Type Ia Supernovae and Dark Energy

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Outline

The Hubble diagram of Type Ia Supernovae
  • evidence for accelerated expansion
  • evidence for/against dust and evolution

Systematics of Type Ia Supernovae
Measuring the equation of state parameter
Distant supernovae

Higher-z SN team (GOODS/HST)

Riess et al. (2003)
The principle

Establish a cosmological distance indicator in the local universe (z<0.05)

- evolution (primary and secondary)
- interstellar and intergalactic dust
- gravitational lensing

Measure objects at cosmological distances

- establish identity of distance indicator
- control measurement errors
**Type Ia Supernovae**

Establish a cosmological distance indicator in the local universe (z<0.05)

- **evolution** → light curve shapes, colours, spectroscopy
- **dust** → colours, spectroscopy
- **gravitational lensing** → difficult, need mapping of light beam

Measure objects at cosmological distances

77 distant SNe Ia (0.3<z<1.0) published

Evidence for good distances

102 SN at 0.01<z<0.2
Hamuy et al. 1995
Riess et al. 1998
Riess et al. 1999
Germany et al. 2002
Jha et al. 2002

The nearby SN Ia sample
Starting from Einstein’s Field equation

\[ G_{ij} = -\frac{8\pi G}{c^4} T_{ij} \]
Friedmann cosmology

Assumption: homogeneous and isotropic universe

Null geodesic in a Friedmann-Robertson-Walker metric:

\[
D_L = \frac{(1 + z)c}{H_0 \sqrt{|\mathcal{M}|}} \int S \sqrt{|\mathcal{M}|} \left(\frac{1 + z}{0} (1 + z)^2 + \mathcal{M}_M (1 + z)^3 + \mathcal{M}_k \right)^{1/2} \, dz
\]

\[
\mathcal{M}_M = \frac{8\pi G}{3H_0^2} \mathcal{M}_M
\]

\[
\mathcal{M}_k = \frac{k c^2}{R^2 H_0^2}
\]

\[
\mathcal{M}_\Omega = \frac{c^2}{3H_0^2}
\]
Cosmology in the Hubble diagram

Assumption:
Lambda is constant
No time-dependence in the equation of state
Supernova cosmology

Tonry et al. 2003
Mean distance between galaxies today is fainter at redshift.

Time

Closed $\Omega_M > 1$

Open $\Omega_M < 1$

$\Omega_M = 0$

-14 - 9 - 7 billion years

today

redshift
Relative Brightness of Supernovae

- Linear scale of universe relative to today
- Eternal expansion
- Eventual collapse
- Expansion first decelerates, then accelerates
- Or always decelerates

Perlmutter 2003
Distant SNe Ia

Distant objects appear fainter than their nearby counterparts.
This is a 3.5σ result (High-z SN Team and Supernova Cosmology Project).

- evolution
- dust
- cosmology

Checks:

Dust
- observations over many filters

Evolution
- spectroscopy

Cosmology
- more distant SNe Ia
Is dust a problem?

Leibundgut 2001
SNe Ia in elliptical galaxies

Determination of host galaxy morphologies

• 38 SNe Ia from the SCP sample

Elliptical galaxies are dust-free

Sullivan et al. 2003
Supernova Cosmology Project Sample

\[ \omega_m = 0.28; \quad \omega_{\Lambda} = 0.72 \]

Sullivan et al. 2003
Hi/Low z SN Ia Spectra; Time Evolution

Evolution?

Spectroscopy of distant SNe Ia
Evolution? - Colours

Leibundgut 2001
209 SNe Ia in one diagram

Tonry et al. 2003
209 SN Ia and medians

Tonry et al. 2003
$H_0 = 63 \text{ km s}^{-1} \text{ Mpc}^{-1}$

155 SNe Ia

No Big Bang

Tonry et al. 2003
SN Ia and 2dF constraints

2dF: \( \Omega_M = 0.2 \pm 0.03 \)

KP: \( h = 0.72 \pm 0.08 \)

Tonry et al. 2003
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Tonry et al. 2003
Supernovae

SN Ia Systematics?

