Observational cosmology and Type Ia Supernovae, Part II

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SN Ia cosmology tutorial

Spectrum

Search

Subtraction

Lightcurve

Reference

Hubble diagram

Cosmology fits

$\Omega_M$, $\Omega_\Lambda$

$\Omega_M$, $\Omega_\Lambda$

$0.25$, $0.75$

$0.25$, $0.00$

$1.00$, $0.00$
Recap of yesterday

**Astrophysics**

\[
m - M = 5 \log_{10} \left( (1 + z) \int_0^z \frac{dz'}{H(z')} \right)
\]

for \( k = 0 \)

**Cosmology**

\[
H(z)^2 = H_0^2 \left[ \Omega_M (1 + z)^3 + \Omega_K (1 + z)^2 + \Omega_\Lambda \right]
\]
Type Ia Supernovae

- Degenerate white dwarf
- Thermonuclear explosion of a CO white dwarf that has reached the Chandrasekhar mass $\sim 1.4 M_\odot$
- Outshines entire host galaxy (for a short time).
- Standard candles $\sim 10$-15% scatter in brightness.
- Spectrum: Silicon, but unlike other SN types, no H or He.

$M \sim -19.3$
SN Ia lightcurve

The SN lightcurve is powered by radioactive decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$
SN Ia spectrum

(courtesy of Jakob Nordin)
Explosion scenario

- Single degenerate
- Double degenerate

- Chemical composition – spectroscopy
- Delay-time distribution
- SN rate vs environment
Delay time and rates

Supernova Cosmology Project
Barbary et al. (2012)

Kankare et al. (2008)

Try to catch SNe Ia as early as possible!
Evolution?

Rubin et al. (in prep.)

SN SCP-0401 @ z = 1.72

11 orbits with HST/ACS

Courtesy of Jakob Nordin
Constraints on dark energy

Assuming a time-independent $w$ and a flat Universe.

$$w = -0.977^{+0.050}_{-0.054}(+0.077)$$
Pros and cons of SN cosmology

Probes expansion rate directly
Most mature technique today
Up to now simple and cheap: acceleration was discovered using 2.5 – 4 m telescopes

Pros:

Cons:
Astrophysical uncertainties:
  – Brightness evolution
  – Dimming along the line of sight
Future will require high instrumental accuracy
### Systematics for the Union2 sample

#### Table 9

<table>
<thead>
<tr>
<th>Source</th>
<th>Error on $w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero point</td>
<td>0.037</td>
</tr>
<tr>
<td>Vega</td>
<td>0.042</td>
</tr>
<tr>
<td>Galactic extinction normalization</td>
<td>0.012</td>
</tr>
<tr>
<td>Rest-frame $U$-band</td>
<td>0.010</td>
</tr>
<tr>
<td>Contamination</td>
<td>0.021</td>
</tr>
<tr>
<td><strong>Malmquist bias</strong></td>
<td><strong>0.026</strong></td>
</tr>
<tr>
<td>Intergalactic extinction</td>
<td>0.012</td>
</tr>
<tr>
<td>Light-curve shape</td>
<td>0.009</td>
</tr>
<tr>
<td>Color correction</td>
<td>0.026</td>
</tr>
<tr>
<td>Quadrature sum (not used)</td>
<td>0.073</td>
</tr>
<tr>
<td>Summed in covariance matrix</td>
<td>0.063</td>
</tr>
</tbody>
</table>

**Notes.** The proper way to sum systematic errors is to include each error in a covariance matrix.
What do we mean by “magnitude”?

\[ m - M = 5 \log_{10} \left( \frac{1 + z}{(1 + z) \int_{0}^{z} \frac{dz'}{H(z')}} \right) \quad \text{for} \quad k = 0 \]
SN Ia at $z = 0$
SN Ia at z = 1
K-corrections are needed for comparing SNe observed at different redshifts.

- Assumption of the spectrum is needed
- Need to correct for dimming
SNe Ia are standard candles... sort of...

\[
B^{\text{max}} - \beta \cdot c + \alpha \cdot x_1 - M_B = 5 \log_{10} d_L(\Omega_M, \Omega_X, w; z)
\]

Fitted peak brightness can be color and light-curve shape corrected to form a standard candle that can be used for measuring relative cosmological distances.

Measured SN properties

Fitted parameters

Discovery!

Brightness (rest-frame \(B^{\text{max}}\))

and color (\(c \sim E(B-V)\)) at maximum

Shape (\(x_1\))

Days since maximum (rest-frame)
**Stretch and color**

**Phillips (1993)**

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**Goobar & Leibundgut (2011)**
Selection effects

Goobar & Leibundgut (2011)
Extinction laws $R_v \sim \beta - 1$

Fig. 1. The Milky Way extinction laws by Cardelli (solid black line) for three different $R_F$ (2, 3.1 and 4) where the highest values of $R_F$ correspond to the flattest curves. We also show the Fitzpatrick law (dotted blue) with $R_F = 3.1$, the SMC extinction law by Prévot (dashed green) with $R_F = 3.1$ and the starburst extinction law by Calzetti (dashed dotted red) with $R_F = 4.05$. $A_\lambda$ is the extinction at wavelength $\lambda$ and $A_V$ is the visual extinction.
What is causing the reddening?

