Living in the Darkness

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1. Our Universe :

Harlow Shapley Vs Heber Curtis 26.4.1920

A. V. Maanen [Rotn. of M31]

Cepheid Variable Stars ⇒ Standard candles

Period	Luminosity
1 day	10^2 Solar Lum.
50 days	10^4 ,, ,,

$L_a = \frac{L_s}{4\pi r^2}$. Edwin Hubble in 1925

M31 & Other Spiral Nebulae are far away from Milky Way

Univ Contains 100b Galaxies

Size of Observable Univ ~ 10,000 Mpc.

2. Evolving ⇒ Creator God

Confession by St. Augustine [354 - 430 A.D.]

Static & Infinite Univ. ⇒ Removes C.G.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{3} T_{\mu\nu}$$

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2\right]$$

$$T_{\mu\nu} = (\rho + p) U_\mu U_\nu + p g_{\mu\nu}$$

If $p = 0$; $\rho = \frac{\Lambda}{4\pi G}$; $a = \frac{1}{\sqrt{\Lambda}}$ for $k = +1$

Olbers paradox? J. P. L. de Chesaaux (1744)
H. W. M. Olbers (1826)

$L_a = \frac{L_s}{4\pi r^2}$;

No. of stars between r & $r + dr$ = $dN = 4\pi r^2 dr . n$

Radiant Energy = $\int_0^\infty L_a \, dN = \int_0^\infty L n \, dr \to \infty$

Infinite Static Univ ⇒ Bright night sky

Solution 1: Interstellar medium absorbs?
But " " are in th. equilib.

Solution 2: Stars are opaque, so not all seen
But every line of sight ends in a star.

Solution 3: Univ. is evolving & finite

Aleksandr Aleksandrovich Friedmann (1922)

$\omega = \frac{p}{\rho} = \frac{1}{3} \Rightarrow \rho a^4 = \text{Const} \Rightarrow a \propto \sqrt{t}$: Radiation

" = " $= 0 \Rightarrow \rho a^3 =$ " $\Rightarrow a \propto t^{2/3}$: Matter

Georges Edouard Lemaitre (1927)

Edwin Hubble & Redshift : (1929)
(V. M. Slipher)

Recessional velocity ($v \approx zc$, for $z \ll 1$)

Comoving distance D

$v = H_0 D$; $H_0 \Rightarrow$ Hubble constant

$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{a(t = \text{today})}{a(t = \text{emission time})}$$

(1+z) is the factor by which Univ. has expanded since a photon has been emitted from a source

So, Univ is expanding. since $t = 0$, $a = 0$

Big-Bang : When everything blows

Beginning of time $\Rightarrow$ Creator God (Λ-removed)

Predictions From Big-Bang

(a) Big Bang Nucleosynthesis:

$\alpha\beta\gamma$ - theory (1948) (BBN)

✓Ralph Alpher - Hans Bethe - ✓George Gammow
???

At $T > 10^9 K$ $n \to p$ $\frac{n}{p} \to \frac{1}{7}$

At $T \simeq 10^9 K \simeq 0.1$ MeV < B.E. of Light nuclei

$n + p \to {}^2D$ ⇒ Deuterium

${}^2D + {}^2D \to {}^4He$

Finally ${}^2D$, ${}^3He$, ${}^4He$, ${}^6Li$, ${}^7Li$ Could form.

Unstable isotopes ${}^3H$, ${}^7Be$, ${}^8Be$ decayed or fused with other nuclei

Lasted for few minutes.

Univ. expands → Temp. falls

All ${}^2D$ were not converted to ${}^4He$

Heavier isotope could not form

Theoretical prediction of Elemental Abundance of these light nuclei

75 % ${}^1H$, 25 % ${}^4He$, ·01 % ${}^2D$, 10^{-10}% Li

has been confirmed experimentally. ([redacted])

Baryon Energy density can be calculated from the E.A. of Light nuclei (4%)

$\Omega_{B0} \simeq .04$

Photon to Baryon ratio $\sim 10^9$

(b) CMBR

George Gammow - Ralph Alpher - Robert Herman
(1948)

If B-B is true :

Univ. evolved Like hot - thick Soup of Plasma containing sub-atomic particles
[e^-, e^+, n, p, γ, ν etc.]

