Radiative transfer in SNIa ejecta
How do we know what we see?

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Motivation

What do we see here?

![SN 2003du spectrum](image)

Log(F$\lambda$) + const

-13.4
-11.5
-8.4
-6.4
-4.6
-2.5
-1.6
-0.6
+0.6
+2.6
+3.7
+6.7
+7.6
+8.5
+9.5
+14.5
+16.6
+18.4
+20.6
+25.6
+30.6
+33.5
+38.4
+44.6
+50.6
+62.5
+71.5
+83.5
+108.4
+141.3
+195.3
+208.7
+220.8
+376.6

(V. Stanishev)
Motivation

What do we see here?

What would we see here?

(V. Stanishev)
Motivation

What do we see here?

SN 2003du

3000 4000 5000 6000 7000 8000 9000

Wavelength [Å]

-15

-10

-5

0

Log($F_{\lambda}$) + const

-13.4

-11.5

-8.4

-6.4

-4.6

-2.5

-1.6

-0.6

+0.6

+2.6

+3.7

+6.7

+9.5

+14.9

+19.5

+20.6

+23.5

+30.4

+50.6

+108.0

+141.3

+208.7

+220.8

+276.0

+376.6

+44.6 +50.6

+62.5

+71.5

+83.5

+108.4 +141.3

+195.3

+208.7

+220.8

+376.6

What would we see here?

just use radiative transfer models...

(F. Röpke)

Daniel Sauer

KITP – 14 Feb 2007
Radiative transfer equation

\[
\frac{1}{h_\nu} \left[ \frac{1}{c} \frac{\partial}{\partial t} + \mathbf{n} \cdot \nabla \right] I_\nu = \frac{1}{h_\nu} \left[ \eta(\mathbf{r}, \mathbf{n}, \nu, t) - \chi(\mathbf{r}, \mathbf{n}, \nu, t) I_\nu \right]
\]
Radiative transfer equation

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\]

Can be solved if source function \( S_\nu = \eta_\nu / \chi_\nu \) is known:

Formal solution (here the plane parallel case)

\[
I_\nu^+(\tau = 0, \mu) = I_\nu^+(\tau_\nu^{\text{max}}, \mu) e^{-\frac{1}{\mu}(\tau_\nu^{\text{max}} - \tau_\nu)} + \int_{\tau_\nu^{\text{max}}}^{\tau_\nu} S_\nu e^{-\frac{1}{\mu}(\tau' - \tau_\nu)} \frac{d\tau'_\nu}{-\mu}
\]

But in general \( \eta_\nu \) and \( \chi_\nu \) are functions of \( I_\nu \)!

⇒ Iteration necessary
Radiative transfer models of SN Ia

**Hydrodynamics**
(from explosion model)
\[ v, \rho, Z, M(^{56}\text{Ni}) \]

**Rate equations**
\[
n_i \sum_{j \neq i} (R_{ij} + C_{ij}) + n_i (R_{ik} + C_{ik})
\]
\[
= \sum_{j \neq i} n_j (R_{ji} + C_{ji}) + n_k (R_{ki} + C_{ki})
\]

**Radiative transfer**
\[
\mu \frac{\partial I_\nu}{\partial r} + \frac{1 - \mu^2}{r} \frac{\partial I_\nu}{\partial \mu} = (S_\nu - I_\nu) \chi_\nu
\]

**Energy Equation**
\[
v \frac{de}{dr} + p_v \frac{d}{dr} \left( \frac{1}{\rho} \right) = \frac{1}{\rho} \int_0^\infty 4\pi \chi_\nu (J_\nu - S_\nu) \, dv
\]

**\( \gamma \) Deposition**
(from light curve code)
\[ L(t), S_\nu^\gamma(r, t), Q_\nu^\gamma(r, t) \]

\[ \text{Deposition} \]
Ingredients of a non-LTE model for SN Ia

Energy pools and transfer

- atomic/ionic internal energy
- energy of radiation field
- thermal kinetic energy

Processes:
- radiative excitation
- radiative de-excitation
- photoionization
- radiative recombination
- collisional de-excitation and recombination
- collisional excitation and ionization
- photoionization
- radiative recombination
- free-free absorption
- free-free emission

(T. Hoffmann)
Radiative transfer models of SNIa (early phases)

...why SNIa are not normal stellar atmospheres.

- fast expanding ejecta with 3D structure
  → time-dependent, 3D problem (special relativity)
- dominated by Fe-group and IME elements
- lots of atomic physics required (lines, cross-sections...)  
- not much true continuum
  → lots of scattering (lines and electrons)
  → temperature mostly decoupled from radiation field.
  → non-thermal “Pseudo-continuum”
  → no useful mean optical depth scale
- energy generation within the ejecta, non-thermal excitation
- high velocities, low densities → non-LTE problem
  ⇒ no simple relationship between macroscopic quantities and micro-physical occupation numbers
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Ti II
Si II
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- high velocities, low densities \( \rightarrow \) non-LTE problem
  \( \Rightarrow \) no simple relationship between macroscopic quantities and
  micro-physical occupation numbers
Radiative transfer models of SNIa (early phases)

Opacity distribution at the “photosphere”

O-star

SNIIa
Radiative transfer models of SNIa (early phases)

Line scattering and fluorescence
Advantages

...yes there are some!

- large grad $\nu \rightarrow$ can use the Sobolev approximation
- homologous expansion $\nu = r/t \Rightarrow \text{grad} \nu = \text{const}$
- no H, He - Fe-group ions have many low-lying levels $\rightarrow$ within an ionization stage LTE is not too bad
- gas temperature only mildly affects radiation field
Advantages

...yes there are some!

