Radiative transfer in SNIa ejecta

How do we know what we see?

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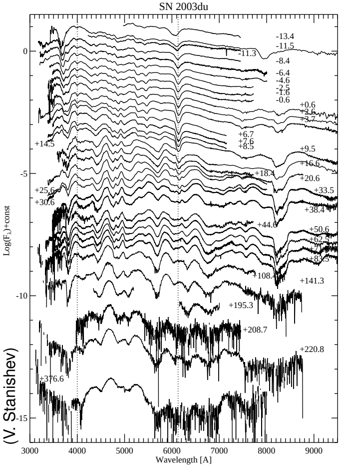
Motivation

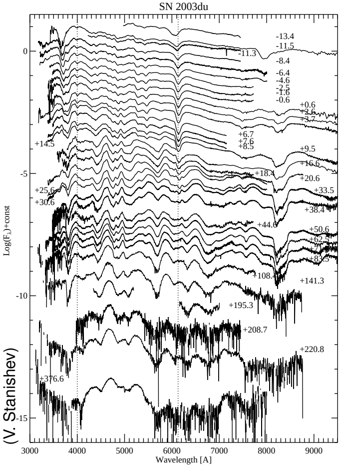
What do we see here?



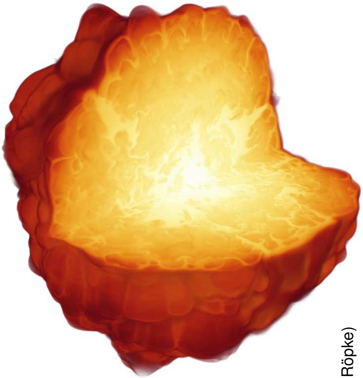
Motivation

What do we see here?

What would we see here?



(V. Stanishev)



(F. Röpke)

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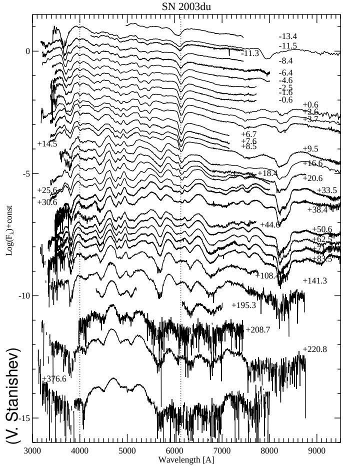

?

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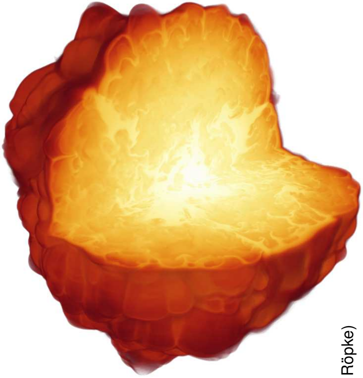

(F. Röpke)

just use radiative transfer models...

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

Matter

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

Radiation

Radiative transfer equation

Matter

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Radiation

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

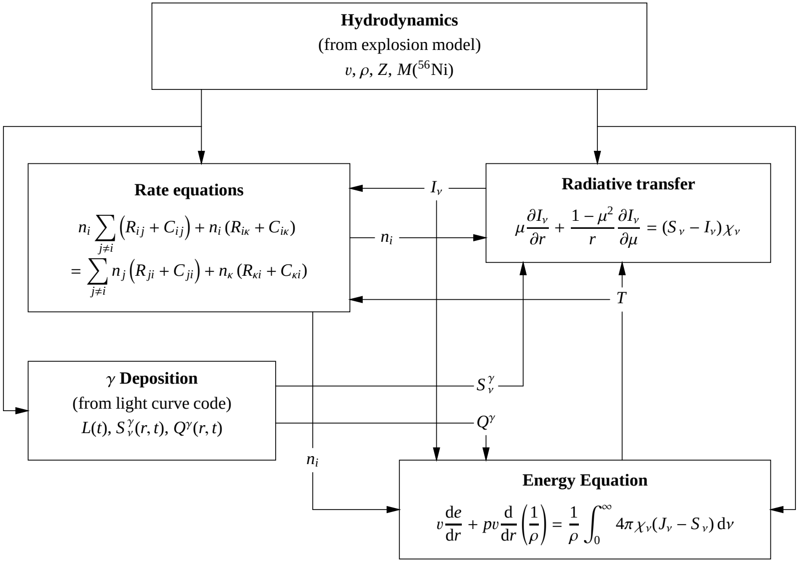
Formal solution (here the plane parallel case)

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

But in general η_ν and χ_ν are functions of I_ν!

