The Past, Present, and Future of Supernova Cosmology

Robert P. Kirshner

Harvard University
Most important slide

At H-band (1.6µ) SN Ia really are standard candles (and there’s much less trouble with dust!)

The Past
1931: Einstein visits Mt Wilson
Einstein & de Sitter banish $\Lambda$ in 1931

They didn’t just set $\Lambda=0$, they *excluded* it from their formalism!

“Einstein-de Sitter”
Flat, critically dense Universe
$\Omega = 1$

Always expanding, always *decelerating*
\( \Lambda \) as the source of cosmic expansion: DeSitter in 1930

Thanks to Jim Peebles
“Everything happens as though the energy in vacuo would be different from zero...we associate a pressure $p = -\rho c^2$ to the density of energy $\rho c^2$ of vacuum. This is essentially the meaning of the cosmological constant $\lambda$."

PNAS 20, 12 (1934)
The Beginning of Supernova Cosmology

Charlie Kowal

Note the imaging technology of 1968!

Monthly searches in the dark of the moon at Palomar with 48” and 18”
Kowal (1968)

✓ Had distances good to ~30% from SN I

Speculated that individual measurements might be good to 5-10%

“It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae.

Fig. 1. The redshift-magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.
The discovery of a type Ia supernova at a redshift of 0.31

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OBSERVATIONS indicate that nearby supernovae of type Ia have similar peak brightnesses, with a spread of less than 0.5 mag (σ), so that they can potentially be used as ‘standard candles’ to estimate distances on a cosmological scale. As part of a long-term search for distant supernovae, we have identified and studied an event that occurred in a faint member of the distant galaxy cluster AC118, at a redshift of z = 0.31. Extensive photometry and some spectroscopy of the event strongly supports the hypothesis that we have detected a type Ia supernova whose time-dilated light curve matches that of present-day supernovae of this class. We discuss the precision to which its maximum brightness can be ascertained, and indicate the implications that such deep supernova searches may have for observational cosmology.

Although supernovae are not as luminous as the brightest galaxies in clusters, they are events rather than objects and so should be less affected by the evolutionary and dynamical complications that have plagued determinations, by magnitude-redshift tests based on first-ranked cluster galaxies, of the deceleration parameter q₀. If a sufficient number of supernovae could be found and they revealed a closely distributed (tight) Hubble diagram, precise photometry of a sufficiently deep sample could provide an interesting constraint on q₀. The effect of a change in q₀ from 0.1 to 0.5 is only 0.13 mag at z = 0.31, rising to 0.22 mag at z = 0.5, so many accurately measured supernovae would be required. Our distant-supernova search programme has been described previously.¹² Our recent estimate of the frequency of occurrence of type Ia supernovae is the lower end of the range determined in nearby galaxies.¹³

Furthermore, even at maximum light such type Ia supernovae would be fainter than V = 21.5 mag, and thus any search strategy needs to reliably detect an absolute change in a galaxy’s flux equivalent to V = 23 mag. Using the 1.5-m Danish telescope at La Silla, Chile, we have monitored ~60 clusters in the redshift interval 0.2 < z < 0.35 over a period of two years. One-hour CCD exposures in good conditions were taken during most months in the period August–April and were immediately compared with suitable frames taken at earlier epochs, by forming difference frames (after smoothing to the same seeing and scaling to the same object intensity). We have already discussed¹¹ the discovery of a probable type Ia supernova at z = 0.28. That particular event was very faint but demonstrated our ability to find genuine events at V = 23.6 mag, a limit more than adequate for detecting type Ia supernovae to z = 0.5. Here we report the first detection of a type Ia supernova (SN1988U),¹⁵ the most distant so far discovered. Photometry of this object allows us to comment on the feasibility of estimating q₀ from a reasonable sample of such events.

The new event was identified in a faint galaxy in the field of the rich cluster AC118. This cluster was identified as part of the southern Abell catalogue¹⁶ and has been extensively studied spectroscopically¹⁷,¹⁸,¹⁹. Although previous spectra exist of the galaxy in which this supernova occurred; the cluster redshift is z = 0.307. The event was found with the Danish 1.5-m telescope on 8 and 9 August 1988 by comparing a V CCD frame with one taken in good conditions during 1986 (Fig. 1). Observations at the 4.2-m William Herschel Telescope (WHT) on 9 August 1988 confirmed both the photometric detection and offset measured at La Silla. Furthermore, the excess light has the same full width at half maximum (FWHM) as that for other stellar objects in the field. Subsequently, the cluster was observed several times on both the WHT and the 1.5-m Danish telescope when conditions and instrumentation permitted; a complete photometric record is given in Table 2.

