Review Notes   Cosmology   ASTR/PHYS 328/428   F20

Basic parameters

Expansion rate H_0

Mass density Ω_m (relative to critical $\rho_c = \frac{3H_0^2}{8\pi G}$)

including Ω_b baryon density

Ω_{CDM} non-baryonic CDM

Cosmological constant Ω_Λ

Power spectrum

σ_8 normalization of amplitude

n tilt

Foundational Observations

Distance Scale

Traditional Distance scale Ladder

- Solar System
- Trigonometric parallax of nearby stars
- Main sequence fitting to star clusters
- Bright star standard candles (e.g. Cepheids)
- Secondary distance indicators
  e.g., Type Ia SN, Tully-Fisher

Absolute methods (independent of the ladder above)

e.g.
- water masers
- gravitational lens time delay
- SZ effect

Fundamental Observations

Age Scale

- Oldest Stars

$t_{GC} = 13.3 \pm 0.1$ Gyr (recent)

consistently in the range

Globular clusters $t_{GC} = 12 - 15$ Gyr

calibration of stellar evolution depends on distance scale

- White dwarf

maximum ages along cooling function

measure drop off in luminosity function

(no WDs fainter than $M \approx 16$)

Account for preceding stellar evolution

$$t_{WD}^{max} = 12.5^{+1.4}_{-3.5} \text{ Gyr}$$

- Radio isotope chronometers eg. Th/Eu

$$t_{TH} = 12.8 \pm 3 \text{ Gyr} \quad \text{oldest star}$$

measure abundances of r-process radioactive elements in ancient, metal poor stars relative to stable elements

- Interstellar dust grains

measure abundances of radio isotopes in meteoritic grains

account for evolution of parent star, evolution preceding it, and age of solar system (each 4 or 5 Gyr):

$t_{grain} \simeq 13.7 \pm 1.3$ Gyr

Fundamental observations

Mass Density

There are <u>many</u> ways to estimate the gravitating mass density of the universe – the over-all $\Omega_m = \frac{\rho_m}{\rho_{crit}}$ $\left(\rho_{crit} = \frac{3H_0^2}{8\pi G} \right)$

To give just a few examples:

- Cluster M/L

  measure mass of cluster (e.g., virial $M \approx \frac{1.5 R_e \sigma^2}{G}$,

  measure luminosity, combine to get M/L (assume to be global)

  measure average luminosity density of the universe j

  by integrating luminosity function of galaxies

  combine to get density: $\rho_m = \frac{M}{L} j$

- weak lensing

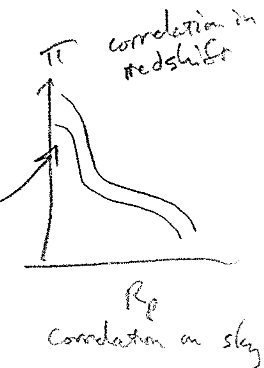
  measure lensing shear over large scales

  $\Omega_m \approx 0.2$ by this method so far

- peculiar velocity field

  masses like clusters distort the Hubble flow

  "finger of god"



  amount of distortion depends on mass

$$\frac{\delta V}{V} \approx \frac{d \ln H}{d \ln \rho} \frac{\delta\rho}{\rho} \approx -\frac{1}{3} \frac{\Omega_m^{0.6}}{b} \frac{\delta N}{N}$$

b is bias factor relating mass ρ and galaxy number density N

  $\Omega_m \approx 0.25$ by this method

- LOTS of others

Fundamental Observations

cosmological constant

Need Λ for many reasons, most especially

- Age problem

  The universe is too young for its contents (t_{GC}) without Λ for observed (H_0, Ω_m)

- Cosmic acceleration

  $q_0 < 0$ as seen in the Hubble diagram for Type Ia SN

- Geometry as seen in the CMB

  The location of the first peak of the acoustic power spectrum tells us the geometry is flat.

  $\Omega_{tot} = 1$ with $\Omega_k \approx 0$

  so $\Omega_m + \Omega_\Lambda = 1$ but independently we measure $\Omega_m < 1$. Need Λ to make up the deficit.

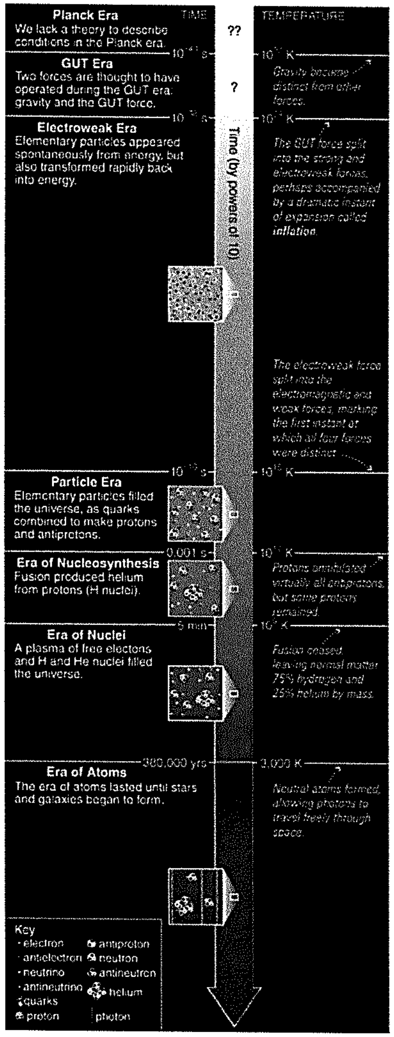


Figure 17.4 This timeline summarizes conditions and transitions that marked the early eras of the universe.