At 10^{-2} s (10 MeV) ⇒ Thermal equilibrium

Univ. was opaque ∵ Thomson Scattering betn. γ & e^-

After 4×10^5 yrs. $T \sim 0{\cdot}25$ eV ≈ 3000 k

Recombination : Photons decoupled.

Alpher & Herman ~ 5 k in Microwave

Robert Dicke & Yakov Zel'dovich (1960)

David Todd Wilkinson & Peter Roll (1964)

Constructing Dicke Radiometer

Arno Penzias & Robert Woodrow Wilson

built D.R. for Radio Astronomy & Satellite Communication : Their Instrument had an excess 3·5 k antenna temp.

" Dicke : Boys we'[redacted]ve been scooped "

Noble in 1978 : $T = 2{\cdot}728 \pm {\cdot}002$ k

Birth of Cosmology $\Omega_R = 5 \times 10^{-5}$ (·005%)

Dark Matter : Fritz Zwicky (1933)

Velocities of Individual Galaxies in
COMA Cluster ⇒ Very large

Virial theorem:

$$K + \frac{U}{2} = 0$$

$$K = \frac{3}{2} M \langle v_r^2 \rangle \; ; \; U = -\frac{GM^2}{R} \qquad R \sim 2\,\text{Mpc.}$$

⇓
Velocity dispersion

holds if $M_{COMA} \gg \sum M_{Galaxies}$

In: 70's Peculiar Velocities in Galaxies

Kepler's law : $v(r) = \sqrt{\frac{GM}{r}}$

$$\therefore \; v(r) \propto \frac{1}{\sqrt{r}}$$

But at large distance from Centre

$v \sim$ Constant $\therefore M \propto r$

Tested for over 1000 Galaxies
observing 21 cm. emission lines of neutral H.

Structure formation also supports the requirement of Cold Dark Matter

$\Omega_{DM} \simeq 0{\cdot}24 \sim 0{\cdot}26$ (24% ~ 26%)

Problems encountered with B.B

1. Why Univ is so Isotropic & homogeneous?
   CMB Isotropy 1 part in 10^5
2. Why Univ is so Inhomogeneous ?
   Small scale structures.
3. How to get rid of Creator God ?

Charles W. Misner suggested :

Neutrino viscosity at the early Univ. might have reduced anisotropy in CMB.

George L. Murphy :

Bulk viscosity can push singularity to infinite past : violates energy condition ($\rho+3p<0$)

Vladimir A. Belinsky & Isaak. M. Khalatnikov :

Dissipative Mechanism due to ν viscosity, really isotropises, modifies B-B-Sing & accounts for Large entropy/Baryon.

Q. G. Initiated : Bryce de-Witt & Stefen Weinberg

⇒ U.V. Divergence ⇒ SUGRA, SUSY, SUPER STRING

QFT in C.S.T : Gravity treated as Classical

⇒ Vacuum is non-trivial

⇒ Creation of matter from Vac. fluc. of ϕ.

Q. Cosmology : $\hat{H}|\Psi\rangle = 0$

Univ. has been created from Nothing.

More Problems:

a) Horizon problem ⇒ Prob. of Isotropy is even worse

b) Flatness " ($k = 0, \pm 1$ ⇒ Curvature param.)

$$3\left(\frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right) = 3H^2 + 3\frac{k}{a^2} = 8\pi G\rho$$: Friedmann eqn.

$k = 0 \Rightarrow \rho_c = \frac{3H^2}{8\pi G}$ ⇒ Critical density

$\therefore \quad \Omega - 1 = \frac{k}{a^2 H^2} \quad ; \Omega = \frac{\rho}{\rho_c}$

Matter dominated era : $a \propto t^{2/3}$

$$\frac{\Omega_{t=100s} - 1}{\Omega_{t=14GYr} - 1} = \left(\frac{t}{t_0}\right)^{2/3} \sim 10^{-11}$$

If $\Omega_{t=14GYr} \sim 1$,

$\Omega_{t=100s} \simeq 1 \pm 10^{-11}$ Incredible ⇒ Fine tuning

$k = 0$ from the beginning ?

Why ?

Unwanted Relics : If B.B starts before $T > 10^9$ GeV

Gravitino ($m \sim 100$ GeV) Survived & no B.B.N.

Monopoles & Other topological defects

Inflation :

$$\left.\begin{aligned} 2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= -8\pi G p \\ \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} &= \frac{8\pi G}{3}\rho \end{aligned}\right\}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$\rho + 3p < 0 \Rightarrow$ Acceleration $\Rightarrow \omega = \frac{p}{\rho} < -\frac{1}{3}$

* Unwanted relics are inflated
* Once Causally connected regions → Beyond Horizon
* Univ. is flattened.

