The extinction law of Type Ia Supernovae

The Nearby Supernovae Factory

CHOTARD Nicolas
23rd Rencontres de Blois
1st June 2011
Outlook

Introduction

* Observational cosmology with SNe Ia
* The Nearby Supernova Factory

SNe Ia variability

* SNe Ia and extinction law
* Spectral analysis
* Empirical extinction law construction

Conclusion
Observational cosmology with SNe Ia

* Hubble diagram: distance modulus vs. redshift
  \[ \mu_B = m_B - M_B = 5 \log(d_L) - 5 \]

* High-z SNe: expansion and cosmological parameters (in \(d_L\))

* Nearby SNe: constrain the degeneracy between cosmology and SNe Ia luminosity

* High quality data of low redshift SNe Ia needed to reduce systematics

* Optimal redshift centered around 0.05: Hubble flow (Linder 06)

\[ \Omega_\Lambda, \Omega_M, w, ... + H_0^2 L_{SN} \]

\[ H_0^2 L_{SN} \]

\[ \mu \]

\[ \Delta \mu \]

\[ z \]

\[ A_{manullah, et al., Ap.J. (2010)} \]

\[ SNFactory \]
Main Goals

* Increase the nearby SNe Ia sample (0.03 < z < 0.08)
* Large sample of flux calibrated spectral time series: control of systematic and standardization
* SNe Ia physics:
  * constrain the models with high quality spectra,
  * spectral properties, extinction study, host analysis, ...

Data sample

* 179 SNe with more than 10 spectra
* ~3000 spectra from -15 to +40 days / max
* redshift coverage from 0.01 to 0.1, median is 0.06
* median first phase: -2
* mean cadence of observation: ~3 days
* spectral coverage 3000 - 9000 Å
SNe Ia: quasi-standard candles

Homogeneity

* similar progenitor (white dwarf)
* similar mass - similar luminosity (Chandrasekhar mass)
* but dispersion around 40% without any correction

Variability

* Sources of variabilities:
  * **intrinsic:**
    * progenitor composition (metallicity),
    * progenitor explosion ($^{56}$Ni mass, viewing angle)
  * **extrinsic:** mainly driven by the host ISM extinction
  * evolution effects: galaxy properties

Empirical corrections to reduce the dispersion:

* light curve width: $\Delta m_{15}$, stretch, $x_1$ BRIGHTER - SLOWER
* color: B-V at max, salt2 color BRIGHTER - BLUER

In the SALT2 formalism: $\mu_B = m_B - M_B + \alpha x_1 - \beta c$

→ dispersion reduced to 0.15 mag

mercredi 1 juin 2011
Dust extinction

* **Dust** in the ISM responsible for an **extinction, function of the wavelength**

* A 2 parameters law:
  * dust properties: $R_V$
  * amount of dust: $E(B-V)$

* **Cardelli extinction law:**
  
  described by:

  $$\frac{A_\lambda}{A_V} = a_\lambda + \frac{b_\lambda}{R_V}$$

  with:

  $a_\lambda$ et $b_\lambda$, given parameters

  $$R_V = \frac{A_V}{E(B-V)}$$

* Absorption for a given wavelength:

  $$A_\lambda = E(B - V) \times (R_V \times a_\lambda + b_\lambda)$$
Which extinction law for SNe Ia?

