Type Ia Supernovae as Distance Indicators

Bruno Leibundgut
What do we want to learn about supernovae?

• What explodes?
  – progenitors, evolution towards explosion

• How does it explode?
  – explosion mechanisms

• Where does it explode?
  – environment (local and global)
  – feedback

• What does it leave behind?
  – remnants
  – compact remnants
  – chemical enrichment

• Other use of the explosions
  – light beacons
  – distance indicators
  – chemical factories
What do we know about supernovae Ia?

• What explodes?
  – progenitors, evolution towards explosion
    • white dwarfs (?), several channels

• How does it explode?
  – explosion mechanisms
    • several channels
      – deflagrations, detonations, delayed detonations, He detonations, mergers

• What does it leave behind?
  – remnants
    • Tycho, LMC
  – compact remnants
    • none, companion (?)
  – chemical enrichment
    • the usual suspects
What do we know about supernovae Ia?

- Where does it explode?
  - environment (local and global)
    - some with CSM (?)
    - all galaxy morphologies
    - dependencies on host galaxies?
  - feedback
    - little

- Other use of the explosions
  - light beacons
    - little use as background source
  - distance indicators
    - ha!
  - chemical factories
    - no significant dust
It is time to give up some cherished paradigms
Type Ia SNe are not standard candles. They are not even standardizable. Maybe some of them can be normalised to a common peak luminosity.
Why no standard candle?

- Large variations in
  - luminosity
  - light curve shapes
  - colours
  - spectral evolution
  - polarimetry

- Some clear outliers
  - what is a type Ia supernova?

- Differences in physical parameters
  - Ni mass
Luminosity distribution

Li et al. 2010
Spectral evolution

Blondin et al. 2006
also Garavini et al. 2007
Bronder et al. 2008
## What is a SN Ia?

### Table 1

Classification Criteria for SNe Iax

| SN Class       | Has Hydrogen? | $|v| \leq 8000$ km s$^{-1}$? | Low $L$ for LC shape | Spec. like SN 2002cx |
|----------------|---------------|-----------------------------|----------------------|----------------------|
| SN Iax         | N             | Y                           | N/                  | Y                    |
| SN II          | Y             | Some                        | N/                  | N                    |
| SN Ib/c        | N             | N                           | Y                   | N                    |
| SLSN I         | N             | Y                           | N                   | N                    |
| Normal SN Ia   | N             | N                           | N                   | N                    |
| Super-Chandra  | N             | Y                           | N                   | N                    |
| SN 1991T       | N             | N                           | Somewhat            | N                    |
| SN 1991bg      | N             | N                           | N                   | N                    |
| SN 2000cx      | N             | Y                           | N                   | N                    |
| SN 2002bj      | N             | Y                           | N                   | Somewhat             |
| SN 2002es      | N             | Y                           | Y                   | Somewhat             |
| SN 2002ic      | Y             | N                           | N                   | N                    |
| SN 2005E       | Y             | Y                           | Y                   | N                    |
| SN 2006bt      | N             | N                           | Y                   | N                    |
| SN 2010X       | N             | N                           | Y                   | N                    |
| PTF 09day      | Y             | Y                           | Y                   | Somewhat             |

Forey et al. 2013
Ni masses from bolometric light curves

Stritzinger 2005
38 well-observed SNe Ia

How can this be a standard candle?
Type Ia SNe do not all come from Chandrasekhar-mass white dwarfs

**TYPE Ia SUPERNOVA EXPLOSION MODELS**

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There are good reasons to believe that perhaps most type Ia supernovae are the explosions of white dwarfs that have approached the Chandrasekhar mass, \(M_{\text{chan}} \approx 1.39 \, M_\odot\), and are disrupted by thermonuclear fusion of carbon and oxygen.

**Abstract**

Because calibrated light curves of type Ia supernovae have become a major tool to determine the local expansion rate of the universe and also its geometrical structure, considerable attention has been given to models of these events over the past couple of years. There are good reasons to believe that perhaps most type Ia supernovae are the explosions of white dwarfs that have approached the Chandrasekhar mass, \(M_{\text{chan}} \approx 1.39 \, M_\odot\), and are disrupted by thermonuclear fusion of carbon and oxygen. However, the mechanism whereby such accreting carbon-oxygen white dwarfs explode continues to be uncertain. Recent progress in modeling type Ia supernovae as well as several of the still open questions are addressed in this review. Although the main emphasis is on studies of the explosion mechanism itself and on the related physical processes, including the physics of turbulent nuclear combustion in degenerate stars, we also discuss observational constraints.
Models of Supernova Explosions: Where Do We Stand?

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Summary. The present status of our understanding of core-collapse and of thermonuclear supernovae is reviewed. It will be argued that the failure of numerical simulations of the collapse of massive stars to produce explosions is probably caused by our incomplete knowledge of the (micro-) physics involved. In contrast, for thermonuclear (type Ia) supernovae the basic physics seems to be well under control and, therefore, it is not surprising that model predictions and observations are in good agreement.

