the $GeCl_4$ is absorbed in water (see figure 1). The $GeCl_4$ is finally converted to GeH_4 , which together with xenon is introduced into a proportional counter in order to determine the number of ^{71}Ge atoms by observing their radioactive decay.

d. Result: Solar Neutrino Problem
Observed Rate only 30-50% of expected rate

3. ppI chain

FUNDAMENTAL ENERGY SOURCE FOR THE SOLAR SYSTEM

$${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{-1}\beta^{+} + \nu$$

$${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}He + \gamma$$

$$2\,{}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}_{1}H$$

ALL EXOTHERMIC

NET: $4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}_{1}\beta^{+} + 2\,\nu + 26.7\text{ MeV}$ nuclear fusion power

Reactions hard to measure:
kT ~ 1 keV compared to Big Bang kT ~ 0.1 – 1 MeV

4. Other Chains

ppII: ^{7}Li catalyst		All produce same net reaction, but each is important at different temperatures and elemental compositions
ppIII: ^{7}Be catalyst		
CNO: ^{12}C catalyst		

5. Stellar Structure: Star in Quasi Equilibrium

a. Hydrogen burning adds a small amount of additional ^{4}He to Universe.

b. Nuclear burning (mass $\Rightarrow$ energy) counterbalances gravitational attraction.

c. $\tau_{sun} \sim 10^{10}$ y ; heavier stars burn faster (HR diagram) – more abundant in early Universe.

d. ^{4}He in core cannot burn easily at 2×10^{7} K due to Coulomb repulsion

e. H envelope continues to burn as ^{4}He accumulates in core.

6. Subsequent Evolution

a. $M \lesssim 10^{33}$ g $\Rightarrow$ White Dwarf (stellar graveyard – calibration candle)

b. $M \gtrsim 10^{33}$ g $\Rightarrow$ Red Giant (evolution continues)

B. Helium Burning: Red Giant Stars (~10%)

1. Gravitation compresses ^{4}He in core: $\left\{ \begin{array}{l} \rho \approx 10^{5}\ \text{g/cm}^{3} \\ T \approx 10^{8}\ \text{K} \end{array} \right\}$

2. Nuclear Reactions

a. LiBeB are highly unstable thermally ; burn up as soon as they are formed ; Accounts for inhibition of heavy element synthesis in Big Bang.

b. Hoyle: 3α Reaction

$$\left.\begin{array}{ll} & {}^{4}_{2}He + {}^{4}_{2}He \rightarrow \left[{}^{8}_{4}Be^{*}\right]; \quad \tau \sim 10^{-16}\ s \\ \text{EXOTHERMIC} & \left[{}^{8}_{4}Be^{*}\right]^{2} + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + \gamma\ ; E_{\gamma}=7.65\ MeV\ (0^{+}) \end{array}\right\}$$

c. Three-body nature of reaction results in low rate

$\tau_{RedGiant} \approx 10^{7} - 10^{8}$ y ; still SLOW, like Main Sequence

d. Sun will become a Red Giant in ~ 5×10^{9} y and then become a White Dwarf.

3. Subsequent Reactions – Richer Chemistry

$$\left.\begin{array}{l} {}^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O + \gamma \\ {}^{16}_{8}O + {}^{4}_{2}He \rightarrow {}^{20}_{10}Ne + \gamma \end{array}\right\} \quad Q = +$$

4. Composition of the Universe at this stage: H, He, (Li), C, O and (Ne)

5. Synthesis of heavier elements in core inhibited by higher Coulomb barriers of O and Ne ; e.g., ${}^{12}C + {}^{12}C \not\rightarrow$

Star in quasi-equilibrium again.