Measuring the Acceleration of the Cosmic Expansion Using Supernovae

Saul Perlmutter

University of California, Berkeley
Lawrence Berkeley National Laboratory

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A philosophical question:

What is the Fate of the Universe?
The Fate of the Universe can be determined from its history:

After inflation, the expansion...
...And supernovae can be used as tools for this measurement.
Astrophysical Journal 1938

THE ABSOLUTE PHOTOGRAPHIC MAGNITUDE
OF SUPERNOVAE*

W. BAADE

ABSTRACT

A compilation of the photometric data for the 78 supernovae known at the end of 1937 is given. Former estimates have been replaced by photometric magnitudes after a redetermination of the magnitudes of comparison stars on the international system. The mean absolute photographic magnitude of the supernovae, derived from this material, is $M_{\text{B-band}} = -14.3 \pm 0.42$ (m.e.) with a dispersion $\sigma_{M_{\text{B-band}}} = 0.8$ mag. This result, together with the spectroscopic evidence, fully confirms the view that two classes of novae, common novae and supernovae, exist. Attention is drawn to the curious fact that 72 per cent of the known supernovae appeared in late-type spirals. B Cassiopeiae and the Crab nebula, which may have been galactic supernovae, are discussed.

When, after Ritchey’s discovery of a nova in the spiral nebula NGC 6946 in 1917, novae were discovered in rapid succession in other extragalactic systems, a new way had been opened to settle the old question as to the constitution and the distances of these systems. The occurrence of novae in them afforded strong evidence for their stellar constitution. Moreover, their distances could be measured as soon as reliable values for the luminosities of the novae of our own galaxy were available. Nevertheless, the first applications of this method by H. D. Curtis and Sandage were very startling, as the data revealed...
But supernovae were not quite good enough “standard candles”
Mid - 1980’s:
Two new developments

1. “Type Ia” supernovae: a more standard candle

Panagia (1985)
Uomoto & Kirshner (1985)
Wheeler & Levreault (1985)
Mid-1980’s
Two new developments

"Type Ia" supernovae:
a more standard candle

- Panagia (1985)
- Uomoto & Kirshner (1985)
- Wheeler & Levreault (1985)
Mid - 1980’s:
Two new developments

2. CCD detectors & computers fast enough for image analysis
CCD detectors & computers fast enough for image analysis

Luis Alvarez suggests to Rich Muller that it is time to re-do Stirling Colgate’s robotic SN search

R. Muller: Berkeley Automated Supernova Search with C. Pennypacker and S.P.
Why is the supernova measurement not easy?

1. Can they be found far enough -- and enough of them -- for cosmology? Can they be found early enough to measure brightness over peak?

2. Can they be identified as Type Ia with spectra, despite how faint they will be? Can their brightness be compared with nearby ones, despite greatly “redshifted” spectra?

3. Are the supernovae standard enough? And how can one eliminate possible dust from diminishing their brightness?

4. Couldn’t the supernovae evolve over 5 billion years?
Problems with Type Ia Supernovae

Rare

Random

can't schedule observations or plan discoveries at new moon

Rapid
difficult to catch on the rise

NB: Norgaard-Nielsen et al. searched intensively for over 2 years, and found just 1 Type Ia supernova several weeks past its peak.
Pennypacker & Perlmutter 1987 proposal:

A novel F/1 wide-field CCD camera for the Anglo-Australian 4-m telescope (AAT)

...A big enough telescope with a wide enough field to search for z > 0.3 Type Ia supernovae in 100s of galaxies with each image.
Pennypacker & Perlmutter 1988 wide-field CCD camera at AAT
Problems
with Type Ia Supernovae as a tool for cosmology

Rare
~1 / 500 years / galaxy

Random
can’t schedule telescope time
or plan discoveries at new moon

Rapid
difficult to catch on the rise
Hamuy et al. (Astronomical Journal 1993), describing the Calan/Tololo Search for supernovae at much lower redshifts:

“What unfortunately, the appearance of a SN is not predictable. As a consequence of this we cannot schedule the followup observations a priori, and we generally have to rely on someone else’s telescope time. This makes the execution of this project somewhat difficult.”

Random

- Can't schedule telescope time or plan discoveries at new moon

Rapid

- Difficult to catch on the rise
Search Strategy

Perlmutter et al (1994)
The Supernova Cosmology Project [S. Perlmutter, S. Deustua, G. Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, J. Melbourne, C. Pennypacker, and I. Small, Lawrence Berkeley Lab. and the Center for Particle Astrophysics; A. Goobar, Univ. of Stockholm; R. Pain, CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy, Cambridge; and B. Boyle, P. Bunclark, D. Carter, and M. Irwin, Royal Greenwich Obs.; with A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope] report eleven supernovae found with the Cerro Tololo (CTIO) 4-m telescope in their 1995 High Redshift Supernova Search:

