AS2001 / 2101

Chemical Evolution of the Universe

Keith Horne Room 315A
kdh1@st-and.ac.uk
http://star-www.st-and.ac.uk/~kdh1/ce/ce.html

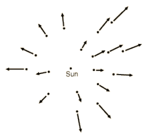
Origin of Chemical Elements

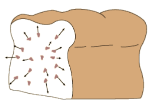
- Big Bang Nucleosynthesis: $t \sim 3$ min
  ^{1}H ^{2}D ^{3}He ^{4}He … ^{7}Li
- Fusion in stars: *We are stardust!*
  … ^{12}C ^{14}N ^{16}O … ^{56}Fe
- Fusion in supernova explosions ($M_* > 8\, M_{sun}$)
  … ^{56}Fe … ^{235}U
- Abundances rise as each generation of stars pollutes the interstellar medium (ISM).

Cosmology Lite

- 1925 Galaxy redshifts $\lambda = \lambda_0\,(1+z)$ $V = c\,z$
  - Isotropic expansion. (Hubble law $V = H_0 d$)
  - Finite age. (t_0 =13 x 10^9 yr)
- 1965 Cosmic Microwave Background (CMB)
  - Isotropic blackbody. T_0 = 2.7 K
  - Hot Big Bang
- 1925 General Relativity Cosmology Models :
  - Radiation era: $R \sim t^{1/2}$ $T \sim t^{-1/2}$
  - Matter era: $R \sim t^{2/3}$ $T \sim t^{-2/3}$
- 1975 Big Bang Nucleosynthesis (BBN)
  - light elements (^{1}H … ^{7}Li) $t \sim 3$ min $T \sim 10^9$ K
  - primordial abundances (75% H, 25% He) as observed!

Isotropic Expansion





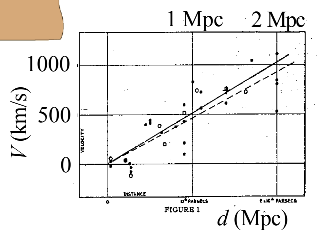
No visible edge.
No centre of expansion.

Hubble law :

$V = H_0\, d$

Hubble constant :

$H_0 \approx 500$ km s^{-1}Mpc^{-1}

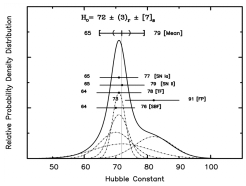


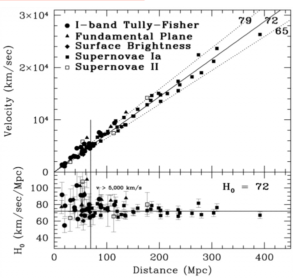
WRONG ! Extinction by interstellar dust then unknown.
Hubble's distances were 10x too small.

HST Key Project

$H_0 \approx 72 \pm 3\ (\pm 7)$ km s^{-1} Mpc^{-1}

Freedman et al.
2001 ApJ 553, 47.





Hubble Law --> Finite age.

$V = H_0\, d$

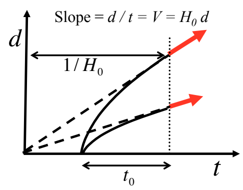
$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\ \text{Mpc}}{72\ \text{km/s}}\right)\left(\frac{3\times10^{19}\ \text{km}}{\text{Mpc}}\right)\left(\frac{1\ \text{yr}}{3\times10^{7}\ \text{s}}\right)$$

$$\approx 13\times10^9\ \text{yr} = 13\ \text{Gyr}.$$

Gravity decelerates:

Matter-dominated: $d \propto t^{2/3}$

$$t_0 \approx \frac{2}{3}\frac{1}{H_0}.$$



Hubble Law --> Finite age.

$V = H_0\, d$

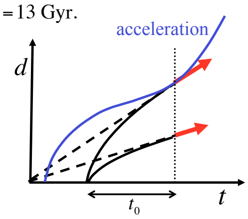
$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\ \text{Mpc}}{72\ \text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\ \text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\ \text{Gyr.}$$

Gravity decelerates:

Dark Energy accelerates

$t_0 > \frac{2}{3}\frac{1}{H_0}$.



Self-assembly of compact structures

Universe expands and cools.