It must end. Cosmological scales then slowly enter horizon.

* Horizon problem solved.
* Flatness " " . $k \to 0$
* No Unwanted relics.

Starts at $\sim 10^{-42}$ s ; ends $\sim 10^{-12}$ s.

Requires ϕ field

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\omega = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V} \simeq -1, \text{ if } \dot{\phi} \approx 0$$

ie. V is flat.

Vac fluctuation of ϕ produces particles.
Univ. reheats ⇒ Big Bang Starts.

Imprint of Inflation :

Q. Vac. fluc $\Rightarrow$ $\delta\phi$ $\rightarrow$ freezed beyond H.

After horizon entry :

$\delta\phi \xrightarrow[\text{fn.}]{\text{Transf}}$ $\delta\rho$ $\rightarrow$ density p

$\delta g_{\mu\nu}$ $\rightarrow$ S-T p

$\delta\Theta$ $\rightarrow$ P. in no. of γ at $\vec{x}$ with momentum along $\hat{n}$

$\downarrow$

CMB Anisotropy

Gravitation $\not\forall$ Random particle motion

$\Downarrow$

tries to increase $\delta\rho/\rho$ attracting more matter to overdense region.

* **Massless neutrinos** : R.M. Wins δ_k falls exponentially.
  HDM

* [redacted] : R.M. ≈ 0, δ_k grows logarithmically, a potential Well is developed.
  CDM

* Baryon + Photon plasma : The fluid Oscillates like a standing Acoustic wave.

Univ expands & cools, e^-'s form atoms Thomson Scatt ceases, γ decouple $\rightarrow$ CMB

Baryons fall in CDM P. Well with same δ_k

$$\delta_k = \frac{\delta\rho}{\rho} = \frac{4}{9}\left(\frac{k}{aH}\right)^2 \mathcal{R}_k \,, \quad \mathcal{R}_k = -\left[\frac{H}{\dot{\phi}} \times \delta\phi_k\right]_t$$

⇒ Series of Peaks & troughs [f^n. of Angular Scale]

1st. peak Correspons Curvature of S-T. [angular Scale]

1st : 2nd ⇒ Baryon density

3rd ⇒ Information about D.M.

1st : 2nd : 3rd ⇒ Type of perturbation. [ang. Scale]

Adiabatic P. ⇒ Fractional overdensities of each matter components (Baryons, γ, ν) are the same

If in a spot 1% of B & 1% of γ overdensities than av. then 1% o-d for ν also.

Ang. Scale of peaks ⇒ 1 : 2 : 3 [Inflation]

Isocurvature P ⇒ $\sum$ F. o-d = 0 [cosmic strings]

If 1% o-d of B & 1% of γ then 2% under-d. of ν [1:3:5]

Observations:

1. COBE : Anisotropy at 7° ang. scale [Well outside the horizon at Last Scatt. Surf.]
   i.e. Primordial form of P detected.
2. BOOMERANG : Reported highest power fluct. at < 1° ⇒ $\Omega_0 \approx 1{\cdot}02 \pm 0{\cdot}04$
3. WMAP : Measured other peaks ⇒ $0{\cdot}2 < \Omega_{m0} < 0{\cdot}4$

Also 1st. : 2nd. : 3rd = 1 : 2 : 3 → DASI / VSA / CBI

Inflation is Confirmed " Planck with ACBAR "

Cosmic Strings ruled out.

SN1a - Data & Recent Acceleration

Expt. $m - M = 5\log_{10}\left(\frac{d_L}{\text{Mpc}}\right) + 25$

$H_0 d_L = z$ for $z \leq 0.2$, $H_0^{-1} = \frac{3000}{h}$ Mpc.