TABLE 1

<table>
<thead>
<tr>
<th>Julian date (1950.0)</th>
<th>Aperture (m)</th>
<th>Seeing (arcsec)</th>
<th>Supernova (V) [mag]</th>
<th>ΔV</th>
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<td>22.15</td>
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<td>1.5</td>
<td>24.44</td>
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</tr>
</tbody>
</table>

* Estimated from frame taken in standard Gunn r filter.*

SN1988U:

SN Ia  z=0.31

For cosmology!

Real-time image registration, scaling, subtraction

Monthly searches

Scheduled follow-up
Brighter stars have slower declines in $B$ and $V$ ($I$ is different)

Mark Phillips (1992)
1998 Data:

Evidence for cosmic acceleration: 20% dimmer than expected

Scatter for one measurement <20%, so a handful gave 3-sigma results
Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!
The Present
Curiously, into 2009, the biggest statistical error in SN cosmology was due to the small size of the low-z sample!

This has now been remedied by the CfA3 sample.

185 Type I Light Curves

Improved Dark Energy Constraints
Dust both dims and reddens
The intercept is well-determined: $H_0$

253 SN Ia used to calibrate the Hubble expansion, $H_0 = 73.8 \pm 2.4$, a 3.3% measurement including systematics (Riess et al. 2011): 0.5% attributed to this diagram!
ESSENCE

Equation of State: SupErNovae
Trace Cosmic Expansion

Chris Stubbs, PI
Full ESSENCE sample is coming soon!
Based on Low z: (Calan-Tololo + CfA1 + CfA2 + CfA3 + Sloan) + 8 from SCP (Kowalski 2008)

ESSENCE + SNLS + Higher-Z + 6 from SCP (from 2001!)

“Union 2”

$\Omega_m = 0.28 \pm 0.01$

$\Omega_\Lambda = 0.72$
Dark energy

Dark matter

Atoms
1 + w = -0.04
+/-0.06 +/− 0.10 (sys)

Consistent with a cosmological constant—but how do we diminish the systematic errors?

Can we use information about host galaxies, from spectra?
Can we avoid problems with dust?

Most promising: NIR observations

Figure from Amanullah et al. (2010)
Pan-STARRS

Medium-Deep Fields

Good light curves at $z \sim 0.4$
Real production now
7 square degrees
0.26 “/pixel
PS1 Medium Deep Field

4 day cadence m~23

z~0.31

several days before maximum light
Spectra from Magellan, MMT, Gemini

Key to the RAISIN program to get restframe IR of SN Ia
Mount Hopkins: CfA Supernova Program

Spectra  UBVRI  JHK_s
Can Spectra Help?

Stéphane Blondin (CPPM, Marseilles)

Has used the CfA Spectral Archive as an independent test, and has explored some other ways of using spectra.

~250 SN Ia, 2000 spectra
Do spectra improve distance measurements of Type Ia supernovae?

