connecting radiative transfer simulations to supernova data in the era of LSST


danny goldstein (uc berkeley)

images: LSST / B. Dilday / Kasen+2009 / NERSC
Motivation

Understanding supernovae is necessary for understanding stellar evolution, compact objects, galaxy evolution, and cosmological systematics.

IMAGES: NASA
Supernovae: open questions

Our current picture of supernovae is far from complete: the explosion mechanisms and progenitors of many subclasses are uncertain.
The role of radiative transfer

Transfer modeling is the bridge between SN ejecta models and data

spectra, light curves
The role of radiative transfer

progenitor

explosion (t~secs)

ejecta (t~1 day)

stellar evolution

hydro model

Ejecta configurations probe SN explosion / progenitor models

spectra, light curves

radiative transfer

IME

Ni
Barriers to data-model comparisons

Cost of transfer simulations

<table>
<thead>
<tr>
<th>SEDONA Transfer Code</th>
<th>1D</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>runtime (cpu-hr)</td>
<td>$10^{2-3}$</td>
<td>$10^4$</td>
<td>$10^{5-7}$</td>
</tr>
</tbody>
</table>

10^{2-7} hours for a typical RT simulation

10^3 model evaluations required to iteratively fit a light curve / spectrum

SNe discovered by 2025

10^6

= 10^{11-16} cpu-hours to fit SNe with RT models

SOURCE: ROCHESTER SN DB, LSST SCIENCE BOOK, D. KASEN
Supernova Emulators

danny goldstein, rollin thomas, dan kasen, peter nugent, stan woosley

tools to efficiently predict the outputs of radiative transfer simulations and rapidly fit data with models

- **Fast**: predict synthetic light curves / SEDs quickly, for any desired set of model parameters; fit observed data with models in minutes

- **Simple**: software package implemented in Python, anyone can make model light curves / SEDs & fit models to observations

- **Reliable**: emulators provide principled prediction error estimates and reveal degeneracies between model parameters

Supernova Emulators

1. Represent models as vectors of physical parameters.
2. Spread out a grid of models in parameter space.
3. Run the grid of models.
4. PCA decompose the resulting light curves / spectra.
5. Model the weights of each PC as a zero-mean, squared exponential gaussian process function of the physics parameters.
6. Infer physics parameters of individual observed SNe by fitting the gaussian process ensemble to observables using MCMC.

FOR STELLAR SPECTRAL EMULATORS, CF CZEKALA+2015
Bolometric Light Curve Challenge

Aldering+2002, Scalzo+2014
Type Ia ejecta model

- **Fiducial Ia ejecta model**
  - $t \sim 1$ day after explosion
  - Homologous expansion
  - Exponential density profile
  - Spherically symmetric
  - Total mass $\leq 1.38 \, M_\odot$

WOOSLEY+2007
Type Ia ejecta model

parameters

- \( M_{Ni} \) – Mass of synthesized \(^{56}\text{Ni}\)

\[ M_{Ni} \]

- \( R_{Ni} \) – \(^{56}\text{Ni}\) Mixing Parameter

- \( M_{IME} \) – Mass of synthesized IMEs

- \( M_{CO} \) – Mass of unburned CO
Type Ia ejecta model

parameters

- $M_{Ni}$ – Mass of synthesized $^{56}Ni$
- $R_{Ni}$ – $^{56}Ni$ Mixing Parameter
Type Ia ejecta model

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- $M_{Ni}$ – Mass of synthesized $^{56}\text{Ni}$
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Type Ia ejecta model

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- $M_{\text{IME}}$ – Mass of synthesized IMEs
Implicit Monte Carlo transport

Stochastic particle propagation

Particle count

Very large number of particles needed to overcome statistical noise: $S/N \approx N^{1/2}$

Strategy: replicate on multiple cores (nearly perfect scaling)

Domain decomposition

Node memory determines size of local domain and hence amount of communication at boundaries

Load balancing

More work on regions with high particle counts, high scattering probability (opacity)

Strategies: population control, adaptive refinement, replicate heavily loaded zones

Type Ia ejecta model

Parameters

- $M_{Ni}$ – Mass of synthesized $^{56}$Ni
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- $M_{IME}$ – Mass of synthesized IMEs
- $M_{CO}$ – Mass of unburned CO

$M_{CO}$
**Type Ia ejecta model**

- **Parameters**
  - $M_{Ni}$ – Mass of synthesized $^{56}$Ni
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- Models gloss over detailed physics of ignition, detonation

- Emulators are model independent – you can use your favorite model
Training Light Curves