"Type Ia Supernova progenitors are not Chandrasekhar-mass white dwarfs”
Ejecta masses

Stritzinger et al. 2006
Ejecta masses

- Large range in nickel and ejecta masses
  - no ejecta mass at 1.4\(M_\odot\)
  - factor of 2 in ejecta masses
  - some rather small differences between nickel and ejecta mass
Ejecta masses

- Super-Chandrasekhar explosions?
  - also
    SN 2006gz, 2007if, 2009dc
  - inferred Ni mass > 1 M☉

Howell et al. 2006
SNe Ia are not a homogeneous class

- Proliferation of information
  - Large samples produce many peculiar and special objects
  - Difficulty to assess what are generic features of the class and what are peculiar modifications to the norm
    - Subluminous
    - Superluminous
    - CSM/no CSM
    - Environmental effects

- What should we give up?
  - multiple progenitor channels
  - multiple explosion mechanisms
  - uniform metallicity

Paradigm 3
SN Ia Correlations

- Luminosity vs. decline rate
- Luminosity vs. rise time
  - Riess et al. 1999
- Luminosity vs. color at maximum
- Luminosity vs. line strengths and line widths
- Luminosity vs. host galaxy morphology
SN Ia Correlations

Luminosity with host galaxy mass and star formation

SN Ia Correlations

- Expansion velocity with colour

Foley 2012
Expansion velocity with position within host galaxy

Wang et al. 2013
Type Ia Supernovae

• Complicated story
  – observational diversity
  – many models
  → need more constraints
Type Ia Supernovae
as distance indicators

Excellent distance indicators!
Supernova cosmology

• Stellar explosions
  → systematics!

• SNe Ia currently the best known individual cosmic distance indicator
  – ~5-10% accuracy on individual SN

• Absolute calibration relies on external sources
  – Cepheids
SN Ia Hubble diagram

- Excellent distance indicators
- Experimentally verified
- Work of several decades
- Best determination of the Hubble constant

Reindl et al. 2005
$H_0$ from supernovae

- Measure the local Hubble diagram
- Calibrate the luminosity of the distance indicator
  - Cepheids
    - LMC
    - NGC 4358
  - nearby SNe Ia

Riess et al. 2011
The importance of $H_0$

- Sets the absolute scale
  - size and age of the universe
- In combination with CMB measurements
  - constrains $w$
  - neutrino mass
  - number of relativistic species

Image: Riess et al. 2011
Supernova Cosmology
The SN Hubble Diagram

High-z Supernova Search Team

Supernova Cosmology Project
Absurd result

negative matter density
Supernova Cosmology 2011

Goobar & Leibundgut 2011

560 SNe Ia

$\mu - \mu_{\text{empty}}$ vs. Redshift ($z$)

$\Lambda$ CDM
et voilà ... 10 years of progress
Recent SNLS results

Sullivan et al. 2011

Conley et al. 2011
Supernova cosmology

- $\omega$ firmly established
  - general agreement between different experiments

<table>
<thead>
<tr>
<th>$N_{SN}$</th>
<th>$\Omega_M$(flat)</th>
<th>$\omega$ (constant, flat)</th>
<th>Light curve fitter</th>
<th>Reference</th>
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<tbody>
<tr>
<td>115</td>
<td>0.263$^{+0.042+0.032}_{-0.042-0.032}$</td>
<td>$-1.023^{+0.090+0.054}_{-0.090-0.054}$</td>
<td>SALT</td>
<td>Astier et al. 2006</td>
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<tr>
<td>162</td>
<td>0.267$^{+0.028}_{-0.018}$</td>
<td>$-1.069^{+0.091+0.13}_{-0.083-0.13}$</td>
<td>MLCS2k2</td>
<td>Wood-Vasey et al. 2007</td>
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<td>178</td>
<td>0.288$^{+0.029}_{-0.019}$</td>
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<td>288</td>
<td>0.307$^{+0.019+0.023}_{-0.019-0.023}$</td>
<td>$-0.76^{+0.07+0.11}_{-0.07-0.11}$</td>
<td>MLCS2k2</td>
<td>Kessler et al. 2009</td>
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<td>288</td>
<td>0.265$^{+0.016+0.025}_{-0.016-0.025}$</td>
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<td>SALT2</td>
<td></td>
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<td>557</td>
<td>0.279$^{+0.017}_{-0.016}$</td>
<td>$-0.997^{+0.050+0.077}_{-0.054-0.082}$</td>
<td>SALT2</td>
<td>Amanullah et al. 2010</td>
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<td>472</td>
<td>$0.269 \pm 0.015$</td>
<td>$-0.91^{+0.016+0.07}_{-0.20-0.14}$</td>
<td>SiFTO/SALT2</td>
<td>Conley et al. 2011</td>
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<td>472</td>
<td>$0.269 \pm 0.015$</td>
<td>$-1.061^{+0.069}_{-0.068}$</td>
<td>SALT2</td>
<td>Sullivan et al. 2011</td>
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<tr>
<td>580</td>
<td>$0.271^{+0.014}_{-0.014}$</td>
<td>$-1.013^{+0.077}_{-0.073}$</td>
<td>SALT2</td>
<td>Suzuki et al. 2011</td>
</tr>
</tbody>
</table>
Systematics

