Overview

The Nobel laureates sought to measure a theoretical "deceleration parameter" for the universe. What did the Laureates find and what does the parameter imply?

1. Historical development of the deceleration parameter

2. Method of measurement

3. Results and implications

4. Future work

Development of General Relativity

- Einstein's published the General Theory of Relativity published in 1915

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$

- In 1917, Einstein introduced the cosmological constant to his field equations to make his universe static

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}$$

- Alexander Friedmann's work in 1924 showed that Einstein's static universe still unstable
- Georges Lemaître obtained similar results independently in 1927

Multiple Galaxies

- In 1912, Vesto Slipher observed the redshift of several nebulae and determined that the bodies moved faster than the Milky Way's escape velocity.
- Edwin Hubble published his discovery that far away "nebulae" were galaxies along with "Hubble's Law"

$$v = H_0 D$$

Cosmological Principle

- The universe is homogeneous and isotropic
- Implies that the energy-momentum tensor is similar to a fluid
- Verified in 1964 with discovery of Cosmic Microwave Background
- Motivated Howard Robertson and Arthur Walker to find a general metric that meets the cosmological principle

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

Friedmann Equations

- The "Friedmann" equations may be found from the Einstein field equations

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

$$(1)\ \ H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$(2)\ \ \frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Deceleration Parameter

- From the Friedmann equations, the “critical” density is derived. It is also beneficial to define density ratios and the equations of state.

$$\rho_c = \frac{3H^2}{8\pi G} \qquad \Omega_i = \frac{\rho_i}{\rho_c} \qquad w_i = \frac{P_i}{\rho_i}$$

- We can now write the deceleration parameter, especially in a matter dominated universe

$$q_0 = \frac{-\ddot{a}a}{\dot{a}^2} = \frac{\ddot{a}}{aH^2} \qquad q_0 = \frac{1}{2}\sum_i \Omega_i(1 + 3_i) = \frac{\Omega_m}{2}$$

Measuring Cosmological Distances

- If we know the intrinsic luminosity of an astronomical object, the luminosity distance can be determined through the formulae

$$d_l = \sqrt{\frac{L}{4\pi l}} \qquad z = \frac{\Delta\lambda}{\lambda} = \frac{a(t_0)}{a(t)} - 1$$

$$d_l(z; H_0, \Omega_i, \Omega_\Lambda) = \frac{1+z}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

Standard Candle

- Type Ia supernovae suspected as good candidates in 1938
- Extremely bright and can be observed over a period of weeks
- Physical features are nearly uniform

Figure 1- Type Ia supernova

Saul Perlmutter

- Supernova Cosmology Project (SCP) started in 1988
- Digital Image Subtraction
- Supernova on Demand
- Observed 42 Type Ia supernovae

Supernova Discovery and Measurement Sequence.

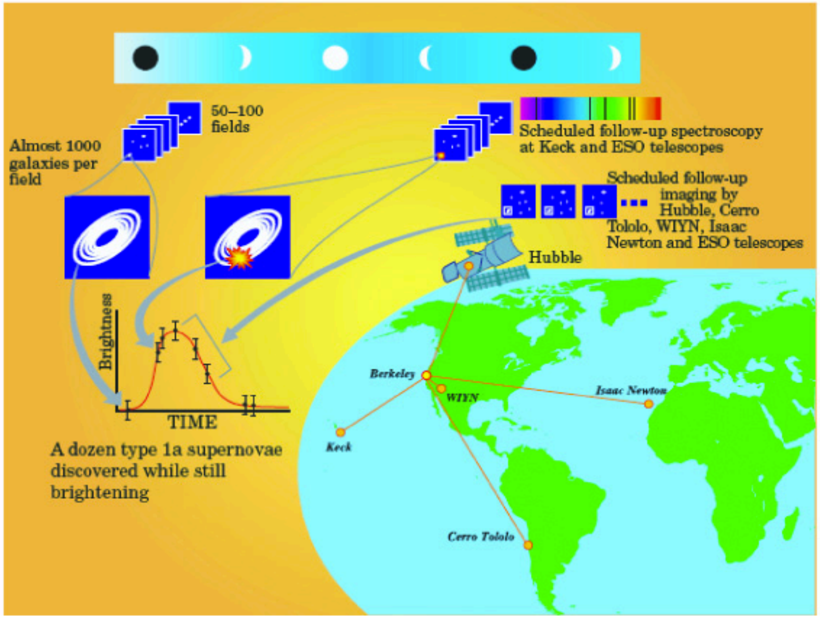
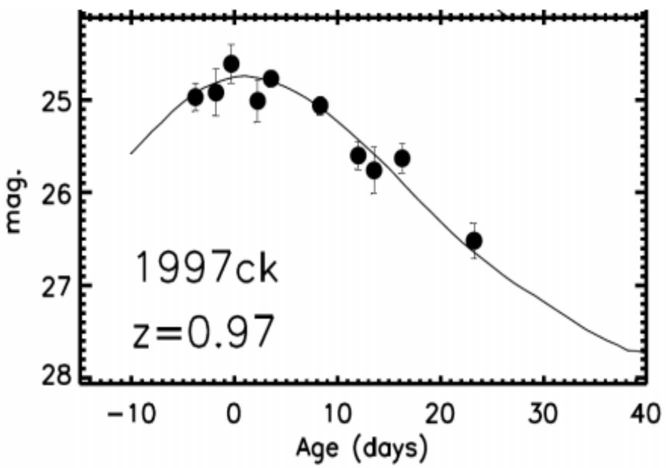