Data $z = 0.026$ $m = 16.08$ ① 1992P

$z = 0.83$ $m = 24.32$ ② 1997ap

Take ① Get d_L & hence $M = -19.09$

Take ② & M , $H_0 d_L = 1.16$

Th. Model. $d_L = \frac{L_s}{4\pi \mathcal{F}} = \frac{1+z}{H_0}\int_0^z \frac{dz}{\sqrt{\sum \Omega_{i0}(1+z)^{3(1+\omega_i)}}}$

Take only matter $\Omega_{m0} = 1$, $H_0 d_L \simeq 0.94$

Take matter ($\omega_m = 0$, $\Omega_{m0} = 0.3$) & Λ ($\omega_\Lambda = -1$, $\Omega_{\Lambda 0} = 0.7$) $\Rightarrow H_0 d_L \simeq 1.19$

Acceleration: $q = -1 - \frac{\dot{H}}{H^2} = \frac{3}{2}\frac{\sum \Omega_{i0}(1+\omega_i)(1+z)^{3(1+\omega_i)}}{\sum \Omega_{i0}(1+z)^{3(1+\omega_i)}} - 1$

For $\Omega_{\Lambda 0} = 0.7$ & $\Omega_{m0} = 0.3$

$q < 0 \Rightarrow z < 0.7 \Rightarrow$ Acceleration is recent phen.

AGE. $t_0 = \frac{1}{H_0}\int_0^\infty \frac{dz}{(1+z)\sqrt{\Omega_{m0}(1+z)^3 + \Omega_{\Lambda 0}}}$

If $\Omega_{\Lambda 0} = 0$ & $\Omega_{m0} = 1$, $t_0 \simeq 9$ Byr

If $\Omega_{\Lambda 0} = 0.7$ & $\Omega_{m0} = 0.3$, $t_0 \simeq 13.1$ Byr.

HE 1523-0901 (A red giant in Milky Way) has age ~ 13.2 Byr.

$\Lambda = ?$ Vacuum energy-density

$= \sum$ zero pt. energies of Q fields with mass M

$\rho_{vac} \simeq 10^{74}\ \text{Gev}^4$ $\langle T_{00} \rangle_{vac} \simeq \frac{c^5}{G^2 \hbar}$

But $3H^2 = 8\pi G \rho + \Lambda \Rightarrow \Lambda \sim H_0^2$

& $\rho_\Lambda = \frac{\Lambda}{8\pi G} \simeq 10^{-47}\ \text{Gev}^4$

ρ_Λ is 10^{-120} order of Mag. less than ρ_{vac}

∴ Dynamical models of D. energy initiated.

* Quintessence ⇒ The fifth force [Searching a V]

  $V \sim \frac{M^{4+\alpha}}{\phi^\alpha}$, $\alpha > 0$; $V = V_0 e^{-\sqrt{2} k \phi}$, $\phi \sim \ln t$

  Tracker field

  $-1 < \omega < -1/3$

* k - essence : [In search of K. E.]

  $S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + k(\phi, x) \right]$; $x = +\frac{1}{2}(\nabla\phi)^2$

* Chaplygin Gas $p = -\frac{A}{\rho^\alpha}$; $0 \leq \alpha < 0.2$ [E.O.S.]

* Holographic D.E. model * hessence
* Brane induced models * Higher Order Curvature terms
  [Gauss - Bonnet , f(R) model]
* Phantom [Reversing the sign of K. E. term
* Scalar tensor theory of Gravity
* Quintom models

$\omega < -1$ is possible.

God ⇒ Light &
Devil ⇒ Darkness }

Horizon Problem:

$$\frac{T_0}{T_d} = \frac{2.73}{3000} = \frac{a(t_d)}{a(t_0)} = \left(\frac{t_d}{t_0}\right)^{2/3}$$

$\Rightarrow \; t_d \simeq 2\times10^5 \, h^{-1}$ years

The dist$^{n.}$ travelled by CMBR

$$= a(t_0)\int_{t_d}^{t_0} \frac{dt'}{a(t')} = 3t_0\left[1-\left(\frac{t_d}{t_0}\right)^{2/3}\right] \simeq 3t_0$$

$$\simeq 6000\, h^{-1}\, \text{Mpc} \simeq d_H(t_0)$$

LSS : A sphere of radius $d_H(t_0)$

P. Horizon at $t_d \simeq 3t_d \simeq 0.168\, h^{-1}$ Mpc.

& today it is

$$\simeq 0.168\, h^{-1}\left(\frac{a(t_0)}{a(t_d)}\right) \text{Mpc} \simeq 184\, h^{-1}\, \text{Mpc}.$$

Angle subtended by this "decoupling horizon" is now $\theta_d = \frac{184}{6000} \simeq 0.03$ rads.

So the sky is splitted into

$\frac{4\pi}{(0.03)^2} \simeq 1.4\times10^4$ patches which were never causally connected before emitting CMBR