Extra-Galactic Astronomy - I
Cosmology

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Part I - Lecture 11

Inflation & Scalar Fields

- Problems with standard cosmological model
- Role of scalar field (`inflaton′) in the early Universe

Alternative Cosmological Models

- (semi-standard): $\Lambda \rightarrow$ Dark energy / modified gravity
- (non-standard): (Quasi) steady state universe

(among several others!)

Problems with standard model

Flatness problem

Total density parameter today is of order unity:
$\Omega_0 = 1 - \Omega_{k0} = O(1)$

In the past,
$\Omega(a) - 1 = -\Omega_k(a) = -\Omega_{k0} a^2 / [\Omega_{r0} + \Omega_{m0} a + \Omega_{k0} a^2 + \Omega_{\Lambda 0} a^4]$
$\rightarrow 0$ for $a \rightarrow 0$

E.g., around $T \sim 1$Mev ($t \sim 1$sec),
$\Omega(a) - 1 \approx -\Omega_{k0} a^2 / \Omega_{r0} \approx -\Omega_{k0} \times 10^{-15}$.

Why was the early universe so finely-tuned to be flat?

Problems with standard model

Horizon problem

Comoving particle horizon at photon decoupling epoch (z_{dec} ~ 1100) in standard cosmology:
$\chi_p \approx 180h^{-1}$Mpc

Comoving angular diameter distance to $z = z_{dec}$:
$d_A/(1+z_{dec}) \approx 6000h^{-1}$Mpc

Expected angle over which CMB temperature is coherent:
$\Delta\theta \approx 2$ deg

Why is the CMB so uniform across the sky?

Fixing the horizon problem

— Recall comoving particle horizon at some epoch t :

$$\chi_{\rm P}(t) = \int_0^t \frac{c\,{\rm d}t'}{a(t')} = \int_0^{a(t)} \frac{{\rm d}a'}{a'}\,\frac{c}{a'H(a')}$$

where $c/[aH(a)]$ is comoving Hubble radius, which always increases in standard scenario, with very little contribution per $\ln(a)$ from early times (during radiation domination, comoving Hubble radius $\sim a$).

— Possible solution: allow for a (brief) phase in which previously causally connected points become temporarily causally disconnected. Only possible if **comoving** Hubble radius decreases.

— Mathematically, requires $d/dt[a\, da/dt/a] = d^2a/dt^2 > 0$, i.e., phase of rapid expansion (`***inflation'***). E.g., possible if $H \approx$ constant in this period (so that $a \approx a_e \exp[H(t-t_e)]$ and $1/aH$ falls exponentially).

— Typical models work at $T \sim 10^{15}$Gev [$a \sim 10^{-28}$, $t{\sim}10^{-32}$s], where comoving Hubble radius ~ 10^{-26} of current value. So even largest observed scales could be causally connected, provided there were at least $\ln(10^{26}) \approx$ **60 e-folds** of increase in scale factor during inflation **and** comoving Hubble radius was large enough at the start of inflation. (Latter is fine since currently observable Universe of size $\sim10^{28}$cm arose from $\sim10^{-26}$cm patch in this scenario.)

Inflation with a scalar field

Simple model: single scalar field `slowly rolling' in a very flat potential.

Energy-momentum tensor:

$$T^{\mu}{}_{\nu} = \partial^{\mu}\varphi\,\partial_{\nu}\varphi - \delta^{\mu}_{\nu}\left[\frac{1}{2}\partial^{\alpha}\varphi\partial_{\alpha}\varphi + V(\varphi)\right]$$

so that

$$\rho = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) \quad ; \quad P = \frac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

Slow roll implies potential term dominates, so $P \approx -\rho$, or $H \approx$ constant.

Successful model requires inflation to end, generating standard model particles and transferring massive amount of entropy from inflaton to the plasma, bringing temperature back up to ~10^{15}GeV — **reheating**.

As by-product, flatness problem also solved ($\Omega \to 1$ exponentially). More importantly, quantum effects also generate tiny fluctuations in gravitational potential, which then couples to standard components — seeds of eventual large scale structure.

Alternatives to standard cosmology

Dark Energy & Modified Gravity

Problems with value of cosmological constant Λ:

— Vacuum energy is the most plausible candidate for Λ, but standard QFT estimates give $\rho_{vac} \sim k^4$ with k = momentum cutoff. If $k \sim m_{Pl}$ then $\rho_{vac} \sim (10^{19}\text{Gev})^4$, whereas observed value is $\rho_\Lambda \sim \rho_{crit0} \sim h^2(3\text{mev})^4$, so that

$\rho_\Lambda / \rho_{vac} \sim 10^{-123}$

— Constant value of Λ is such that $\rho_\Lambda \sim \rho_m(a{\sim}1)$, despite ~36 e-folds of expansion with well-understood physics, which seems like too much of a coincidence.

Gives rise to the notion of dynamical component that can produce $q_0 < 0$. Experience with inflation makes scalar fields (\`quintessence', \`K-essence') a natural choice. These can be tuned to \`solve' coincidence problem, but they do not address the vacuum energy problem.

Alternatively, postulate that GR doesn't work on largest scales. Leads to alternative models such as \`f(R) gravity'.

Alternatives to standard cosmology

Steady State Cosmology

Formulated by Bondi & Gold (1948) and Hoyle (1948) and developed further by Hoyle & JVN in 1960's. Motivated partly by discrepancies in measuring age of the Universe from H_0 (leading to t_0 ~ 2Gyr), but mainly by theoretical / philosophical considerations:
— Notion of singular beginning is problematic (e.g., for action principle)
— Notion that cosmological principle should also apply in time (`Perfect Cosmological Principle')

Led to theory with constant H & ρ, $a \sim \exp(Ht)$ and creation of matter with $V^{-1}\mathrm{d}M/\mathrm{d}t = 3H\rho$ = constant. Field theoretic formulation by Hoyle led to description of creation process using scalar field C.

Several theoretically beautiful features and concrete predictions for distance-redshift relations, event horizons, etc. Also incorporated `bubble' model, predating inflation by ~20 years. Key difference from Big Bang model: absence of early hot phase.

Eventually killed in 1964-65 due to two observations: ***(a)*** observation of deuterium at levels consistent with BBN and ***(b)*** discovery of thermal and isotropic CMB radiation.

Alternatives to standard cosmology

Quasi Steady State Cosmology

Introduced by Hoyle, Burbidge & Narlikar (1993). Amalgamated ideas from SSC (creation field with negative energy density) and Hoyle-Narlikar action-at-a-distance cosmologies from 1964.

Main qualitative feature: creation events occur periodically, interspersed with long phases of no creation. Leads to model with periodic cycles of expansion & contraction, superimposed on very long term deSitter-like expansion.

Substantially more complicated than SSC, with several (4-5) free parameters.
— Light elements can be produced: creation events produce `Planck particles' which then decay into Standard Model species.
— Dark matter explained as dead stars from previous cycles.
— Explanation of thermal CMB spectrum requires presence of iron `whiskers' (created in supernovae) that interact with starlight from any given cycle and thermalise it. CMB is then sum total of this thermalised radiation from all previous cycles.
— Explaining CMB anisotropy spectrum and LSS data is a big challenge.

*[See **An Introduction to Cosmology** by JVN for details + discussion on falsifiability, etc.*
*For a detailed (and very sharp!) critique, see **http://www.astro.ucla.edu/~wright/stdystat.htm**]*