Rescuing Type Ia Supernovae from Dust: Bayesian Inference with Near-Infrared and Optical Data

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Rescuing Type Ia Supernovae from Dust: Bayesian Inference with Near-Infrared & Optical Data

1. Big Picture: SN Ia & Cosmology

2. Data: PAIRITEL SN Project

Wood-Vasey, Friedman+08 (WV08)
Friedman+11 in prep.

3. Analysis: Estimating Dust and Distance

Mandel, Wood-Vasey, Friedman, & Kirshner 09
Mandel, Narayan, & Kirshner 11a
Friedman+11 in prep.
Mandel+11b in prep.
Type Ia Supernovae (SN Ia)

- Thermonuclear explosions of White Dwarf stars in binary systems.
  - Very bright.
  - Can detect in distant galaxies.

- Explode at ~1.4 solar masses →
  - Similar peak intrinsic luminosities

- Almost *Standard candles*: Same intrinsic brightness (L).

- **Distance**: Given L, get d from apparent brightness (F).

\[ F = \frac{L}{4\pi d^2} \]
SN Ia are Standardizeable Candles

Optical B-Band (1 parameter)  NIR J-Band (4 parameter)

J. Frieman 2008 (FIG 12)  (from Kim 2004)

Mandel, Wood-Vasey, Friedman, & Kirshner+2009 (FIG 4,5)
Type Ia Supernova Cosmology

• Measure light curves (LCs) of SN Ia at many wavelengths (brightness vs. time)

• Measure redshift $z$ from spectrum

• Estimate distances $\mu$ to SN Ia from observed LCs + models, priors

• Measure $\mu$, $z$ for many SN Ia

• Compare to theoretical model $\mu(z, \Omega)$

$\rightarrow$ constrain cosmological params $\Omega = (\Omega_M, \Omega_\Lambda, w)$
**Dust: Getting in the Way**

- Dust along line of sight: SN Ia host galaxy + Milky Way
- Dims apparent brightness (*extinction*)
  (Some dimming due to *intrinsic luminosity variation*)
- Preferentially absorbs bluer light (*reddening*)
  (Some redder colors due to *intrinsic color variation*)
- Makes object appear further away
- Ignore dust → systematic overestimate of distance
- Measure dust inaccurately → systematic distance error
Near-Infrared vs. Optical

Optical SN Ia Cosmology
• Reddening from dust extinction + intrinsic color variation
  Dominant systematic distance error

Advantages of Near-Infrared vs. Optical
• Less sensitive to dust extinction
• NIR SN Ia intrinsically more standard
• Ground-based JHK observations at low-z

• Rest-frame NIR observations of high-z SN Ia must be done from space (WFIRST, JWST)
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Scientific Goals:

• Study NIR properties of large, homogeneous, ground-based, low-z, bright SN Ia data set

• NIR+Optical $\rightarrow$ more accurate & precise distances

• Understand dust in other galaxies

• ? High-z cosmology (WFIRST)

• **Thesis: Double published set of NIR SN Ia LCs**
  $\sim 60 \rightarrow \sim 120$
**Peters Automated InfraRed Imaging TELEscope**

- **PAIRITEL 1.3m**: 2MASS telescope
- **Robotized in 2004**: (Bloom+06)
- **Autonomous queue scheduled obs.**
- **20+ science projects + SN follow-up**

**PAIRITEL SN Project**

- **~30% time since 2005**
- **Homogeneous data set, tested camera**
- **Simultaneous JHK, ~nightly cadence**
- **Photometric calibration → 2MASS**
- **Optical Phot., Spectra (1.2m, 1.5m)**

PAIRITEL JHKs: SN2006D
Wood-Vasey, Friedman+2008 (FIG 1)
PAIRITEL Supernovae By Type

152 SN
2005-2010
71% Ia
18% Ib/c
11% II

108 Ia

~20 Ia (~28 SN) avg. full season

Observing Season

04-05*  05-06  06-07  07-08  08-09  09-10  Total

Number of SN

~20 Ia (~28 SN) avg. full season
21 PAIRITEL JHKs SN Ia Light Curves

Normal SN Ia LCs $\rightarrow$ 2 NIR peaks

Peculiar-Ia 05bl, 05hk, 05ke excluded from LC template

Fig 2: Wood-Vasey, Friedman+08

Phase Relative to B-band Maximum [days]
Friedman+11 in prep.

Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.
CfAIR2: PAIRITEL SN Ia Light Curves

Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.

Friedman+11 in prep.
Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.
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CfAIR2: PAIRITEL SN Ia Light Curves

**snPTF10bs (Type Ia) PAIRITEL/CIA**

- **sn2005bo (Type Ia) PAIRITEL/CIA**
- **sn2009ds (Type Ia) PAIRITEL/CIA**

**sn2005sq (Type Ia) PAIRITEL/CIA**

**sn2007s (Type Ia) PAIRITEL/CIA**

Clear LC structure.