Extinction?  Intrinsic variations?  Perhaps it is a Combination of both...?

Circumstellar?  Intergalactic?  Observer

SN Host galaxy
Different sources of reddening?

Nordin et al. (2011)

Interstellar dust extinction?

Intrinsic?

SALT2 c

Local
SDSS NTT/NOT
SNLS VLT

Nordin et al. (2011)
Circumstellar Dust

Could CS dust explain SN colours (Wang 2005, Goobar, 2008)?

Folatelli et al. (2010)
Na I D in 2006X

Patat et al. (2008)

Sternberg et al. (2011)

Table 1. Classification of absorption features.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Blueshifted</th>
<th>Redshifted</th>
<th>Single/Symmetric</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW (QSO)</td>
<td>10</td>
<td>13</td>
<td>6</td>
<td>29</td>
</tr>
<tr>
<td>MW (QSO+SNe)</td>
<td>22 [23]</td>
<td>26 [29]</td>
<td>23 [28]</td>
<td>71 [80]</td>
</tr>
</tbody>
</table>

Milky Way (QSO+SNe)

- Blueshifted: 31%
- Redshifted: 32.4%
- Single/Symmetric: 36.6%

SNe Ia: 22.7%
Reddening vs ejecta velocity?

Figure 4. $\Delta m_{15}$-corrected absolute $V$ mag at maximum brightness vs. the host-galaxy reddening. The filled symbols are SNe with $z \geq 0.01$ or Cepheid-based distances, and the open symbols are nearby objects that were not included in the fit. The two solid lines show the best-fit $R_V$ for SNe in the HV and Normal groups, with dotted lines indicating 2σ uncertainties. The dashed line represents the Milky Way reddening law.
How do we solve this mystery?

UV – NIR data are called for!
Can we circumvent the problem?

Freedman et al. (2009)

Figure 14. Top panel: \( i \)- and \( B \)-band Hubble diagrams for 21 low-redshift and 35 high-redshift SNe Ia from the CSP, uncorrected for reddening. Bottom panel: the residuals about the best fit to these data. The values for rms scatter about the best fit to these data are labeled. The rms value in brackets excludes the most discrepant (highly reddened) SNLS 05D1hn.

(A color version of this figure is available in the online journal.)
Atmospheric emission

![Graph showing atmospheric emission spectra with optical and IR regions highlighted.](image-url)
SN properties vs host properties

Epoch -9 to -2 days

Spearman = 0.53

Epoch 0 to 8 days

Spearman = -0.67

Nordin et al. (2011)
Host evolution

SN brightness depends on the host galaxy mass!
Kelly et al. (2010), Sullivan et al. (2010), Lampeitl et al. (2010)

Higher host mass – brighter SN

The low-z sample has a are hosted by more massive galaxies than the high-z data

But now we are correcting for this (Conley et al., 2011 and Suzuki et al., 2012)
The SN Ia host environment

Red vs blue galaxies

Sullivan et al. (2006)
Choose a special environment!
Observing the unobservable
Using massive galaxy clusters as natural telescopes

1. A Distant Source
   Light from a distant supernova is emitted in all directions.

2. A Lens of 'Dark Matter'
   Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3. Focal Point: Earth
   Most of this light is scattered, but some is focused and directed toward Earth.
The Refsdal method (MNRAS, 1966)

Primarily the Hubble constant, but also DE!

In the event of a strongly multiply lensed SN.

or... cluster mass distribution.

Measure!

\[
\Delta t = \frac{\Delta \theta^2}{2} \frac{D_d D_s}{D ds} \left( 1 + z_d \right) f(r_{\text{flux}});
\]

\[
D_{ij} = D_{ij}(z_i, z_j; H_0, \Omega_M, \Omega_X, w_X)
\]
Future surveys

Ground (optical)

PanSTARRS (2010-2015) 4 x 1.8-meter/ 3 sq.deg; ~5000 SN z<1
DES (2012-2016): 4-meter/ 3 sq.deg; ~3000 SN z<1
LSST (2020?): 8-meter/ 9 sq.deg; ~250000 SN z<1 /yr (!)
+ Low-z surveys: SNFactory, PTF, CSP; SkyMapper,...
+ Next generation of 30-40 m telescopes for spectroscopic follow-up

Space (2018+?)

JWST (6.5-meter / 4 sq.arcmin, i.e not really wide field)
WFIRST? (NASA), EUCLID (ESA):1.2 - 1.5-meter class telescopes,
Currently porposed SN survey in Euclid not suitable for DE.
Good luck with SN2012cg!