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<td>Nov. 19</td>
<td>0 29 04.26 + 7 51 20.0</td>
<td>22.4</td>
<td>0&quot;.6 W, 1&quot;.4 S</td>
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<td>1 01 20.41 + 4 18 33.8</td>
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<tr>
<td>1995as</td>
<td>Nov. 19</td>
<td>1 01 35.30 + 4 26 14.8</td>
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<td>0&quot;.7 W, 0&quot;.7 N</td>
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<td>1995at</td>
<td>Nov. 20</td>
<td>1 04 50.94 + 4 33 53.0</td>
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<td>1995au</td>
<td>Oct. 29</td>
<td>1 18 32.60 + 7 54 03.5</td>
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<tr>
<td>1995aw</td>
<td>Nov. 19</td>
<td>2 24 55.54 + 0 53 07.5</td>
<td>22.5</td>
<td>0&quot;.2 W, 0&quot;.2 S</td>
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<tr>
<td>1995ax</td>
<td>Nov. 19</td>
<td>2 26 25.80 + 0 48 44.2</td>
<td>22.6</td>
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<td>1995ay</td>
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<td>22.7</td>
<td>0&quot;.9 W, 1&quot;.4 S</td>
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<tr>
<td>1995az</td>
<td>Nov. 20</td>
<td>4 40 33.59 - 5 30 03.6</td>
<td>24.0</td>
<td>1&quot;.6 W, 1&quot;.7 N</td>
<td></td>
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<tr>
<td>1995ba</td>
<td>Nov. 20</td>
<td>8 19 06.46 + 7 43 21.2</td>
<td>22.6</td>
<td>0&quot;.1 E, 0&quot;.2 N</td>
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The spectra (Keck, Nov. 26-28) are consistent with type-I supernovae (except SN 1995av, a probable type II) at the redshift of the host galaxy: \( z = 0.45, 0.46, 0.49 \) (preliminary type-I identification), \( 0.65, 0.16, 0.30, 0.4 \) (supernova redshift only), \( 0.61, 0.48, 0.45, 0.39 \). Photometry obtained on Nov. 21-23 at CTIO (A. Walker) and Nov. 23-27 at WIYN (D. Harmer, D. Willmarth) indicates that SNe
Why is the supernova measurement not easy?

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3. Are the supernovae standard enough?
   And how can one eliminate possible dust from diminishing their brightness?

4. Couldn’t the supernovae evolve over 5 billion years?
And, in fact, the spectra do look like noise...until you know what you are looking for.
Observed Wavelength (Å)
Type Ia spectrum redshifted to $z = 0.3$
Type Ia spectrum redshifted to $z = 0.42$
Type Ia spectrum redshifted to $z = 0.5$
Type Ia spectrum redshifted to $z = 0.55$
Type Ia spectrum redshifted to $z = 0.55$. 
“Cross-Filter”
K corrections

Kim, Goobar, & Perlmutter (1995)

Supernova rest frame

Supernova at $z = 0.45$

wavelength (Å)
Why is the supernova measurement not easy?

1. Can they be found far enough -- and enough of them -- for cosmology? Can they be found early enough to measure brightness over peak?

2. If found, they won’t be bright enough to identify as Type Ia with spectrum. And how can their brightness -- greatly redshifted -- be compared with nearby ones?

3. Are the supernovae standard enough? And how can one eliminate possible dust from diminishing their brightness?

4. Couldn’t the supernovae evolve over 5 billion years?
Type Ia?  

Panagia (1985)

Leibundgut & Tammann  
A&A (1990)
Nearby Type Ia Supernova

Type Ia Supernovae

B fainter

more redshift

Nearby Type Ia Supernova

Throw out red supernovae: they are dimmed by dust or peculiar

log cz

B magnitude

fainter
Observed dispersion of nearby Type Ia peak brightness:

Branch & Miller (1993)

40% -- 50% observed dispersion reduced to 30% dispersion by selection based on color

"Calan/Tololo Supernova Search"

A beautiful, well-measured set of nearby supernova
now observed dispersion goes down to ~18% after color selection
Lightcurve Width-Luminosity Relation

Characterized by:
- Phillips: \( \Delta M \)
  \( (1993-) \)
  \( +15 \) days
- Decline Rate

Riess, Press, & Kirshner:
- Light Curve Shape (LCS)

Perlmutter et al.:
- Timescale "stretch factor"
  \( s \)
  \( s > 1 \): Broader/Slower lightcurves are Brighter
  \( s < 1 \): Narrower/Faster light curves are Fainter
  \( \sim 60 \) days rest frame
Type Ia Supernovae

Throw out red supernovae: they are dimmed by dust or peculiar

B magnitude

log cz

more redshift

fainter
Compare color distributions, or correct each SN individually for its color, assuming a dust color law.
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SN Ia Host Galaxies: Morphological Classification with HST/STIS Imaging

- E/So
  - 1995ax E/S0
  - 1996ck E/S0
  - 1997h E/S0
  - 1994al S0

- Sa/Sb
  - 1997aj Sa/pec
  - 1996cg Sab
  - 1997f Sbb
  - 1992bi Sm/Irr

- Sc/Sd
  - 1995az Sc
  - 1997i Sb/c
  - 1994an Scd
  - 1995as S/Irr
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5. What if Einstein’s “Cosmological Constant” (Λ) exists? It will fight against gravity due to mass (M) in the universe
   -- how can you tell if there is less M or more Λ or vice versa?