4 forces 4 phase transitions when $kT \sim E$

elementary particle soup (quarks, gluons, leptons, bosons)

1. ***Strong force*** (quarks exchange gluons) :
   quarks -> hadrons (baryons (qqq), mesons ($q\bar{q}$))
   e.g. protons and neutrons ($T \sim 10^{12}$ K, $t \sim 10^{-4}$ s)
2. ***Weak force*** (exchange of vector bosons W^+, W^-, Z^0) :
   neutrons -> protons
   baryons -> atomic nuclei ($\sim 10^9$ K, ~ 3 min)
3. ***Electro-magnetic force*** (photons) :
   nuclei + electrons -> neutral atoms (3000 K, 3×10^5 yr)
4. ***Gravity*** (gravitons):
   galaxies of stars, some with planets, some with life.
   (--> black holes --> evaporate to elementary particles.)

Cosmological Models

Assume a Universe filled with uniform density fluid.
[OK on large scales > 100 Mpc]

Density: $\rho = \Omega\, \rho_c$ Energy density: $\varepsilon = \rho\, c^2$

Critical density: $\rho_c \equiv \frac{3\,H_0^{\,2}}{8\pi\, G} \approx 10^{-26}\text{kg m}^{-3} \approx \frac{1.4\times10^{11}\text{Msun}}{(\text{Mpc})^3}$

3 components:

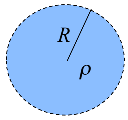
1. ***Radiation*** $\Omega_R \approx 5\times10^{-5}$
2. ***Matter*** $\Omega_M \sim 0.3$ { "Dark Matter" $\Omega_D \sim 0.26$ baryons $\Omega_B \sim 0.04$
3. "***Dark Energy***" $\Omega_\Lambda \sim 0.7$

Total $\Omega = \Omega_R + \Omega_M + \Omega_\Lambda = 1$

Only ~4% is matter as we know it!

Critical Density

- Newtonian analogy:



escape velocity :

$$V_{esc}^{\ 2} = \frac{2\,G\,M}{R} = \frac{2\,G}{R}\left(\frac{4\pi\,R^3\rho}{3}\right) = \frac{8\pi\,G\,R^2\rho}{3}$$

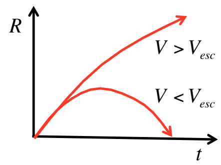
Hubble expansion :

$V = H_0\, R$

critical density :

$$\left(\frac{V_{esc}}{V}\right)^2 = \frac{8\pi\, G\rho}{3\,H_0^{\,2}} = \frac{\rho}{\rho_c}$$

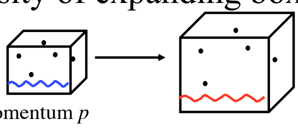
$$\rho_c = \frac{3\,H_0^{\,2}}{8\pi\, G}$$



Energy Density of expanding box

volume R^3

N particles



particle mass m momentum p

$$\text{energy}\ \ E = h\nu = \sqrt{m^2c^4 + p^2c^2} = m\,c^2 + \frac{p^2}{2m} + ...$$

Cold Matter: ($m > 0,\ p << mc$)

$E \approx m\,c^2 = \text{const}$

$$\varepsilon_M \approx \frac{N\,m\,c^2}{R^3} \propto R^{-3}$$

Radiation: ($m = 0$)

Hot Matter: ($m > 0,\ p >> mc$)

$\lambda \propto R$ (wavelengths stretch) :

$$E = h\,\nu = \frac{h\,c}{\lambda} \propto R^{-1}$$

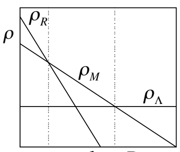
$$\varepsilon_R = \frac{N\,h\,\nu}{R^3} \propto R^{-4}$$

3 Eras: radiation…matter…vacuum

radiation : $\rho_R \propto R^{-4}$

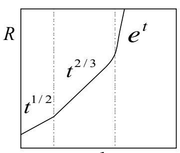
matter : $\rho_M \propto R^{-3}$

vacuum : $\rho_\Lambda = \text{const}$



$a \equiv \frac{R}{R_0} = \frac{1}{1+z}$ z = redshift

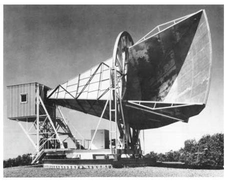
$$\rho = \frac{\rho_{R\,0}}{a^4} + \frac{\rho_{M\,0}}{a^3} + \rho_\Lambda$$



$\rho_R = \rho_M$ at $a \sim 10^{-4}$ $t \sim 10^4$ yr

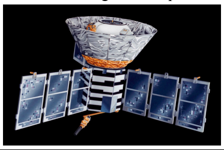
$\rho_M = \rho_\Lambda$ at $a \sim 0.7$ $t \sim 10^{10}$ yr