- Contamination
- Photometry
- K-corrections
- Malmquist bias
- Normalisation
- Evolution
- Absorption
- Local expansion field

“[T]he length of the list indicates the maturity of the field, and is the result of more than a decade of careful study.”
Systematics

• Current questions
  – calibration
  – restframe UV flux
    • redshifted into the observable window
  – reddening and absorption
    • detect absorption
      – through colours or spectroscopic indicators
    • correct for absorption
      – knowledge of absorption law
  – light curve fitters
  – selection bias
    • sampling of different populations
  – gravitational lensing
  – brightness evolution
Required phenomenology

- photometric calibration
- normalisation
  - ("standardizable candle"; "standard crayon")
  - different light curve fitters
    - $\Delta m_{15,\text{SALT, SiFTO, MLCS}}$

Goobar & Leibundgut 2011

SNLS SN04D2gp
$z=0.732$
What next?

• Already in hand
  – >1000 SNe Ia for cosmology
  – constant $\omega$ determined to 5%
  – accuracy dominated by systematic effects

• Missing
  – good data at z>1
    • light curves and spectra
  – good infrared data at z>0.5
    • cover the restframe B and V filters
    • move towards longer wavelengths to reduce absorption effects
  – restframe near-infrared Hubble diagram
I-band Hubble diagram

• Currently only 35 SNe Ia

Goobar & Leibundgut 2011

560 SNe Ia

Freedman et al. 2009

\[ \mu - 5 \log \left( \frac{H_0}{\text{km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}} \right) \]

\[ \Delta \mu \]

Redshift
J- and H-band Hubble diagrams

Barone-Nugent et al. 2012 (YJH)

Kattner et al. 2012

Kattner et al. 2012

RMS=0.131 mag

RMS=0.224 mag
Supernova Cosmology – do we need more?

• Test for variable $\omega$
  – required accuracy $\sim 2\%$ in *individual* distances
  – can SNe Ia provide this?
    • can the systematics be reduced to this level?
    • homogeneous photometry?
    • further parameters (e.g. host galaxy metallicity)
    • handle $>100000$ SNe Ia per year?

• Euclid
  – 3000 SNe Ia to $z<1.2$ with IR light curves (deep fields) $\rightarrow$ restframe I-band Hubble diagram
  – 16000 SNe discovered
Cosmology – more?

Goobar & Leibundgut 2011
(courtesy E. Linder and J. Johansson)
Distant SNe with CANDELS and CLASH

- Multi-cycle HST Treasury Programs

**CANDELS**
Pls: S. Faber/H. Fergusson

**CLASH**
Pl: M. Postman

**HST MCT SN Survey**
Pl: A. Riess

SN discoveries and target-of-opportunity follow-up
SNe Ia out to z≈2
Determine the SN rate at z>1 and constrain the progenitor systems
SNe Ia at high redshifts (z>1.5)

- ratio \((\Omega_{DE}/\Omega_M)_0=2.7; (\Omega_{DE}/\Omega_M)_{z=1.5}=0.173\)
  - with \(w_0=-1\pm0.2\) and \(w_a=-1\pm1\); \(w=w_0+w_a(1-a)\)
- within these uncertainties the observed magnitudes change less than 0.1m
  - direct test for evolution!
- at z>1.5 age of the universe is <4Gyr
  - low-mass stars are still on the main sequence
  - SN Ia progenitors from more massive progenitor stars
  - constrain progenitor models of SNe Ia
4 arguments for a SN Ia at $z=1.55$

1. color and host galaxy photo-z
2. host galaxy spectroscopy
3. light curve consistent with normal SN Ia at $z=1.55$
4. SN spectrum consistent
SNe Ia at $z>1$

- SN Ia at $z=1.91$

Jones et al. 2013

SN UDS10Wil

- Type Ia
  - Best $\chi^2 / \nu = 18.6/11$

- Type Ib/c
  - Best match: SN SDSS-017548 (Type Ic)
  - Best $\chi^2 / \nu = 35.5/11$

- Type II
  - Best match: SN SDSS-000018 (Type II-P)
  - Best $\chi^2 / \nu = 51.1/11$

Jones et al. 2013
SN UDS10Wil at z=1.91
SNe at $z>1$
Where are we …

SN Factory
Carnegie SN Project
SDSSII
ESSENCE
CFHT Legacy Survey
Higher-z SN Search (GOODS)
Euclid/WFIRST/LSST
Plus the local searches: LOTOSS, CfA, ESC
Summary

• Concentrate on $\lambda$ not covered so far
  – particular IR is interesting
    • reduced effect of reddening
    • better behaviour of SNe Ia(?)

• Understand the SN zoo
  – many (subtle?) differences observed in recent samples (PanSTARRS and PTF)
    • subluminous and superluminous
  – understand potential evolutionary effects
    • spectroscopy important $\rightarrow$ PESSTO
    • DES?, LSST?, Euclid follow-up?