Type Ia Supernova Inference: Hierarchical Bayesian Models for Optical and Near Infrared Light Curves, Velocities, Dust, and Cosmic Distances


Mandel, Foley, Kirshner et al. 2011, in prep. (Optical + Spectra)

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Outline

• Statistical Inference with SN Ia Data
  • Hierarchical Bayesian Framework for Structured Probability Models for Observed Data
• Describing Physical Populations & Individuals, Multiple Random Effects
• Statistical Computation for SN Ia Hierarchical Models (BayeSN)
• Application & Results:
  • Nearby CfA NIR and Optical SN Ia Light Curves
  • Nearby CfA Optical LCs and Spectral Lines
Supernova Cosmology: Constraining Cosmological Parameters using Luminosity Distance vs. Redshift

Credit: Gautham Narayan

Using Optical LCs of SN Ia: Need accurate distances! Host Galaxy Dust is a Major Confounding Factor

Monday, June 13, 2011
Reading the Wattage of a SN Ia: Empirical Correlations

- Width-Luminosity Relation: an observed correlation (Phillips)
- Observe optical SN Ia Light Curve Shape to estimate the peak luminosity of SN Ia: ~0.2 mag

- Color-Luminosity Relation

- Methods:
  - $\Delta m_{15}(B)$
  - MLCS, Abs LC vs Dust
  - SALT, App. Color single factor

Intrinsically Brighter SN Ia have broader light curves and are slow decliners
Type Ia Supernova Apparent Light Curve
(CfA3 and PAIRITEL @ FLWO)

Near Infrared (JH)

Optical (BVRI)
Statistical inference with SN Ia

• SN Ia cosmology inference based on empirical relations
• Statistical models for SN Ia are learned from the data
• Several Sources of Randomness & Uncertainty
  1. Photometric errors
  2. “Intrinsic Variation” = Population Distribution of SN Ia
  3. Random Peculiar Velocities in Hubble Flow
• Apparent Distributions are convolutions of these effects
• How to incorporate this all into a coherent statistical model? (How to de-convolve?)
Advantages of Hierarchical Models

• Incorporate multiple sources of randomness & uncertainty
• Express structured probability models adapted to observed data
• Hierarchically Model (Physical) Populations and Individuals simultaneously: e.g. SN Ia and Dust
  • Learn Intrinsic Covariances: Color/Luminosity/Light Curve Shape
  • Estimate Extrinsic Effects: Dust Reddening/Extinction
• Full (non-gaussian) probability distribution = Global, coherent quantification of uncertainties
• Completely Explore & Marginalize Posterior trade-offs/degeneracies/joint distributions
• Deals with incomplete/missing data problems
  • Make best inference/estimate for the observed data
• Modularity makes Model Expansion easy
Directed Acyclic Graph for SN Ia Inference with Hierarchical Modeling

- Intrinsic Randomness
- Dust Extinction & Reddening
- Peculiar Velocities
- Measurement Error

"Training" - Learn about Populations

Generative Model

Global Joint Posterior Probability Density Conditional on all SN Data
Directed Acyclic Graph for SN Ia Inference: Distance Prediction

\[ A^s_V, R^s_V \quad \text{Training} \]

\[ A^p_V, R^p_V \quad \text{Prediction} \]

\[ \mu_s \quad \text{SN Ia AbsLC Pop} \]

\[ \mu_p \quad \text{Dust Pop} \]

\[ s = 1, \ldots, N_{SN} \]

\[ D_s \quad D_p \]
Statistical Computation with Hierarchical SN Ia Models: The BayeSN Algorithm

- **Strategy:** Generate a Markov Chain to sample global parameter space (populations & all individuals) => seek a global solution

- Chain explores/samples trade-offs/degeneracies in global parameter space for populations and individuals

Multiple chains globally converge from random initial values
Practical Application of Hierarchical Model: NIR SN Ia

Why are SN Ia in NIR interesting?

