Introduction review on cosmology with Type Ia supernovae

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Les rencontres de Moriond, march 2008
Outline

Introduction :
- Usage of standard candles in cosmology
- What is a type Ia supernova (SN Ia)
- Brief history of cosmology with SNe Ia

Two approaches in recent SNe Ia analyses :
- SNe modeling
- Treatment of SNe colors
- Priors

Some words about systematic uncertainties :
- Systematic uncertainties must be propagated in cosmology fits
- What are the dominant sources of uncertainties
- What can be expected for future surveys

Conclusions
Usage of standard candles for cosmology

The metric for a homogeneous and isotropic Universe

$$ds^2 = dt^2 - R^2(t)(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2))$$

+ general relativity give the Friedman-Lemaitre-Robertson-Walker equations :

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3} \rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}$$

=> link the expansion rate of the Universe to its content and curvature

With light as a messenger, we have three observables connected to the expansion history :

- the redshift $z$, $z = R_0/R(\text{at emission})-1$ (subscript 0 means now)
- fluxes of objects of known luminosity vs $z$, luminosity distance $d_l(z) = (1+z) r(z)$
- angles of objects of known size vs $z$, angular distance $d_a(z) = r(z)/(1+z)$

where $r(z) = \frac{c}{\sqrt{\Omega_k}} S_k \left( \sqrt{\Omega_k} \int \frac{dz}{H} \right)$, $H = \frac{dR/dt}{R}$, $\Omega_k = -\frac{k}{(R_0 H_0)^2}$
Usage of standard candles for cosmology (bis)

- both nearby and distant candles needed to distinguish models

- parameters degeneracy:

=> standard candles at 0<z<1 measure well a single cosmological parameter (second one with much lower precision)

Model with a constant equation of state for Dark Energy: $w = p/\rho$
Type Ia Supernovae

Thermonuclear explosion of a star:
- very bright: $10^{10}$ sun luminosity
- rare: ~ 1 per galaxy per millennium
- light curve duration: ~ 1 month
- peak brightness dispersion ~ 40%
- precision on distance modulus ~ 0.15

- identified by spectroscopy,
  broad absorption features =>
  ejecta velocity and chemical composition

- progenitor is likely to be a white dwarf fed
  with material from a companion star
Analysis steps of a SNe Ia survey

- **Detection**:
  - novel technique with SNLS: “rolling search”
    - same fields are observed every 4 days
    - => full light-curve of SNe (no missing early-time data)
    - => better control of the selection bias
  - the lower the redshift, the larger the required field of view
    - => nearby SNe are now technically more difficult to detect than high-z SNe (for an equivalent exposition)

- **Spectroscopic identification**:
  - photometric pre-selection or ranking required
  - limitation of high-z surveys
    - (SNLS: equivalent time allocation on CFHT (3.6m) for photometry as for 8m-class telescopes for spectroscopy)
  - => alternative: photometric identification (see talks by Bazin, Ripoche)

- **Photometry**
- **Calibration**
  - calibration is fundamental for SNe cosmology
  - it is one of the main limitations today (more details later)

- **Light-curve fitting / distance estimate**

  (fit of Hubble diagram)
Light-curve fitting / distance estimate

The goal is to compare fluxes at different $z$:
- at the same wavelength (range)
- at the same phase of the supernova light curve

What is measured is a limited set of photometric observations at various phases and in few filters.

$\Rightarrow$ a full model of the spectral evolution of the SN is needed to 'interpolate' measurements across phase x wavelength.

$$\frac{f(z_1, T_{\text{rest}})}{f(z_2, T_{\text{rest}})} = \left(\frac{d_L(z_2)}{d_L(z_1)}\right)^2$$
Light-curve fitting / distance estimate

In all published high-z cosmology analyses:

- The **flux at maximum light integrated in a redshifted B-band** is the luminosity indicator (this is partly arbitrary)

- Two other photometric parameters that correlate with luminosity are used to improve distance estimate:
  - a **light curve shape**: $\triangle$, stretch, $X_1$
  - a **color** (B-V)

- some spectroscopic observables correlate with luminosity but can not be used at high-z because of a limited S/N and wavelength range

- the CMAGIC technique uses an original color-magnitude diagram to estimate distances but it requires high S/N measurements in the 'tail' of the light curve.

Different models are used to derive those parameters.

Their usage to determine distances also differ.

Wrong color relations introduce a bias on cosmology:
History of high-z SNe Ia surveys

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(same low-z dataset used to derive cosmology!)

On-going surveys: SDSS, SNLS, ESSENCE, GOODS

On-going low-z programs

SN Factory
Carnegie (follow-up)
KAIT
CFA (follow-up)
...

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- SN Factory
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- ...