- Large \( \nabla v \rightarrow \) can use the Sobolev approximation
- Homologous expansion \( v = r/t \Rightarrow \nabla v = \text{const} \)
- No H, He - Fe-group ions have many low-lying levels → within an ionization stage LTE is not too bad
- Gas temperature only mildly affects radiation field

Depending on the constraints (time, funding...): use suitable approximations to the full problem.
(Semi-)analytic approaches

- D. Arnett (1982) analytic derivation of light curve behaviors
  ⇒ “Arnett’s Rule”: the luminosity at peak is roughly equal to the deposition of $\gamma$-photons

\[ L_p = \alpha R(t_p) M(^{56}\text{Ni}) \]

⇒ Estimate for the $^{56}\text{Ni}$ mass.

- Pinto & Eastman (2000): semi-analytic description of LC properties and opacity treatment for radiative transfer in SNIa
Parameterized approach

SYNOW (D. Branch)

→ highly parameterized
→ line identification in observed spectra
→ Caution: unphysical results possible!
Solving the transfer equation
... toward the full non-LTE problem

Spectra:
- PHOENIX (Baron/Lentz/Hauschildt)
- WMbasic (Pauldrach)
- CMFGEN (Dessart/Hillier)
- HYDRA (Höflich)

→ non-LTE usually stationary and spherically symmetric
→ limited use for analyzing observed spectra
→ “forward modeling” of explosion models
(However: Explosion models are 3D now...)

LC:
Blinnikov/Sorokina, Iwamoto et al, Höflich:
radiation-hydro with approximated non-LTE
low wavelength resolution
Monte Carlo methods

Concept: instead of solving the transfer equation explicitly, follow the random walk of photon packets through the ejecta.

- any geometry possible
- parallelizes easily
- naturally conserves the radiative energy
- resource intensive to get good MC statistics (memory/time)

with Sobolev escape probabilities and MC estimators
→ derive $S$ which can be used in the formal integral (Lucy)
→ reduce MC noise even with low statistics!
Monte Carlo methods

- P. Mazzali/L. Lucy
  - spectra code (approx. non-LTE, sph. sym., no time dep.)
  - LC with gray opacity
  - nebular spectral code (non-LTE with $\gamma$-dep. + positrons)
  - generalisation to 3D: M. Tanaka (early time spectra), K. Maeda (LC, nebular spectra)

- S. Sim: LC (3D, currently gray)

- D. Kasen/R. Thomas: 3D-spectra with time dep. effects (LTE)
Applications (I)

UV spectra of SNIa

- Monte Carlo spectral synthesis code (Mazzali/Lucy)
- stationary, spherically symmetric, W7 density
- stratified composition
- $L$ emitted at the “photosphere”
- Input: $Z(\nu)$, $\rho(\nu)$, $L$, $t$, $v_{\text{ph}}$
The UV part of SNIa spectra

Why is the UV interesting?

- that’s what you see at high-z
- so far not many observations → properties of SNIa in the UV are not as well known as in other bands (variations, correlations?) (see also Lentz et al 2001)
- probes the high velocities → progenitor-properties?
- are SNIa standard candles in the UV?
The UV part of SNIa spectra

**SN 2001ep** (\(t = 29\) d)

- \(L = 6.1 \times 10^{42}\) erg/s
- \(v_{ph} = 6500\) km

**SN 2001eh** (\(t = 29\) d)

- \(L = 1.2 \times 10^{43}\) erg/s
- \(v_{ph} = 7000\) km
Metallicity dependence of the UV

Vary metal abundance for $v > 13000$ km/s
Effect on the photometry

- model flux integrated in WFPC2 filters
- change in $m$ relative to base model

$\Rightarrow$ $L$ can go both ways!
Interpretation

- reverse fluorescence \textcolor{red}{red} \rightarrow \textcolor{blue}{blue} is an important process in the outer part
- emitted spectrum depends on line distribution in wavelength space (see Pinto&Eastman 2000)
Conclusions from the UV models

- UV flux can react sensitively to changes in the physical conditions in the outermost layers of the ejecta
- increased metallicity can lead to an increased UV-flux
Application (II)

3D light curves from off-center ignition SNIa

Observational evidence?
- sources for intrinsic scatter in properties of “normal” SNIa
- outliers and odd-balls
- source of polarization?

Theoretical aspects
- uncertainty in the ignition process could lead to asymmetries
- DDT?
- other detonation scenarios (Plewa et al 2004, Röpke et al 2007)

(→ Stuart Sim at the conference)
SNIIa light curves from different viewing angles

- Monte Carlo LC code (→ Sim 2007)
- use Monte Carlo estimators to extract information needed for the formal solution as last step in the simulation (Lucy 2005)
- 3D time-dependent transport and energy deposition for $\gamma$-photons.
- gray bolometric treatment for optical photons. (composition dependence: $\kappa \propto 0.9 X_{FeGr} + 0.1$)
Off-center ignition SNIa
(Röpke et al. 2007)
Viewing angle effect

Hubble diagram
(Stritzinger&Leibundgut 2005)
→ model cannot be ruled out by the dispersion of observed objects!
Main conclusion

if a significant fraction of SNIa explode like this...

- viewing angle effects could contribute to the intrinsic scatter in the Hubble diagram
- effect unlikely to follow the known LC-width relation
- asymmetry of the probability distribution → potential observational bias

- ... topic needs further investigation