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Received XXX; accepted XXX

ABSTRACT

We investigate the use of a wide variety of spectroscopic measurements to determine distances to low-redshift Type Ia supernovae (SN Ia) in the Hubble flow observed through the CfA Supernova Program. We consider linear models for predicting distances to SN Ia using light-curve width and color parameters (determined using the SALT2 light-curve fitter) and a spectroscopic indicator, and evaluate the resulting Hubble diagram scatter using a cross-validation procedure. We confirm the ability of spectral flux ratios alone at maximum light to reduce the scatter of Hubble residuals by \(\sim 10\%\) [weighted rms, or WRMS = 0.189 \pm 0.026 mag for the flux ratio \(R(6630/4400)\)] with respect to the standard combination of light-curve width and color, for which WRMS = 0.204 \pm 0.029 mag. When used in combination with the SALT2 color parameter, the color-corrected flux ratio \(R(6420/5290)\) at maximum light leads to an even lower scatter (WRMS = 0.175 \pm 0.025 mag), although the improvement has low statistical significance (< 2\(\sigma\)) given the size of our sample (26 SN Ia). We highlight the importance of an accurate relative flux calibration and the failure of this method for highly-reddened objects. Comparison with synthetic spectra from 2D delayed-detonation explosion models shows that the correlation of \(R(6530/4400)\) with SN Ia absolute magnitudes can be largely attributed to intrinsic color variations and not to reddening by dust in the host galaxy. We consider flux ratios at other ages, as well as the use of pairs of flux ratios, revealing the presence of small-scale intrinsic spectroscopic variations in the iron-group dominated absorption features around \(\sim 4300\) \(\text{Å}\) and \(\sim 4800\) \(\text{Å}\). The best flux ratio overall is the color-corrected \(R(4610/4260)\) at \(t = -2.5\) d from maximum light, which leads to \(\sim 30\%\) lower scatter (WRMS = 0.143 \pm 0.020 mag) with respect to the standard combination of light-curve width and color, at \(\sim 2\sigma\) significance. We examine other spectroscopic indicators related to line-profile morphology (absorption velocity, pseudo-equivalent width etc.), but none appear to lead to a significant improvement over the standard light-curve width and color parameters. We discuss the use of spectra in measuring more precise distances to SN Ia and the implications for future surveys which seek to determine the properties of dark energy.

Key words. supernovae: general — cosmology: observations
We’ve looked for spectral features that are correlated with reduced scatter in the Hubble diagram (see also Bailey et al. A & A 500, 117 (2009))
And we have looked at spectral features whose astrophysics we understand.
Spectra and Light-Curve Shape
Correction using light curves alone: SALT2 ($x_1,c$)

WRMS = 0.213 mag
Correction using spectra alone: $R(6540/4580)_{\tau=-2.5\,d}$

WRMS = 0.182 mag
Correction using light curves and spectra: $c, R^c(4610/4260)_{t=-2.5\, d}$

WRMS = 0.143 mag

Distance Modulus [mag]

Residuals

CMB-frame Redshift
Spectra and Light Curves

Models form a sequence that spans the observed relation— but do the spectra look right?

Yes and no.

Blondin et al. MNRAS in press
Can Spectra Help?

Some.

(If you were building a satellite for dark energy would you include an R~300 spectrograph?)

(Would you expose to do more than get the redshift and secure the type?)

See also Chotard et al. astro-ph 1103.5300
Maeda et al. MNRAS (2011)
The biggest uncertainties now are **systematic errors** and the worst of these come from dust and light curve fitters.
Dust both dims and reddens -- but less so in the infrared
Make the measurements in the infrared!

J, H, K_s image from PAIRITEL
Theory by Dan Kasen (2006)- expect smallest variance in the IR: Pioneering work by Krisciunas & CTIO group shows this is actually true! CfA: Wood-Vasey et al. 2008
Kaisey Mandel

Using a Bayesian model to combine optical and IR data for SN Ia, predict distances, and determine dust properties.

Needs Job!

BayeSN inference:
Kaisey Mandel
H-band (1.6 microns) works best
IR + Optical

Get **better distances** & learn about **properties of the dust** by using observations over the range from B (0.4 $\mu$) to K (2.2$\mu$)

We want to know the ratio of absorption to color change (we measure colors but want to know absorption)

Milky Way dust $R_v = 3.1 = A_v / E(B-V)$, but hints are that SN dust is not the same ($R_v = 1.7$ !)
Uses optical and IR data from CfA and CSP

TYPE Ia SUPERNOVA LIGHT CURVE INFERENCE: HIERARCHICAL MODELS IN THE OPTICAL AND NEAR-INFRARED

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Received 2010 November 23; accepted 2011 February 1; published 2011 April 1