Friedman+11 *in prep.*

Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.
CfAIR2: PAIRITEL SN Ia Light Curves

Clear LC structure, but large gaps in coverage

Friedman+11 in prep.

Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.
CfAIR2: PAIRITEL SN Ia Light Curves

Clear LC structure, but sparser data.

Friedman+11 in prep.

Forced DOPHOT on p2/p3 mosaics. SN coords from Opt images. No galaxy subtraction.
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Bayesian Inference

\[ P(\theta \mid D, H) \propto P(D \mid \theta, H) \cdot P(\theta \mid H) \]

**Posterior Density**
- of parameter \( \theta \),
- conditioned on the data \( D \), assuming model \( H \)

**Likelihood:**
- Probability of data \( D \),
- given model \( H \) with parameters \( \theta \)

**Prior**
- on model \( H \)
- parameter \( \theta \)

\( H - Hypothesis \): Generative Model for data \( D \)

Derive **inferences** on model parameters \( \theta \) from posterior
Hierarchical Bayesian Inference

\[
P(\{\theta_i\}; \alpha | \{D_i\}) \propto \prod_{i=1}^{N} P(D_i | \theta_i) \frac{P(\theta_i | \alpha)}{P(\theta_i)} \frac{P(\alpha)}{}
\]

**Joint Posterior**

Density of parameters \(\{\theta_i\}\) for \(N\) objects & hyperparameters \(\alpha\), given all data \(\{D_i\}\)

**Joint Likelihood:** Probability of data \(D_i\), given parameters \(\theta_i\)

**Population Prior:** Probability of parameters \(\theta_i\) given hyperparameters \(\alpha\)

**Hyperprior** on population hyperparameters \(\alpha\)

\(D_i\) - Data for individual object \(i\)

\(\theta_i\) - model parameter for individual object \(i\)

\(\alpha\) - hyperparameters modeling population distribution

Inferences on model parameters \(\{\theta_i\}\) from joint posterior
Hierarchical Bayesian Inference

Model Assumptions & Priors

• Model the population of objects (hyperparameters)
• Model observed & missing data (parameters)
• Model uncertainty from multiple sources

Statistical Inference

• **Training**: Infer population hyperparameters given data from a set of “training” objects

• **Prediction**: Infer parameters for individual object given its data + population hyperparameters.
Mandel+11a

Type Ia Supernova Light Curve Inference: Hierarchical Models in the Optical and Near Infrared

• ~60 NIR (WV08, CSP); ~110 Opt (CfA3: Hicken+09a)

• Statistical model for NIR+Opt SN Ia LCs

• Models uncertainty from multiple sources

• Deals naturally with missing data

• JH + BVRI improves SN Ia distance precision ~60%

• Hubble Diagram RMS distance modulus err:
  NIR+Opt: 0.11 mag  Opt: 0.15 mag
Model: Measuring SN Ia Distances

\[ \mu = m - M - A(a + br) \]

- \( \mu \) = Distance Modulus
- \( m \) = Apparent magnitude*
- \( M \) = Absolute Magnitude**

\( r = R_V^{-1} \) Host galaxy dust law slope
\( A = A_V \) V-band host galaxy extinction
\( a, b \) CCM law parameters (known from spectra)

*\( m \) Already corrected for time dilation, K-corrections and Milky Way Extinction
**\( M \) not corrected for LC shape

\[ E = A(a + br) \]

Color excess from CCM dust law \( \rightarrow \) extinction as a function of wavelength

- To measure color excess \( E \), we must estimate the host galaxy extinction \( A = A_V \), and dust law slope \( r = 1/R_V \)
Training
Infer population params for SN Ia intrinsic Light Curves & Dust.
Condition on observed LCs $D_s$ + redshifts $z_s$ for all SN in sample.

Prediction
Infer distance $\mu_p$ to a SN.
Condition on observed SN Light Curve data $D_p$ + population params from training (not redshift $z$)

Mandel+11a (FIG 1)
Sources of Uncertainty

• **intrinsic LC shape & color variations**

• **dust extinction & host galaxy reddening**

• **peculiar velocity & distances**

• **photometric measurement error**

*Uncertainties for redshift & time dilation, K-corrections, & Milky Way extinction included in photometric error budget*
Measuring Dust: Standard Method

\[ E = O - C = A(a + br) \]

Color excess from CCM dust law → extinction as a function of wavelength

\[ O = \text{Observed color} \quad r \equiv R_V^{-1} \]

Host galaxy dust law slope

\[ C = \text{Intrinsic color} \quad A \equiv A_V \]

V-band extinction

\[ E = \text{Color excess} \quad a, b = \]