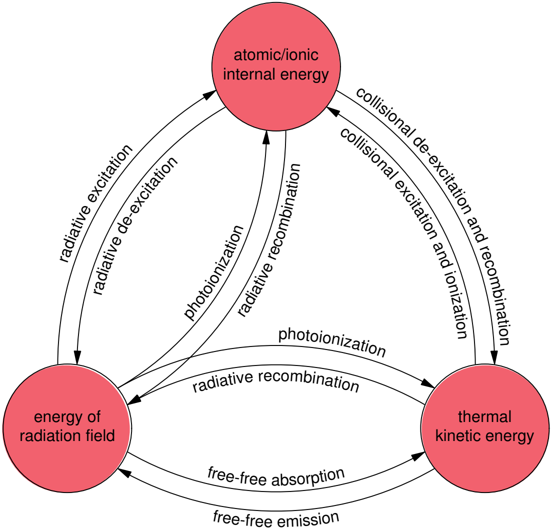
$\Rightarrow$ Iteration necessary

Radiative transfer models of SNIa



Ingredients of a non-LTE model for SN Ia

Energy pools and transfer



(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

Radiative transfer models of SNIa (early phases)

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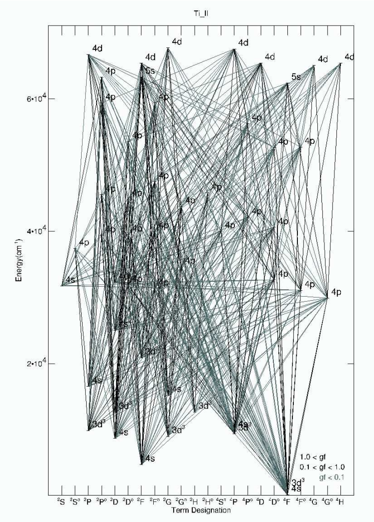
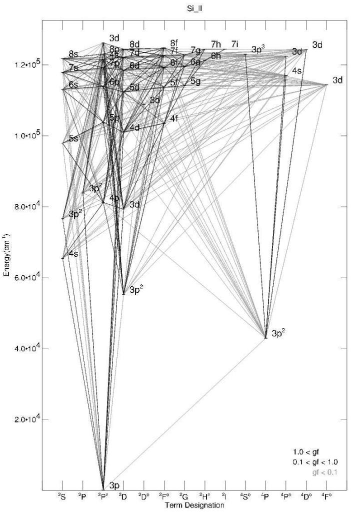
TiII





SiII

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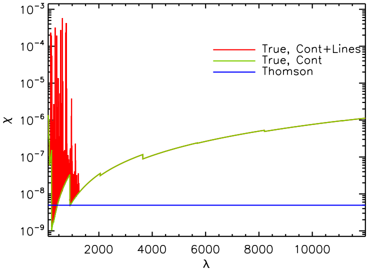
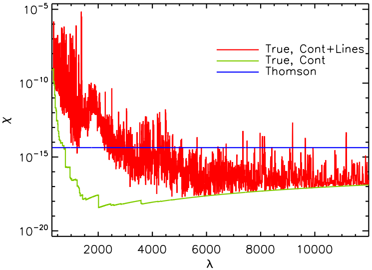
Radiative transfer models of SNIa (early phases)

Opacity distribution at the "photosphere"



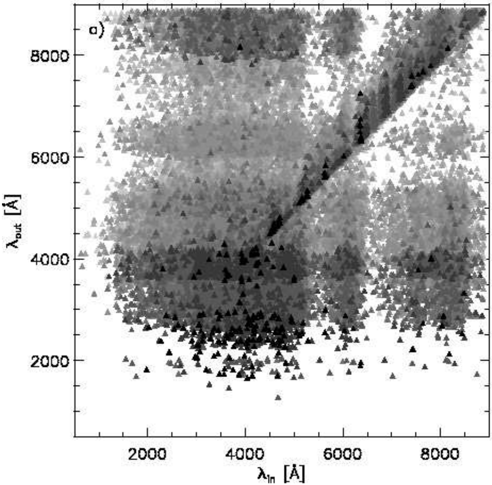
O-star



SNIa

Radiative transfer models of SNIa (early phases)

Line scattering and fluorescence



Advantages

. . . yes there are some!

- large grad $v \rightarrow$ can use the Sobolev approximation
- homologous expansion $v = r/t \Rightarrow \text{grad}v = \text{const}$
- 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

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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 γ-photons

$$L_{\mathrm{p}} = \alpha R(t_{\mathrm{p}}) M(^{56}\mathrm{Ni})$$

⇒ Estimate for the ^{56}Ni mass.