* **SNe Ia dispersion dominated by extinction variability**
* **Recurrent issue** in SNe Ia analysis: measurement of the **extinction law (Rv)**
* Nearby SNe independent from cosmology: direct estimate of the absorption

![Graph showing extinction laws](image)


- **SALT2 (Guy07)**: \( \beta = 1.8 \) (‘Rv=0.8’)
- **MLCS2k2 (Hicken09)**: \( Rv = 1.7 \)
- **SNLS 3 years (Guy10)**: \( \beta = 3.2 \) (‘Rv=2.2’)
- Some other analysis: \( 1.5 < Rv < 2.5 \)
- Our galaxy: \( Rv = 3.1 \)

**Lower values** than the Milky Way one usually found

- Large dispersion in these values

**Difficulty:** SNe Ia variability is a **mix of intrinsic + extrinsic** components

**Our Solution:** Measure the **intrinsic variability** with **spectral indicators**
Spectral analysis at max

Typical SN Ia Spectral Features at max

Features | Wavelengths
---------|----------------
CaIIH&K  | 3934,3968
SiII;Col | 4128,4131;4145,4161
MgII triplet | 4481
Fell blend | 4923,5018,5169
SiIIW    | 5433,5453(L);5606,5640(R)
SiII     | 5958,5979
SiII 6355 | 6347,6371
O1 triplet | 7772,7774,7775
CaII IR triplet | 8498,8542,8662
Spectral analysis at max

Typical SN Ia Spectral Features at max

Flux [Erg/cm² / s/Å]

Wavelength [Å]

Cal H&K
SII; Coll
Mg II triplet
Fell blend
Si II
Si II 6355
O I triplet
Ca II IR triplet

EW_{Ca}
EW_{Si}
Spectral analysis at max

Equivalent widths:

\[ EW = \sum_{i=1}^{N} \left( 1 - \frac{f_{\lambda}(\lambda_i)}{f_{c}(\lambda_i)} \right) \Delta \lambda_i \]

- Insensitive to dust extinction (less than 2%)
- Correlated to absolute magnitude and stretch
- Measurement of the intrinsic part of the variability

Sample: 76 SNe Ia which have
- a good phase sampling
- a spectrum at max (+/- 2.5 days around max)

Measurements (on each spec at max):
- EWs (Si and Ca)
- absolute magnitudes (Hubble residuals)

2 set of filters:
- 5 broad synthetic filters (UBVRI-like)
- 200 narrow synthetic filter («spectral»)
Separating the variabilities

**GOAL**: Construct a mean extinction law for SNe Ia

**1st step**: Correct the Hubble residuals from intrinsic variabilities to get the relative absorptions $\delta A_\lambda$ (up to a constant term)

**Three cases**:
(a) SNe Ia are perfect candles: only extrinsic variability
(b) Intrinsic variability described by a «stretch-like» parameter: $\text{EW}^{\text{Si}}$
(c) Intrinsic variability described by **two parameters**: $\text{EW}^{\text{Si}}$ and $\text{EW}^{\text{Ca}}$

$$\delta M_\lambda = \begin{cases} 
\delta A^0_\lambda & (a) \\
 s^{\text{Si}}_\lambda \text{EW}^{\text{Si}} + \delta A^{\text{Si}}_\lambda & (b) \\
 s^{\text{Si}}_\lambda \text{EW}^{\text{Si}} + s^{\text{Ca}}_\lambda \text{EW}^{\text{Ca}} + \delta A^{\text{Si+Ca}}_\lambda / 10 & (c) 
\end{cases}$$
Construct the extinction law

**GOAL**: Construct a mean extinction law for SNe Ia

**1st step**: Correct the Hubble residuals from intrinsic variabilities to get the relative absorptions \( \delta A_\lambda \) (up to a constant term)

**2nd step**: Use the relation between the \( \delta A_\lambda \) to construct the law

**Linear model**: 

\[
\delta A_\lambda(i) = \gamma_\lambda \delta A^*_V(i) + \eta_\lambda
\]

**Estimation of \( R_V \)** when forcing:

\[
\gamma_\lambda \equiv \frac{A_\lambda}{A_V} = a_\lambda + \frac{b_\lambda}{R_V}
\]

Cardelli extinction law
Results on the $\gamma_\lambda$

**Perfect candles**

\[ \gamma_\lambda \equiv \frac{A_\lambda}{A_V} \]

**EW$^\text{Si}$ correction** («stretch-like»)

Residual intrinsic variability!

