Review notes ASTR/PHYS 328/428 second exam

Big 2 numbers: H_0, Ω

$$\Omega_X = \frac{\rho_X}{\rho_c} \qquad \rho_c = \frac{3H_0^2}{8\pi G}$$

Friedmann equation $\quad H = \frac{\dot{a}}{a} \qquad a = \frac{1}{1+z}$

$$H^2 = H_0^2\left(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_\Lambda\right)$$

Five Classic Tests

$D_L - z$	Standard Candles
$D_A - z$	standard Rods
$N(z)$	Number counts with redshift
$N(m)$	Number counts with magnitude
Tolman test	Cosmological surface brightness dimming

The number count tests differentiate between FLRW models because they're sensitive to the cosmic volume element $dV(z, q_0)$. To employ them, we must integrate over the luminosit function

$$\Phi(L) = \Phi^*\left(\frac{L}{L^*}\right)^{-\alpha} e^{-L/L^*}$$

and account for its evolution with redshift

integrated luminosity density $j \simeq \Phi^* L^* \Gamma(\alpha+1)$

Distance Scale

- Solar System
  - earth-sun distance
- Trigonometric Parallax
  - statistical & secular parallax; moving clusters
- Main Sequence Fitting
- Bright Star Standard Candles
  - Cepheids, RR Lyraes, TRGB
- Secondary Distance Indicators
  - Type Ia SN, Tully-Fisher, Fundamental Plane, SB Fluctuations
- Absolute Methods
  - Gravitational lens time delay, SZ effect, water masers

- Trigonometric methods absolute
  - same as land surveys - use Pythagoras!
- Secondary Distance Indicators
  - Generally relate a distance dependent quantity (luminosity or size) to a distance independent quantity that is correlated with it.
  - e.g., Cepheid P-L relation: the period P is used as an indicator of the luminosity L
- Absolute Methods
  - make use of physics that is distance-independent
  - e.g., the speed of light is constant, but light must traverse a different path for each image in a gravitational lens, so measuring the time delay between images constrains the distance through $c\Delta t$.

Age Constraints

- Oldest stars

  Fit HR diagrams of globular clusters

  typically find $t_{GC} = 12 - 14$ Gyr

- White dwarf cooling curves

  Radiative cooling rate reasonably well understood

  Find drop-off point in WD luminosity fcn corresponding to WDs that have cooled the most

  Accounting for preceding stellar evolution, get $t_{WD} = 12.5^{+1.4}_{-3.5}$ Gyr

- Radioactive isotope chronometers

  Chart decay of long-lived isotopes of Thorium & Uranium

  Abundances of r-process elements in oldest stars gives

  $t_{Th} \approx 12.8 \pm 3$ Gyr

- Interstellar dust grains

  measure isotopic abundance ratios $O^{16,17,18}$ in interstellar grains; work back to source star and its evolutionary timescale

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

Early Universe

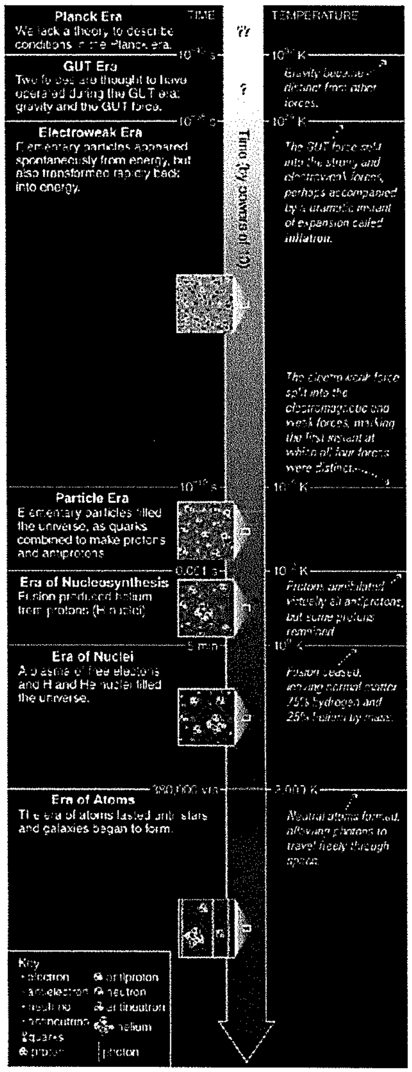
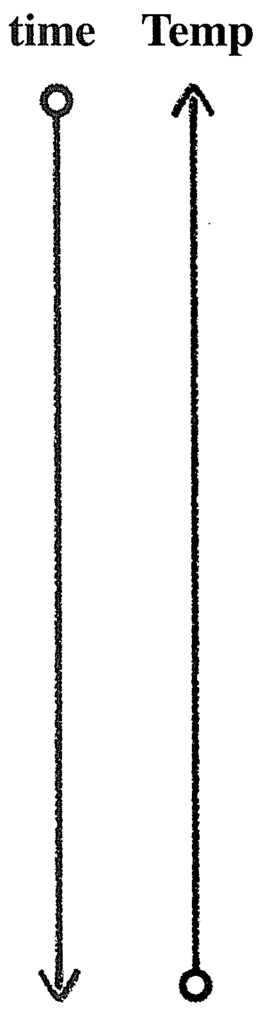


Figure 17.4 This timeline summarizes conditions and transitions that marked the early eras of the universe.



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	Multicellular life on earth
$t \sim 13.7 \times 10^{9}$ yr	You are now

Early U radiation dominated

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

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

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

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

Decoupling means to fall out of thermal equilibrium - i.e., when it becomes impossible for the radiation field to spontaneously create particle-antiparticle pairs.

Early Universe

Radiation domination

Since $\rho_m \sim a^{-3}$ (matter density)

but $\rho_r = \frac{\varepsilon_r}{c^2} \sim a^{-4}$ (radiation energy density)

there is a time in the early universe when a is small enough that $\rho_r > \rho_m$.

In this early period of radiation domination,

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

so the temperature of the radiation field T can be a proxy for a or z and we have

$$T^2 t = \text{constant} \approx 10^{10}\ K^2 s$$ depending only on fundamental constants

Particle - anti-particle pairs exist in equilibrium with the radiation field, but "freeze-out" as the temperature declines as the universe expands

$T(z)$ is the temperature of the relic background radiation — what we detect as the 3K CMB today was much hotter in the past

There should also be a corresponding cosmic neutrino background with $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$

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 $\Omega_m > \Omega_b$.)