The diagram shows the relationship between cosmological constant density ($\Omega_\Lambda$) and mass density ($\Omega_M$). The line with the label "hypothetical SN at $z = 0.5$" is included to illustrate a specific scenario. The text "cosmological constant density" is added to the diagram as a label.

cosmological constant density

hypothetical SN at $z = 1.0$
hypothetical SN at $z = 0.5$

$\Omega_\Lambda$

$\Omega_\text{M}$

mass density
Almost 1000 galaxies per field

Scheduled Follow-Up Imaging at Hubble, WIYN, Isaac Newton

scheduled follow-up spectroscopy at Keck

RESULT: ~12 Type Ia supernovae discovered while still brightening, at new moon

Berkeley Lab
WIYN
Keck
Cerro Tololo

with Tony Tyson & Gary Bernstein’s “Big Throughput Camera”
Supernova Cosmology Project

redshift distribution of Type Ia supernovae as of 1998

$N_{SN}$ vs Redshift
effective $m_B$ vs redshift $z$

Calan/Tololo (Hamuy et al, A.J. 1996)

Supernova Cosmology Project

$\Omega_M, \Omega_\Lambda =$

- (0, 1)
- (0.5, 0.5)
- (1, 0)
- (1.5, -0.5)
- (2, 0)

Flat $\Lambda = 0$
After inflation, the expansion...
After inflation, the expansion...
Expansion History of the Universe

After inflation, the expansion...

- relative brightness
- expands forever
- or collapses

Decelerates, and either...

Average Distance Between Galaxies Relative to Today's Average

Billions Years from Today

redshift

0.0 0.5 1.0 1.5 2.0 2.5 3.0

0 0.5 1.0 1.5 2.0 2.5 3.0
After inflation, the expansion either...

- First decelerates, then accelerates.
- Or always decelerates.

The diagram shows the expansion history of the universe, with axes for relative distance between galaxies (y-axis) and billions of years from today (x-axis). The timeline extends from the past to the future, with a transition point indicating today's time frame.
Atomic Matter 4%

Dark Matter 24%

Dark Energy 72%

...or a modification of Einstein’s Theory of General Relativity?
Everybody talks about the dark energy, but nobody does anything about it.
After inflation, the expansion either...

- first decelerates, then accelerates
- or always decelerates

- expands forever
- collapses
Expansion History of the Universe

Average Distance Between Galaxies Relative to Today’s Average

Billions Years from Today
Union2 Compilation

Amanullah et al. (2010)
Supernova Cosmology Project

Distance Modulus

Redshift
Expansion History of the Universe

Euclid
WFIRST
LSST
BigBOSS
...

Scale of the Universe Relative to Today's Scale

0.0
0.5
1.0
1.5
2.0
2.5
3.0

Weak Lensing

Supernovae

Baryon Osc.

past  today  future

Billions Years from Today
The Supernova Cosmology Project [S. Perlmutter, S. Dermisek Goldhaber, D. Groom, Z. Hori, K. Kim, J. Lee, J. C. Penny, and I. Small, Lawrence Berkeley Lab., and for Particle Astrophysics; A. Goobar, Univ. of Stockholm; CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy, Cambridge; and B. Boyle, P. Buncclark, D. Carter, and M. I. Royal Greenwich Obs., with A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope] report eleven supernovae found with the Cerro Tololo (CTIO) 4-m telescope in their 1995 High Redshift Supernova Search:

- SN 98bk (Couch et al., 1998) and SN 98bj (Couch et al., 1998) with C. Petrosian and M. Windhorst at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope; and A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope.

- SN 98ex (Couch et al., 1998) also at the Keck telescope.

- SN 98bj (Couch et al., 1998) also at the Keck telescope.

- SN 98cl (Couch et al., 1998) also at the Keck telescope.

- SN 98cw (Couch et al., 1998) also at the Keck telescope.

- SN 98cy (Couch et al., 1998) also at the Keck telescope.

- SN 98da (Couch et al., 1998) also at the Keck telescope.

- SN 98db (Couch et al., 1998) also at the Keck telescope.

- SN 98dx (Couch et al., 1998) also at the Keck telescope.

- SN 98dy (Couch et al., 1998) also at the Keck telescope.

- SN 98dz (Couch et al., 1998) also at the Keck telescope.

These supernovae provide new evidence for the acceleration of the universe and support the accelerating dark energy model.