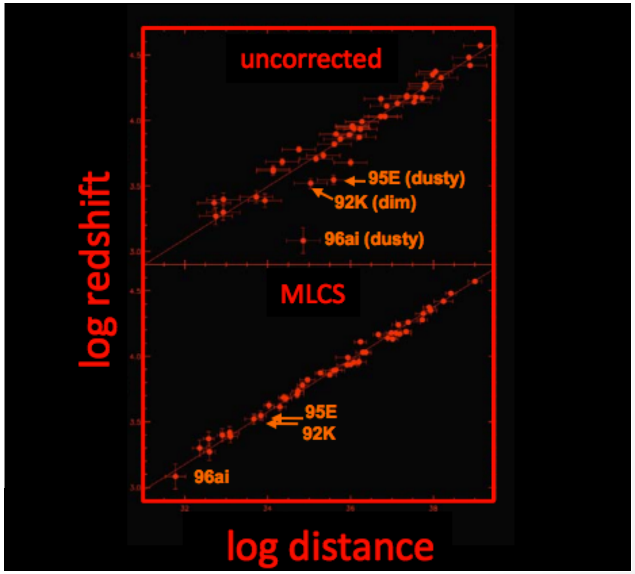
Figure 2-Supernova on Demand

Brian Schmidt and Adam Riess

- High-z Supernova Search Team (HST) formed in 1994
- 16 Type Ia observations published around same time as SCP with more signal per object than SCP
- Multicolor Light Curve Shape
- "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant" in 1998

(Left) Figure 3- Example of light curve for a supernova





(Right) Figure 4- Multicolor Light Curve Shape

Results

- If universe was matter dominated, results should have been ~25% brighter
- The calculated deceleration parameter was negative
- The cosmological constant must drive the acceleration of the universe

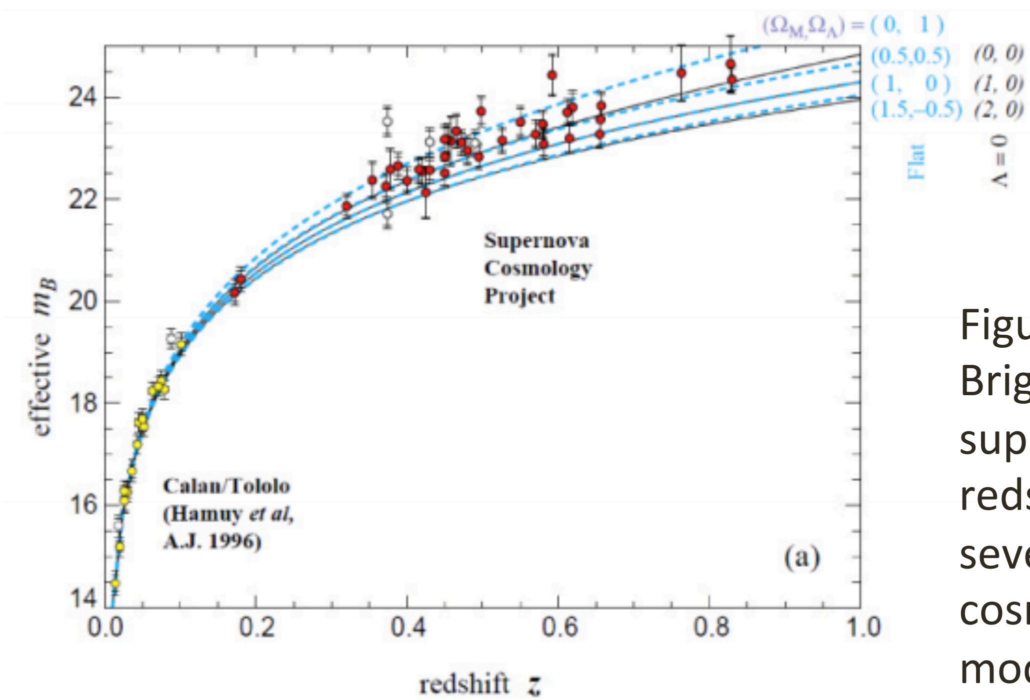


Figure 5- Brightness of supernovae vs. redshift fit to several cosmological models

Results

- Georges Lemaître suggested that Λ is a vacuum energy as early as 1934
- Several theories describe the origin of dark energy
  - Quantum fluctuations and spontaneous symmetry breaking
  - An inflationary epoch in the early universe
- Early universe ($z>1$) seems to slow down as originally predicted

Future work

1. What is the source of dark energy?
2. Why are the mass densities on same order?
3. Is General Relativity a sufficient theory?

References

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