1965 The Bell Lab antenna

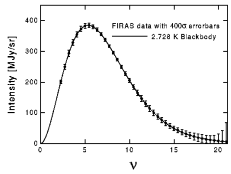


Penzias & Wilson
Discovered the CMB

1992 NASA - COBE
COsmic Background Explorer



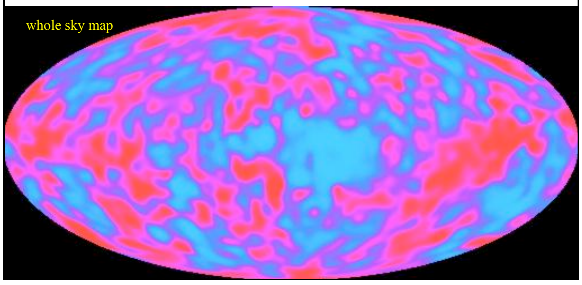
The CMB spectrum
A perfect Blackbody!



1992 COBE

temperature ripples: $\frac{\Delta T}{T} \sim 10^{-5}$

angular resolution: $\Delta\theta \approx 7^{\circ}$

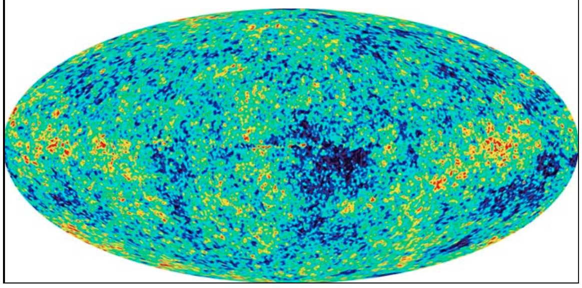


2004 WMAP

Wilkinson Microwave Anisotropy Probe

preferred angular scale: $\Delta\theta \approx 1^{\circ} \Rightarrow \Omega \approx 1.0$

The seeds of galaxies



Cosmic Microwave Background (CMB)

Blackbody temperature $T = 2.728\ \mathrm{K}$

energy density $\varepsilon_\nu = \frac{8\pi\, h}{c^3} \frac{\nu^3}{\exp(h\nu/kT) - 1}$

$\varepsilon = \int \varepsilon_\nu\, d\nu = \alpha\, T^4 \approx 4.2 \times 10^{-14}\ \mathrm{J\ m^{-3}}$ (Tut. sheet 1)

mean photon energy $\overline{h\nu} \approx 3\, k\, T = 7 \times 10^{-4}\,\mathrm{eV}$

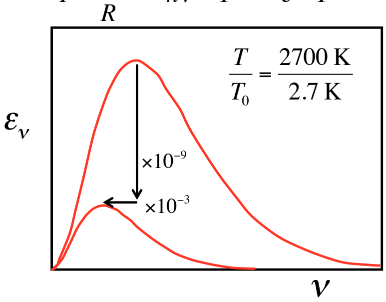
photon density $n_\gamma = \varepsilon / \overline{h\nu} \approx 4 \times 10^8 \frac{\text{photons}}{\mathrm{m}^3}$

baryon density $n_B = \rho_B / m_p \approx 0.2 \frac{\text{baryons}}{\mathrm{m}^3}$

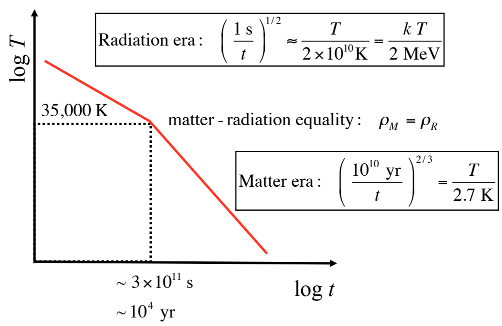
ratio $\frac{\text{photons}}{\text{baryons}} \sim 10^9$ Why?

Adiabatic Expansion preserves the Blackbody spectrum

$T \propto \frac{1}{R} \qquad h\nu \propto T \qquad \varepsilon \propto T^4$



Cooling History: T(t)



In the early Universe
($kT > E$) photons break up atomic nuclei
binding energies:

Deuterium ~ 2 MeV $T \sim 10^9$ K $t \sim 100$ s

Iron ~ 7 MeV $T \sim 10^{10}$ K $t \sim 1$ s

Earlier still, neutrons and protons break into quarks

mass energies: $T \sim 10^{12}$ K $t \sim 10^{-4}$ s

neutron ~ 939.6 MeV

proton ~ 938.3 MeV

This takes us back to the quark soup!

Next time we will run the clock forward!