The Type Ia Supernova Hubble Diagram

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The original Hubble Diagram (Galaxies)

**Fig. 9.** The Formulation of the Velocity-Distance Relation.
A modern Hubble Diagram
The expansion of the universe

Luminosity distance in an isotropic, homogeneous universe as a Taylor expansion

\[ D_L = \frac{cz}{H_0} \left\{ 1 + \frac{1}{2} (1-q_0)z - \frac{1}{6} \left[ 1 - q_0 - 3q_0^2 + j_0 \pm \frac{c^2}{H_0^2 R^2} \right] z^2 + O(z^3) \right\} \]

\[ H_0 = \frac{\dot{a}}{a} \quad q_0 = -\frac{\ddot{a}}{a} H_0^{-2} \quad j_0 = \frac{\dddot{a}}{a} H_0^{-3} \]
Supernovae

SN 1937C: Baade and Minkowski

Fig. 1.—Photographic light-curve of supernova in IC 4182
The nearby SNe Ia offer excellent coverage for a few objects:
- fairly complete picture
- allows detailed comparisons

SN 2003du
European Supernova Collaboration
The nearby SN Ia sample

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

Evidence for good distances

Tonry et al. 2003
The nearby SN Ia Hubble diagram

Luminosity $L$ either from models or through the distance ladder (e.g. Cepheids)

$H_0 = c \zeta \sqrt{\frac{4 \pi F}{L}}$

Stritzinger & Leibundgut 2005
$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4\pi F}{L}} = cz\sqrt{\frac{4\pi F}{E_{Ni}}} \propto cz\sqrt{\frac{4\pi F}{M_{Ni}}}$

- **Hubble law**
- **Luminosity distance**
- **Arnett’s rule**
- **Ni-Co decay and rise time**

Need bolometric flux at maximum F and the redshift $z$ as observables.
Comparison with models

![Diagram showing comparison between different models, including MPA, W7, and SN1999aa. The graph plots H₀ (km s⁻¹ Mpc⁻¹) against the solar mass of ⁵⁶Ni.](image)
Measure deceleration

Riess et al. 2004
Adding jerk ...

\[ q(z) = q_0 + z \frac{dq}{dz} \]

- Constant Acceleration, \( q_0 = \), \( \frac{dq}{dz} = 0 \) \( (i_0 = 0) \)
- Coasting, \( q(z) = 0 \)
- Acceleration-Deceleration, \( q_0 = \), \( \frac{dq}{dz} = ++ \)
- Acceleration+Jerk, \( q_0 = \), \( i_0 = ++ \)

Riess et al. 2004
Friedmann cosmology

Assumption:
homogeneous and isotropic universe

Null geodesic in a Friedmann-Robertson-Walker metric:

\[ D_L = \frac{(1 + z)c}{H_0 \sqrt{|\Omega_k|}} S \left\{ \sqrt{\Omega_k} \int_0^z \left[ \Omega_k (1 + z')^2 + \Omega_M (1 + z')^3 + \Omega_\Lambda \right]^{-\frac{1}{2}} \, dz' \right\} \]

\[
\Omega_M = \frac{8\pi G}{3H_0^2} \rho_M \\
\Omega_k = -\frac{kc^2}{R^2 H_0^2} \\
\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}
\]
Evidence for the $\Omega_?\$
The equation of state parameter $\omega$

General luminosity distance

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S \left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[ \Omega_\kappa (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+\omega_i)} \right]^{\frac{1}{2}} dz' \right\}$$

- with $\kappa = 1 - \sum_i \Omega_i$ and $\omega_i = \frac{p_i}{\rho_i c^2}$

$\omega_M = 0$ (matter)

$\omega_R = ?$ (radiation)

$\omega_\Lambda = -1$ (cosmological constant)
$w < -0.73(95\%)$
And on to a variable?

Ansatz:

\( \phi(z) = \theta_0 + \theta' z \)
SN Projects

SN Factory
Carnegie SN Project

ESSENCE
CFHT Legacy Survey

Higher-z SN Search (GOODS)

SNAP
Four redshift regimes

$z < 0.05$

- Define the characteristics of Type Ia Supernova
- Understand the explosion and radiation physics
- Determination of $H_0$

$z < 0.3$

- Explore the systematics of SNe Ia
- Establish distance indicator
Four redshift regimes (cont.)

$0.2 < z < 0.8$
- Measure the strength of the cosmic acceleration (dark energy)

$z > 0.8$
- break the degeneracy
- measure matter density

All redshifts
- Measure details of dark energy
The SN Ia Hubble diagram

• powerful tool to
  • measure the absolute scale of the universe $H_0$
  • measure the expansion history ($q_0$)
  • determine the amount of dark energy
  • measure the equation of state parameter of dark energy
Warning to the theorists:

Claims for a measurement of a change of the equation of state parameter \( w \) are exaggerated. Current accuracy is inadequate for too many free parameters in the analysis.
Type Ia supernovae appear currently the most promising route to provide a possible answer to what the Dark Energy is.

All redshifts need to be covered

- distant SNe Ia alone are useless
- nearby SNe Ia are the source of our understanding of the distance indicator