time

Temp

Cosmic Timeline

Time	Event
$t \sim 10^{-43}$ s	Planck scale (*speculative*)
$t \sim 10^{-38}$ s	GUT scale (*speculative*)
$t \sim 10^{-35}$ s	Inflation (*speculative*)
$t \sim 10^{-12}$ s	Standard Model forces emerge
$t \sim 10^{-8}$ s	WIMPs decouple (*speculative*)
$t \sim 10^{-5}$ s	quarks condense into baryons (*baryogenesis*)
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends
$t \sim 1$ s	neutrinos decouple
$t \sim 4$ s	electron-positron annihilation ends
$t \sim 10^{2}$ s	Big Bang Nucleosynthesis
$t \sim 10^{5}$ yr	Matter-radiation equality
$t \sim 4 \times 10^{5}$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^{6}$ yr	Gas temperature decouples from radiation
$t \sim 10^{7}$ yr	Dark Ages
$t \sim 5 \times 10^{8}$ yr	Cosmic dawn (first stars)
$t \sim 10^{9}$ yr	Galaxies form
$t \sim 4 \times 10^{9}$ yr	Peak star formation
$t \sim 9 \times 10^{9}$ yr	Sun forms
$t \sim 13 \times 10^{9}$ yr	Life on earth

Early U radiation dominated

$$t \lesssim 10^5 \text{ yr}$$

$$a \sim t^{1/2}$$

$$T \sim a^{-1}$$

$$Tt^2 \sim \text{constant}$$

Early Universe

Aside from the hypothetical period of exponential expansion during Inflation, the early universe is radiation dominated with

$$a(t) \sim t^{1/2} \qquad T \sim a^{-1} \sim (1+z) \qquad \varepsilon_r = \alpha T^4$$

α = radiation constant

Can substitute T for a in Friedmann equation to find that $\underline{\underline{T^2 t = \text{constant}}}$
where the constant depends only on physical constants.

Particle - antiparticle pairs exist in equilibrium with the radiation field until they "freeze out" at a time when the temperature T_γ drops below the energy required for spontaneous pair production

electron - positron freeze-out occurs shortly after the neutrino background decouples from the radiation background, so the $e^- - e^+$ entropy contributes to T_γ but not T_ν.
Consequently, these relativistic backgrounds differ in temperature by

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

where the $\frac{4}{11}$ comes from the difference in degrees of freedom for bosons (photons) and fermions (neutrinos)

$$I_\pm = \int_0^\infty \frac{x^3\,dx}{e^x \pm 1} \qquad \begin{array}{l} + \text{ bosons} \\ - \text{ fermions} \end{array} \longrightarrow \qquad \begin{array}{l} \varepsilon_r = \alpha T_\gamma^4 \\ \varepsilon_\nu = \frac{7}{8}\alpha T_\nu^4 \end{array}$$

Cosmic Microwave Background (CMB)

A fundamental ~~tenat~~ of the Hot Big Bang cosmology is that the universe should be full of a relic radiation field. This was discovered in the '60s and is now known as the CMB.

It has a perfect thermal spectrum with $T_{\gamma,0} = 2.75$ K.

The surface of last scattering at $z = 1090$ marks the transition from an opaque plasma to a transparent atomic gas after recombination forms free electrons and protons into hydrogen.

The CMB temperature is very uniform on the sky – it is very nearly the same in every direction we look: the early universe obeys the cosmological principle, being both homogeneous and isotropic when $t_{ls} = 3.8 \times 10^{5}$ yr.

There is a dipole moment on the sky due to our motion wrt the CMB of ~ 600 km s^{-1} (discovered in '70s)

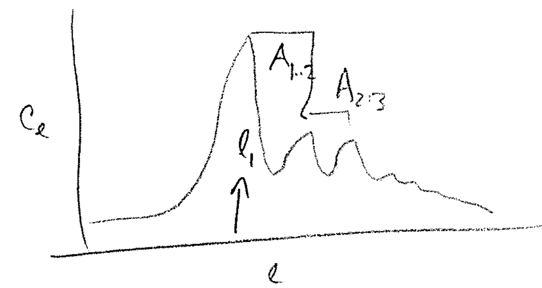
There are fluctuations on smaller scales at the level $\frac{\Delta T}{T} \approx 10^{-5}$

(discovered in '92)

These fluctuations represent early seeds for the formation of large scale structure, which were predicted to have a larger amplitude ($\frac{\Delta T}{T} \sim 10^{-2}$). That this is not the case is one line of evidence for non-baryonic cold dark matter, which is needed to grow structure in the allotted time.

(The other primary line of evidence for CDM is $\Omega_m > \Omega_b$.)

The pattern of fluctuations in the CMB, quantified as the acoustic power spectrum, is a sensitive probe of cosmic parameters



- The location of the first peak, ℓ_1, is primarily sensitive to the geometry of the universe. Its observed location indicates that the universe is flat $|\Omega_k| < 0.005$.

- The amplitudes of the peaks and their ratios $A_{1:2}, A_{2:3}, \ldots$ are sensitive to the matter content of the universe. Alternate compression and rarefaction peaks are a competition between baryonic drag and the net driving term provided by non-baryonic dark matter.

Large Scale Structure

LSS starts from the small fluctuations seen in the CMB: $\delta = \frac{1}{3}\frac{\Delta T}{T}$
From this initial condition, structure grows as $\delta \sim a(t)$.
The dark matter forms structure first. The baryons subsequently fall into the halos formed by CDM after they fully decouple from the photons (not till $z \sim 200$).