**EW$^\text{Si}$ and EW$^\text{Ca}$ corrections**

Classic extinction law

\[ R_V = 2.8 \pm 0.4 \]
Results on the $\gamma_\lambda$

\[ \gamma_\lambda \equiv \frac{A_\lambda}{A_V} \]

Perfect candles (a)

$\gamma_\lambda$ correction («stretch-like») (b)

Residual intrinsic variability!

EW$_{Si}$ and EW$_{Ca}$ corrections (c)

Classic extinction law

$R_V = 2.8 \pm 0.4$

Results on the $\gamma_\lambda$

(a) Perfect candles
$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$

(b) EW$^\text{Si}$ correction («stretch-like»)
Residual intrinsic variability!

(c) EW$^\text{Si}$ and EW$^\text{Ca}$ corrections
Classic extinction law
$$R_V = 2.8 \pm 0.4$$

Results on the $\gamma_{\lambda}$

Perfect candles

$\gamma_{\lambda} \equiv \frac{A_{\lambda}}{A_V}$

EW$^{Si}$ correction («stretch-like»)

Residual intrinsic variability!

EW$^{Si}$ and EW$^{Ca}$ corrections

Classic extinction law

$R_V = 2.8 \pm 0.4$

But need to introduce a dispersion into the fit...

Covariance matrix

**Why?**
Using the measured covariance matrix only: $X^2 >> 1$
Extra dispersion matrix needed to set the $X^2$ to 1 (as in all cosmological fits with SNe Ia)

**How?**
Using the residual $r_\lambda(i)$ to the $\gamma_\lambda$ fit to construct the additionnal covariance matrix

for each of the 3 cases (a,b,c)

Introduction of a **color dispersion**, not usually used

* Anti-correlation mostly increases with the wavelength differences
* Same pattern for broad filters and narrow band (spectral) correlations

*For the case (c): 2 intrinsic corrections*

Reminder:
\[
\delta A_\lambda(i) = \gamma_\lambda \delta A^*_V(i) + \eta_\lambda (+r_\lambda)
\]

Anti-correlation mostly increases with the wavelength differences
Same pattern for broad filters and narrow band (spectral) correlations

**Extra dispersion matrix needed to set the $X^2$ to 1**
(as in all cosmological fits with SNe Ia)

**Using the residual $r_\lambda(i)$ to the $\gamma_\lambda$ fit to construct the additionnal covariance matrix**
Covariance matrix

**Why?**:
Using the measured covariance matrix only: $X^2 >> 1$
Extra dispersion matrix needed to set the $X^2$ to 1 (as in all cosmological fits with SNe Ia)

**How?**:
Using the residual $r_\lambda(i)$ to the $\gamma_\lambda$ fit to construct the additionnal covariance matrix

*For each of the 3 cases (a,b,c)*

Introduction of a **color dispersion**, not usually used

* Anti-correlation mostly increases with the wavelength differences
* Same pattern for broad filters and narrow band (spectral) correlations

For the case (c): **2 intrinsic corrections**

Reminder:

$$\delta A_\lambda(i) = \gamma_\lambda \ \delta A_V^*(i) + \eta_\lambda \ (+r_\lambda)$$

**Intrinsic corrections**

**Dispersion in color**

**Cardelli-like extinction law**

**Higher value of RV**
Conclusion / What’s next

Result:

* **Two variables** correlated to the **intrinsic variability**

* **Extinction law** compatible with a **Cardelli law**

* **Dispersion in color**

* **Rv value** compatible with the **Milky Way one**

* Better understanding of the extinction is important to reduce systematic effects in cosmological analysis

Open questions:

* Dispersion: intrinsic or extrinsic residuals variabilities?

* Is the result the same at another phase?

* Correlation of the matrix to other quantities (spectral variables, host quantities...)?

* ... A lot of further spectral analysis are in progress with the SNFactory spectral sample