(*)
### Light-curve fitting / distance estimate

**Two very different approaches:**

| **MLCS**  
(as used by GOODS and ESSENCE) | **SALT and SIFTO**  
(as used by SNLS) |
|-------------------------------|-----------------------------|
| Directly extract a distance estimate from light-curves  
=> need a training set of SNe for which we know a priori the distance | 2 steps : light-curve fitting without distance information (can use high-z SNe for training), distance estimate with a combination of the parameters |
| 1) Apply k-corrections : transform photometric measurements to standard rest-frame bands  
2) Fit corrected light curves to a set of templates | Full model of the spectral sequence  
- integrated spectrum compared to data  
-> better error propagation |
| Consider the (B-V) color excess as a measurement of host galaxy extinction | The relation between the measured color and the luminosity is fitted at the same time as cosmology. |
## Light-curve fitting / distance estimate

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Improving light curve fitters using distant SNe

(cannot be done easily with a direct distance estimator like MCLS)

- Using high-z SNe permits to model rest-frame UV emission without the difficulty of UV calibration from the ground (or need to use space telescopes)
- Using SNe at various redshifts permits to scan photometrically the wavelength range between instrumental filters (otherwise one relies on interpolation of order of 100nm)
- Today, the statistics are better at high-z
- Most systematics due to the SN modeling are turned into statistical uncertainties because the accuracy of the model scales with the number of SNe

Example:
SALT(trained on nearby SNe) vs SALT2(trained on SNLS high-z data)
### Light-curve fitting / distance estimate

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MLCS assumptions:

- MLCS (GOODS, ESSENCE) models the SN diversity with a single parameter ($\Delta$) (in addition to an overall magnitude).

- The offset of the B-V color of data w.r.t. the model is attributed to extinction by dust in the line of sight.

- As a consequence:
  1) This color difference can only be positive -> use a prior (dust extinction makes SNe redder)
  2) The correction to “unredden” SNe is given by a dust absorption model: the Cardelli et al. (1989) extinction law

- There is clear evidence against this assumption.
- It biases the estimation of cosmological parameters.
- The usage of a color prior artificially converts statistical uncertainties into systematics.
SNe colors: intrinsic and/or extinction?

**Brighter-bluer relation**
Tripp et al. (1998)
\[ \mu_B \propto \beta(B-V) \]
\[ \beta \approx 2 \text{ is incompatible with } R_B = 4.1 \text{ (Milky Way extinction)}. \]

**Color relations**
Guy et al. (2005, 2007)
The color relations of SNe are incompatible with Cardelli extinction law.

**Hubble bubble**
Conley et al. (2007)
the “Hubble bubble” (higher local value of \( H_0 \))
(Jha et al., 2007) disappears when \( \beta \) is fitted on the data.
SNe colors: effect of a prior statistics -> systematics

- The ESSENCE collaboration (Wood-Vasey et al., 2007) uses a prior for the (B-V) excess of SNe:
(on the figure Av = 3.1 E(B-V))

- This is convenient to reduce statistical uncertainties on color and hence distance moduli

- In addition, the prior is chosen a function of redshift to correct for Malmquist bias
(only bright blue SNe are observed in the highest redshift bin)

- The uncertainty on this redshift-dependent prior is the dominant systematic uncertainty on w:

\[ \sigma(w, \text{prior}) = 0.1 \] for a total systematic budget of 0.13
(\[ \sigma(w, \text{prior} + \text{hubble bubble}) = 0.117 \])

- Statistical uncertainties have been converted into systematics
In SNLS, for each SN, three parameters are derived:

- magnitude ($m^*_B$), stretch ($s$), and a color ($c$)
- no prior is applied
- the distance estimate is a linear combination of those parameters:

$$\mu_B = m^*_B - M + \alpha (s - 1) - \beta c$$

(sufficient to describe the data)

- coefficients $\alpha$ and $\beta$ are fitted at the same time as cosmology (and marginalized over, same for $M$)

- we find $\beta \sim 2$ (+- 0.2)

**Criticism:**

"$c$ is a single parameter that mixes intrinsic color and dust reddening. Hence, evolution of the ratio of the two with $z$ may change the value of $\beta$"

-> one can fit a correction:

$$-(\beta'_0 + \beta' z)c$$
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Conclusions
Systematic uncertainties

**Measurement uncertainties:**
- Photometry
- Calibration
- Light curve fitters (k-correction systematic errors)

**Astrophysical uncertainties:**
- SNe evolution
- Evolution of dust properties
- Core-collapse contamination
- Gravitational magnification
- Intergalactic extinction
- Peculiar velocities

Systematic uncertainties are today of the same order of magnitude as stat.