SEDONA Monte Carlo Transfer Code (LTE) time dependent multiwavelength radiative transfer with radioactive decay

400 cpu-hr per LC

SEDONA: KASEN, THOMAS, AND NUGENT 2006
PGM - Bolometric LC Fitting

- fit model params
- training model 1 params
- training model N params
- fit PC i weight
- training model 1 PC i weight
- training model N PC i weight
- hyperparams
- observed bolometric LC

PC i

ALL UNKNOWN PARAMETERS ARE FIT SIMULTANEOUSLY
The Emulator SN Ia Model

\[ p(L^{em} | A, X, x) = p(a | A, X, x) = \prod_{i=1}^{N_{pc}} p(a_i | A_i, X, x) \]

**Simulation input parameters**

**PC coefficients of SED**

**PCs are independent**

\[ p(a_i | A_i, X, x) = \int p(a_i | A_i, X, x, \ell_i) p(\ell_i) d\ell_i \]

\[ L^{em}(a) = \sum_{i=1}^{N_{pc}} a_i \tilde{\xi}_i \]

SED and PC coefficients are related deterministically

**GP with 0 mean, squared exp. covar., cond. on** \( A_i, X \).

\( \ell = \text{GP Hyperparameters} \sim \text{specifiable prior} \)
Fitting Model to Bolometric LCs

- Used STAN Hamiltonian Markov Chain Monte Carlo (HMC) code to fit the model to observations
- HMC achieves excellent performance and parameter space coverage
- 4000 emulated light curves realized for each observed light curve in HMC fit
Validation

5-fold cross-validation on simulated light curves

obtained excellent fits to other simulated light curves

true parameters always recovered w/in 68% CI

Example fit and true param values
Emulator Fits to Data

$L \left( 10^{43} \text{ erg s}^{-1} \right)$ vs. Time (Days) for various supernova events.
Detailed Look at Fits

SNF20070506-006

Fit Params

<table>
<thead>
<tr>
<th>Residual (10^2 erg s^-1)</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNi (M⊙)</td>
<td>0.70</td>
<td>0.72</td>
<td>0.74</td>
</tr>
<tr>
<td>MIME (M⊙)</td>
<td>0.46</td>
<td>0.50</td>
<td>0.55</td>
</tr>
<tr>
<td>MCO (M⊙)</td>
<td>0.05</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>RNi (M⊙)</td>
<td>0.83</td>
<td>0.92</td>
<td>1.06</td>
</tr>
<tr>
<td>MEj (M⊙)</td>
<td>1.28</td>
<td>1.32</td>
<td>1.35</td>
</tr>
</tbody>
</table>

resid ~ 10% peak L

SN2008ec

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<td>MNi (M⊙)</td>
<td>0.30</td>
<td>0.32</td>
<td>0.33</td>
</tr>
<tr>
<td>MIME (M⊙)</td>
<td>0.49</td>
<td>0.59</td>
<td>0.71</td>
</tr>
<tr>
<td>MCO (M⊙)</td>
<td>0.04</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>RNi (M⊙)</td>
<td>0.58</td>
<td>0.77</td>
<td>0.95</td>
</tr>
<tr>
<td>MEj (M⊙)</td>
<td>0.88</td>
<td>0.99</td>
<td>1.10</td>
</tr>
</tbody>
</table>

95%

68%
reconstructing ejecta structures

SN2011fe

consistent with Chandrasekhar mass

\[ M_{\odot} \]

\[ M_{Ej} \]
\[ M_{IME} \]
\[ M_{Ni} \]
\[ R_{Ni} \]

\sim 0.7 \text{ solar masses of IME}

\sim \text{half a solar mass of nickel 56}

nickel well mixed out into the atmosphere

e tc.
The SN Ia Landscape
Extending the model:
SEDs, Multi-band light curves
Example Spectral Components
Fit broadband photometry

Example 10-band fit to SN2005el realized from SED emulator—still working on plotting confidence intervals.
Sample underlying SED

predicted sed

data
Outlook and Conclusions

\[ 10^{-3} \times 10^3 \times 5 \times 10^5 = 500k \]

cpu hours for a typical multi-band emulator realization

realizations required to fit a light curve / spectrum

total SNe discovered by 2025

- Need to move away from chi-by-eye model-data comparisons and toward systematic, unbiased, model-based population studies
- Will be computationally feasible to perform simulation-based physics inference for large samples of SNe using SN emulators
- Ia parametrized model just an exercise – next step is to use Multi D simulations for Ia’s and other transients.