ABSTRACT
We have constructed a comprehensive statistical model for Type Ia supernova (SN Ia) light curves spanning optical through near-infrared (NIR) data. A hierarchical framework coherently models multiple random and uncertain effects, including intrinsic supernova (SN) light curve covariances, dust extinction and reddening, and distances. An improved BateSN Markov Chain Monte Carlo code computes probabilistic inferences for the hierarchical model by sampling the global probability density of parameters describing individual SNe and the population. We have applied this hierarchical model to optical and NIR data of 127 SNe Ia from PAIRITEL, CfA3, Carnegie Supernova Project, and the literature. We find an apparent population correlation between the host galaxy extinction $A_V$ and the ratio of total-to-selective dust absorption $R_V$. For SNe with low dust extinction, $A_V \lesssim 0.4$, we find $R_V \approx 2.5–2.9$, while at high extinctions, $A_V \gtrsim 1$, low values of $R_V < 2$ are favored. The NIR luminosities are excellent standard candles and are less sensitive to dust extinction. They exhibit low correlation with optical peak luminosities, and thus provide independent information on distances. The combination of NIR and optical data constrains the dust extinction and improves the predictive precision of individual SN Ia distances by about 60%. Using cross-validation, we estimate an rms distance modulus prediction error of 0.11 mag for SNe with optical and NIR data versus 0.15 mag for SNe with optical data alone. Continued study of SNe Ia in the NIR is important for improving their utility as precise and accurate cosmological distance indicators.

Key words: distance scale – methods: statistical – supernovae: general
Modeling SN Ia Light Curves: Using the Optical + IR to learn about dust and distance

Kaisey Mandel, RPK & Gautham Narayan
Andy Friedman thesis-- will have ~80 NIR light curves from PAIRITEL
Optical: standardizable candles

IR: standard candles! (and less trouble with dust!)

The IR is not strongly correlated with the Optical
Odd thing:
$R_v$ looks $\sim 3.1$ for low extinction
$R_v$ looks lower when extinction is high (different mechanism?)
See also Folatelli AJ 109, 120 (2010)

Figure 10. Marginal posterior estimates of inferred color excess $E(B-V)$ due to host galaxy dust vs. inferred extinction $A_V$, assuming the linear correlation
The Payoff

\[ h = 0.72 \]
\[ \sigma_{\text{pec}} = 150 \text{ km/s} \]

CfA3+PTEL+CSP+lit
140 BVRI(JH) SN Ia

Residual Err (All, \( cz > 3000 \text{ km/s} \)) = 0.14 mag
Residual Err (Opt Only \( cz > 3000 \text{ km/s} \)) = 0.15 mag
Residual Err (Opt+NIR & \( cz > 3000 \text{ km/s} \)) = 0.11 mag
Could we get this advantage for the high-z supernovae? RAISIN
Measuring Ejecta Velocity Improves Type Ia Supernova Distances
Foley & Kasen ArXiv1011.4517
B-V color and velocity are correlated
Ryan Foley
Clay Fellow at CfA
The CfA data are helpful because there are spectra at many epochs. This permits a good interpolation to $v_{\text{max}}$. 
Velocity is correlated with B-V color and these help account for departures from the light curve shape. Use BayeSN!
Using Kaisey’s BayeSN method—there is definitely a correlation between B-V color and ejecta velocity as measured in the Si II lines.

Applying this decreases the prediction error to ~0.12 mag.
The Future
Skymapper-- a (small) southern Sloan
Fermilab project hopes to uncover why universe expansion is accelerating
BY KEVIN DANNA NOV 03, 2010
Use WFC3 to get rest frame IR of moderate redshift SN Ia! SNIA in the IR = RAISIN
Spectra from Magellan, MMT, Gemini

Key to the RAISIN program to get restframe IR of SN Ia-- inspired by CSP
One month of panSTARRS also finds an accelerating universe!

Very big range in redshift all with a single system.

Select a sample to minimize systematics.
Could we get this advantage for the high-z supernovae?
Only in space!

Rest frame IR measurements of z~1 supernovae are not possible from the ground

**Go as far into the IR as technically feasible!**

Sky is very bright in NIR: >100x brighter than in space

Sky is not transparent in NIR: absorption due to water is very strong and extremely variable
Odd thing:

$R_V$ looks $\sim 3.1$ for low extinction

$R_V$ looks lower when extinction is high (different mechanism?)

See also Folatelli
Uncertainty in extinction law produces uncertainty in dark energy!

Adding the IR really helps
A pilot sample (next HST Cycle)

A real contribution to our knowledge of dark energy
JWST will be excellent for the rest frame IR of SN Ia at $0.2 < z < 1$
Astro 2010 top priority:
- BAO (slitless)
- Weak Lensing
- SN - medium-z restframe IR
- micro-lensing for planets
- IR survey
- IR only
First wide-field survey telescope