-> they are being reduced

-> still, they now have to be included in the cosmological fits

GOODS, Riess et al. (2004)
\[ w = -1.02 \pm 0.13 \text{ (stat), no quoted sys.} \]

SNLS, Astier et al. (2006)
\[ w = -1.023 \pm 0.090 \text{ (stat) \pm 0.054 (sys)} \]

ESSENCE, Wood-Vasey et al. (2007)
\[ w = -1.05^{+0.13}_{-0.12} \text{ (stat 1 \sigma) \pm 0.13 (sys)} \]
Calibration uncertainties

Example: SNLS-3 LCDM fit

\[
\left( \frac{d_L(z_2 = 0.5)}{d_L(z_1 = 0)} \right)^2 = \frac{f_2(z_2 = 0.5, \hat{B})}{f_1(z_1 = 0, \hat{B})} = 10^{\frac{0.4 \left[ m_{2}(R) - m_{1}(B) \right]}{ \int \phi_{SN}(\lambda)B(\lambda(1 + z_1))d\lambda}} \times \frac{\int \phi_{SN}(\lambda)R(\lambda(1 + z_2))d\lambda}{\int \phi_{ref}(\lambda)B(\lambda)d\lambda} \times 10^{0.4 \left[ m_{ref}(R) - m_{ref}(B) \right]} \times \frac{\int \phi_{ref}(\lambda)R(\lambda)d\lambda}{\int \phi_{ref}(\lambda)B(\lambda)d\lambda}
\]

B-R color of the flux reference (Vega)

1% uncertainty in B-R
\( \iff \) 225 SNe at \( z \sim 0.5 \)

20000 SNe requires calibration at 0.1% !

Dominant uncertainties:
- Nearby SNe calibration (Landolt system difficult to model, heterogeneous dataset)
  \( \iff \) will be solved with new nearby dataset not anchored to Landolt: SDSS SNe survey

- Primary standard flux and magnitudes (in a given mag. system, here Vega and Landolt)
  \( \iff \) challenge for future surveys like LSST, SNAP, ...
    \( ? \) Instrumental calibration of telescopes
    \( ? \) Space calibration of primary standard stars
Supernova evolution

We are worried by the possible influence of the environment on SNe luminosity:
- metallicity
- age of the stellar population
  -> selection according to the age of the SN progenitor
    (likely correlated to luminosity)
- evolution with z of the nature and density of dust in host galaxy

-> Ideally: a predictive theoretical model tell us what we need to look at

-> In practice two approaches:

- Photometric and spectroscopic comparison of low and high-z SNe.
  -> No significant signal of evolution up to now:
    (in colors, stretches, ejecta velocities and composition)
  -> Limited test due to poor S/N at high-z

- More powerful: Comparison of SNe properties as a function of their host galaxy
Comparison of SNe properties as a function of their host galaxy
-> split the SN sample in two groups with diff. environments

Mannucci (2005), Sullivan et al. (2006) :
~ spirals

Star Formation Rate (SFR)
(from colors of host galaxies)

strech

-> SNe exploding in star forming galaxies have a larger stretch
(and hence are brighter)
-> Proof of the influence of environment!

However,
when corrected for stretch distance moduli do not correlate with SFR
Uncertainties due to evolution are additional statistical uncertainties (and not systematics)

- SNe properties correlated to their environment should show up when separated in different host galaxy groups:

A Hubble diagram fit with two sets of parameters \((M, \alpha, \beta)\) for active and passive galaxies permits to convert the associated uncertainties into statistical ones through the marginalization over those parameters.

- The same applies to the potential dust evolution:
  One can fit \(\beta\) as a function of redshift

(Using the cosmology dataset to improve the SN modeling also helps convert modeling uncertainties into statistical ones)

This is important (and good news) for future surveys:
- ESSENCE, SNLS, GOODS dataset is of order of 500 high-z SNe.
- Many more (~100000) are expected for the LSST project.
Conclusion about current high-z SNe surveys:

- All current SNe surveys tell us $w \sim -1$ (+- 0.1)

- Still, some important differences in the distance estimators

- All high-z surveys currently share (almost) the same low-z sample for their cosmological fits
  
  -> Selection bias of this sample is impossible to model precisely
  -> The calibration scheme used is inadequate for the required accuracy of current and future surveys

- The colors of the primary standard is one of the main limitations today.

- Systematic uncertainties have to be included in cosmological fits
Challenges for SNe cosmology

1) SNe phenomenology: the unfolding of the effects of intrinsic color variation and dust extinction reddening is needed

2) When treated correctly, uncertainties due to k-correction (SN model), dust or SN evolution with redshift scale down with the size of the survey (number of SNe)

3) Calibration will be the dominant source of uncertainty for future large projects (≈0.1% required)

4) Short term priority of SNe cosmology is now low z surveys:
   - improved statistics
   - improved calibration
   - control of selection bias
   - better understanding of SNe diversity