Explosions not fully understood

- many possible models
  - Chandrasekhar-mass models
  - deflagrations vs. detonations

Progenitor systems not known

- white dwarfs yes, but ...  
  - double degenerate vs. single degenerate binaries

→ Evolution very difficult to control
The SN Ia luminosity can be normalised

Bright = slow
Dim = fast
Nature of the Dark Energy?

Currently two proposals:

• cosmological constant

THE ACCELERATING UNIVERSE
Breakthrough of the Year
Nature of the Dark Energy?

Currently two proposals:

• **cosmological constant**
• **quintessence**
  – decaying particle field
  – signature:
    – equation of state parameter $\omega \neq 1$ with \[ \omega = \frac{p}{\rho c^2} \]
On to new physics?

Both quintessence and the cosmological constant would require additions beyond the current standard model of physics. Type Ia Supernovae (together with additional information on \(\_M\)) can distinguish between those two possibilities

- required is a large *homogeneous* set (about 200) of distant \((0.2 < z < 0.8)\) supernovae
The equation of state parameter \( \Box \)

General luminosity distance

\[
D_L = \frac{(1 + z)c}{H_0 \sqrt{\Box}} S \sqrt{\frac{z}{0}} (1 + z^{\Box})^2 + \int i \Box_i (1 + z^{\Box})^{3(1+\Box_i)}^{\Box_i^{1/2}} \, dz
\]

- with \( \Box = 1 \Box_i \Box_i \) and \( \Box_i = \frac{p_i}{\Box_i c^2} \)

\( \Box_M = 0 \) (matter)

\( \Box_R = \_ \) (radiation)

\( \Box_L = -1 \) (cosmological constant)
SN Ia and 2dF constraints

\[ \Omega_M h = 0.2 \pm 0.03 \]

\[ h = 0.72 \pm 0.08 \]

Tonry et al. 2003
$w < 0.73 (95\%)$

Tonry et al. 2003
200 Ground-based SN Ia

$w = -0.8 \quad \Omega_m = 0.35$ Flat Universe
systematic errors
- 0.01 mag
- 0.02 mag
- 0.04 mag

68.3%
95.4%
99.7%

200 nearby SN Ia + Flatness (CMB)
2dF and Sloan
Results

Supernovae measure distances over a large cosmological range

They are complementary to the CMB measurements in that they can measure the dynamics of the cosmic expansion

- map the cosmological expansion

  - SNe Ia indicate accelerated expansion for the last 6 Gyr
  - There are indications that the accelerations turns into a deceleration at z>1 (>8 Gyr)
  - dynamic age of the universe $H_0 t_0 = 0.95 \pm 0.04$
    (13 Gyr for $H_0 = 72 \text{ km s}^{-1}\text{Mpc}^{-1}$; 15 Gyr for $H_0 = 64 \text{ km s}^{-1}\text{Mpc}^{-1}$)
It’s not all done yet …

Tonry et al. 2003
GOODS (Higher-z) Supernovae

Find supernovae at $z>1.2$ from the GOODS ACS observations

Riess et al. (2003)
GOODS Supernovae

VLT spectrum

FORS2 - 300I - 3.5h integration (6. Nov '02)

Ca II H&K
z=1.31
Summary (Problems)

Supernova systematics

• unknown explosion mechanism
• unknown progenitor systems
• light curve shape correction methods for the luminosity normalisation (SCP vs. HZT)
• signatures of evolution in the colours?
• spectroscopy?
The Future

Future experiments will distinguish between a cosmological constant or quintessence

- ESSENCE, CFHT Legacy Survey, VST, VISTA, NGST, LSST, SNAP
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Systematic uncertainties depend on our understanding of the supernovae

- nearby samples, explosion models, radiation hydrodynamics
Einstein's cosmological constant cannot be explained within the current particle physics models.

Quintessence

Signatures of higher dimensions: some theories of gravity work in higher dimensions - leakage from there into the 4-dimensional world would effect the Friedmann equation.

Phantom energy: dark energy will tear the universe apart (Big Rip).
Summary

Only Type Ia supernovae can currently provide a possible answer to what the Dark Energy is:

• what is \( _? \)?
• what is \( d_/dt ? \)
• what is the future of the universe?