- Host Galaxy Dust presents a major systematic uncertainty in supernova cosmology inference
- Dust extinction has significantly reduced effect in NIR bands
- Observe in NIR!: PAIRITEL / CfA

\[ \lambda \text{-dependence of dust extinction} \sim \text{reddening} \]
Nearby SN Ia in the NIR: PAIRITEL

Observed in NIR
J (λ=1.2 μm)
H (λ=1.6 μm)
Ks (λ=2.2 μm)

Credit: Michael Wood-Vasey, Andrew Friedman
Figure 1: 142 CfA Light curves from 2000-2004 (UBVRI) and 2004-2007 (UBVri)
**Optical+NIR Hierarchical Inference: Individual SN Ia**

**Mandel, Narayan & Kirshner (2011)**

**Marginal Posterior of Dust**

**PTEL+CfA3 Light-curves (Moderate Extinction)**
Population Analysis:
Intrinsic Covariance Structure

Intrinsic Correlation Maps for Peak Luminosities and Decline Rates

NIR (H-band) provides nearly uncorrelated information on luminosity distance
Modeling Dust Population:
Apparent Population Correlation btw $A_V$ and $R_V$

$R_V \sim \lambda$-dependence
of dust extinction
$\sim$ reddening

$P(R^{-1}_V | A_V) = N( R^{-1}_V | 0.36 + 0.14 A_V, \sigma^2 = 0.04^2)$

- Circumstellar dust at High $A_V$? Multiple Scattering - Goobar08
- Maybe a mixture of inter- and circum-stellar dust?
Cross-Validated Nearby $\text{Optical+NIR}$ Hubble Diagram

**Opt+NIR Improves Overall Precision $\sim (0.15/0.11)^2 \approx 2$ !**

(Relative Weight in Hubble Diagram)

**Using Opt+NIR is like doubling the Optical-Only sample!**

Opt+NIR @ $z \sim 0.3$ improves $\sigma(w)$ by $\sim 1.5$ vs. Opt-Only
Hierarchical Model Expansion: SN Ia Ejecta Velocities and Optical LCs

- Foley & Kasen (2011): Peak Intrinsic B-V color is correlated with Si II velocity
- Velocity can help determine intrinsic color, improve SN Ia dust and distance estimates

SN Ia Spectrum near Maximum

[Graph showing SN Ia spectrum with high velocity and normal silicon peaks]
Model Expansion:
Hierarchical Model for SN Ia LCs and Velocities

\[ \Omega_M, \Omega_\Lambda \]
\[ w, h \]

\[ D \]
\[ \mu_s \]
\[ z_s \]
\[ A_V, R_V \]

\[ s = 1, \ldots, N_{SN} \]

Use BVRI light curves and v(Si II) from spectra
Estimating the Correlation Structure of SN Ia intrinsic colors and ejecta velocities

Velocity tells you Intrinsic Color, helps correct for host galaxy dust

App. Color is IntCol + Dust
Mean Intrinsic Color vs. Velocity

Summary: Statistical Methodology

- Constructed Hierarchical Bayesian framework useful for coherently modeling Populations and individuals with multiple random effects
- Intrinsic Supernova Covariance Structure (Opt+NIR colors/luminosity/light curve shape and spectral lines)
- Extrinsic Dust extinction and reddening
- BayeSN: an efficient MCMC for computing posterior inferences with SN Ia hierarchical models
- Cross-Validation: Test sensitivity of predictions to finite training set
Summary: Scientific Conclusions

• SN Ia Optical with NIR: Estimate dust, smaller distance uncertainty and better precision than with Optical alone (0.11 vs 0.15 mag)

• Differential trend of $R_V$ vs $A_V$: Circumstellar dust at high extinction?

• Rest-Frame NIR obs of SN Ia at high-z will improve constraints on $\omega$, less sensitive to a systematic error in dust $R_V$

• New Significant Correlations btw spectral velocities and Optical Colors provides additional information for dust and distance estimates