CCM law parameters (known from spectra)

Relate extinction between bandpasses

• Assume subset \( X \) of SN Ia have 0 reddening (\( E=0 \))

• Use subset to estimate intrinsic color curves (\( C_0=O_X \))

• For other SNs, measure observed color curves \( O_s \)

• Estimate Color Excesses: \( E_s = O_s - C_0 \)

• Determine \( A_V, R_V \) from \( E_s \), CCM law, multiple colors
Estimating Opt-NIR Color Excesses

Friedman+11

V-J

V-H

V-K

Friedman+11 in prep.
**Measuring Dust: Bayesian Method**

Model SN, dust populations for single color at single time

Gaussian: Observed color $O$

$$P(O|C, A, r) \propto \exp \left( \frac{-(O - C - A(a + br))^2}{2\sigma_o^2} \right)$$

Exponential: Extinction $A$

$$P(A|\tau) \propto \exp \left( \frac{-A}{\tau} \right); \quad A \geq 0$$

Gaussian: Intrinsic color $C$

$$P(C|\mu_c, \sigma_c) \propto \exp \left( \frac{-(C - \mu_c)^2}{2\sigma_c^2} \right)$$

Gaussian: Dust law slope $r$

$$P(r|\mu_r, \sigma_r) \propto \exp \left( \frac{-(r - \mu_r)^2}{2\sigma_r^2} \right)$$

Hyperparameters of SN, dust populations $\alpha$

$$\alpha = (\mu_c, \sigma_c; \tau; \mu_r, \sigma_r)$$

Hard Part: Mandel+2011a determines $P(\alpha|O)$: posterior probability of population hyperparameters $\alpha$, conditioned on observed color data $O$ (computed w/ MCMC).

Uses ALL SN color data (not just assumed $E=0$ subset)

Estimate intrinsic color pop. distribution hyperparameters $\mu_c, \sigma_c$. 

5/7/11

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**Measuring Dust: Bayesian Method**

**Easy Part:** For each SN compute $P(A,r|O,\alpha)$: the posterior probability of $A,r$ given observed color $O$ & hyperparameters $\alpha$

$$P(A, r|O; \alpha) \propto \exp\left(-\frac{A}{\tau}\right) \times \exp\left(-\frac{(r - \mu_r)^2}{2\sigma_r^2}\right) \times \exp\left(-\frac{(E - \mu_E)^2}{2\sigma_E^2}\right)$$

$$\mu_E = O - \mu_c, \quad E = A(a + br), \quad \sigma_E^2 = \sigma_o^2 + \sigma_c^2, \quad A > 0.$$

Eq. adapted from: Mandel, Wood-Vasey, Friedman & Kirshner 09; Mandel+11a.

Fig adapted from: Fig 3 of Mandel+11a

NIR (WV08) + Opt (CfA3) LCs of sn2005eq fitted w/ multi-band LC model → observed color data $O$ → Estimate best fit $A_v, R_v$ & uncertainties

$P(A_v,R_v|O,\alpha)$: Posterior probability of $A_v, R_v = 1/r$ for sn2005eq given observed color data $O$ and population hyperparameters $\alpha$
Improved Distances: NIR+Optical data

\[ P(\mu | D, \alpha) \]

JH + BVRI → SN distance estimates more: accurate & precise

\[ P(A_V, \mu | D, \alpha) \]

Conditions on NIR+Opt SN Ia LC data: PTEL, CSP, CfA, & literature (not \( z \))

Figs 17-18: Mandel+11a
NIR+Optical Hubble Diagram

127 SN Ia
JH + BVRI

RMS scatter:
NIR+Opt: 0.11 mag
Opt: 0.15 mag

Low-z NIR SN Ia crucial anchor for cosmology

Fig 16: Mandel+11a
Conclusions: Previous Results w/ Thesis Data

(No correction for NIR LC shape or reddening)

- SN Ia are rest-frame H-band standard candles (~0.15 mag)
  Wood-Vasey, Friedman+08

(No correction for NIR reddening)

- NIR only LC shape model: JHK intrinsic variances [mag]
  \[ \sigma(M_J) = 0.17 \pm 0.03, \quad \sigma(M_H) = 0.11 \pm 0.03, \quad \sigma(M_K) = 0.19 \pm 0.04 \]

- JHK Hubble diagram 0.10-0.15 mag scatter. No Opt data.
  Mandel, Wood-Vasey, Friedman, & Kirshner 09

(Correction for Opt+NIR LC shape and reddening)

- JHBVRI vs. BV data improves accuracy (dust extinction systematics), and precision (distance errors ~60% smaller)

- Hubble diagram RMS: NIR+Opt: 0.11 mag, Opt: 0.15 mag
  Mandel, Narayan, & Kirshner 11