The History of Cosmic Expansion from Supernovae Near and Far

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What we see

Type Ia Supernovae
• Homogeneous: 1.4 $M_{\odot}$, $10^{51}$ ergs, a few $10^{10} L_{\odot}$
• Can be seen halfway
By 1998 two teams measured >100 SNe Ia at 0.01 < z < 1.0

Surprise!

The Universe is accelerating, propelled by dark energy.

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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Received 1998 March 13; revised 1998 May 6

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE


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Using HST, find and measure type Ia supernovae at 0.9<z<1.7

• To look for evidence of preceding deceleration (i.e., confirm dark energy)
• Characterize the nature of dark energy (i.e., its equation of state)

Awarded 134 (+399 with GOODS) orbits in 2002-2003,
90 orbits in 2003-2004 and 270 Orbits in 2004-2005

P.I. Riess (STScI),
Ferguson (STScI)
Strolger (STScI), Tonry (UH)
Filippenko (UCB), Jha (UCB),
Li (UCB), Kirshner, (CfA)
Challis, (CfA), Casertano,
(STScI)
Dickinson (STScI), Giavalisco

Innovations Required: ToO without spectral confirmation via host phot-z’s, U-band LC, grism spectroscopy with HST (Riess)
Our first higher-z SN Ia, Aphrodite

Aphrodite (z=1.3)

ACS grism spectrum

Highest z spectrum of a SN

ACS F850lp

NICMOS F110W

viz
3 cycles
135 SNe of all types, ~50 SNe Ia, ~25 SNe Ia at $z>1$
~10 SN Ia in *Elliptical* Hosts (low dust content) with $0.9<z<1.7$

- Lancaster $z=1.2$
- Thoth $z=1.3$
- Sasquatch $z=1.4$
- Ramone $z=1.0$
- Vilas $z=0.9$
- Thames $z=1.0$
- Redford $z=1.2$
- Ferguson $z=1.0$
- 97ff $z=1.7$
The New SN Ia Hubble Diagram (Riess et al. 2004)

6 of the 7 highest redshift SNe Ia (2003)

2005: 19 of the 20 highest Redshift SNe known
Taylor Expansion of the left handside of the Friedman Eq: $a(t)$

$$d_l(z,H_0,q_0,j_0) = \frac{cz}{H_0} \left[ 1 + \frac{1}{2} (1-q_0) z - \frac{1}{6} (1-q_0 - 3q_0^2 + j_0) z^2 + O(z^3) \right]$$

$$H(t) = \dot{a}/a, q(t) = -(\ddot{a}/a)(\dot{a}/a)^2, j(t) = (\dddot{a}/a)(\ddot{a}/a)^3$$
Probing Dark Energy

Two fundamental properties/clues of dark energy: its strength, \( w_0 = w(z=0) \) AND is it dynamic or static i.e. is \( w' = dw/dz = 0 \)?

\[
d_L = \frac{c}{H_0} (1 + z) \left\{ \int_0^z d'z' \left[ (1 + z)^3 \Omega_M + (1 - \Omega_M)(1 + z)^{3(1+w_0-w')} e^{3w'z} \right]^{-1/2} \right\}
\]

• We have doubled our knowledge of \( w_0 \) and \( w' \) in 1 year with HST
• Einstein's model now looks better than ever,
• We should double our current progress again in upcoming publication of latest SNe stay tuned!
Two SN-based Routes to Constraining Dark Energy

More SNe Ia More precise

"Single most important complement to the CMB for measuring the dark energy equation of state is a determination of the Constant to better than a few percent." Wayne Hu, astro

- updating SN Ia $M_{V,B}$ calibration
- replace LMC with NGC4258
Calibration of $H_0$ from 1937C!

ACS Provides for a Reliable Recalibration of $H_0$ from Modern SNe Ia

With HST we are now calibrating 4 from 1990’s and

Ground: SN 1994ae

ACS: Cepheids
A New Approach to Taming Possible SN Ia Evolution in JDEM SN–Dark Energy Studies (Riess and Livio, *in prep*)

• JDEM mission concepts (e.g., SNAP) propose to average 1000’s of SNe Ia at 0<z<1.5 to measure the eq. of state of DE

• Such measurements will rely on our ability to detect and calibrate possible SN Ia evolution to ~1%

• A powerful method to do this is to observe SNe Ia at even higher redshifts, 1.5<z<3.0, where sensitivity to evolution is increased (e.g., global metallicity evolves by at least as much as at z<1.5, Kulkarni et al. 2005) and sensitivity to dark energy is decreased

• Such observations require flux measurements at 25<H & K<27 mag, well within reach of JWST, JWST should be able to measure 100’s such SNe Ia
Summary:

• SNe Ia are being used to trace the history of cosmic expansion; they reveal present, cosmic acceleration and the need for dark energy.

• With HST we have discovered the highest redshift SNe Ia; they show a preceding epoch of decelerating expansion (as confirming the reality of acceleration).

• With growing precision, SNe Ia at all redshifts are being used to determine the equation of state of dark energy (value and sign) and should, in the future, help determine the nature of Dark Energy and perhaps the fate of the Universe.

• Additional studies of SNe Ia locally to improve the calibration and at the ever higher redshifts to tame evolution are important continued progress in Dark Energy studies.