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

Parameterized approach

SYNOW (D. Branch)

$\longrightarrow$ highly parameterized

$\longrightarrow$ line identification in observed spectra

$\longrightarrow$ 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)

$\longrightarrow$ non-LTE usually stationary and spherically symmetric

$\longrightarrow$ limited use for analyzing observed spectra

$\longrightarrow$ “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
$\rightarrow$ derive S which can be used in the formal integral (Lucy)

$\longrightarrow$ reduce MC noise even with low statistics!

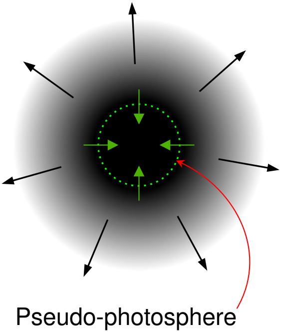
Monte Carlo methods

- P. Mazzali/L. Lucy
  - spectra code (approx. non-LTE, sph. sym., no time dep.)
  - LC with gray opacity
  - nebular spectral code (non-LTE with γ-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: $Z(v)$, $\rho(v)$, L, t, v_{ph}



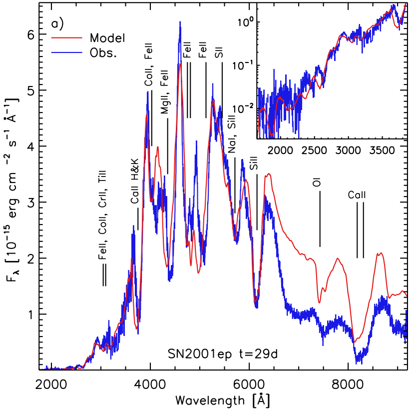
The UV part of SNIa spectra

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

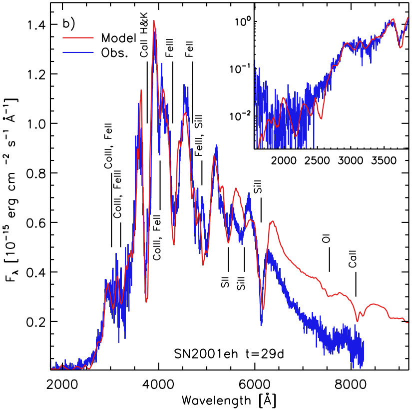
SN 2001ep ($t = 29\,\mathrm{d}$)



$L = 6.1 \times 10^{42}$ erg/s

$v_{ph} = 6500$ km

SN 2001eh ($t = 29\,\mathrm{d}$)

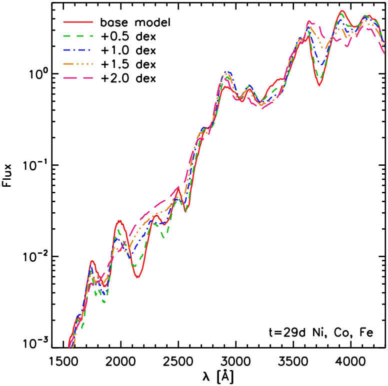


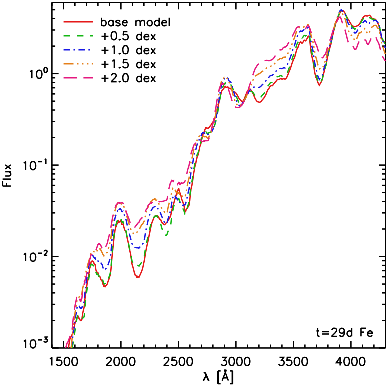
$L = 1.2 \times 10^{43}$ erg/s

$v_{ph} = 7000$ km

Metallicity dependence of the UV

Vary metal abundance for $v > 13000$ km/s

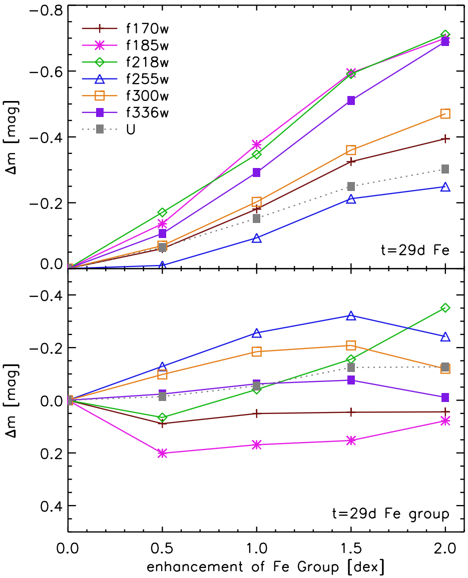




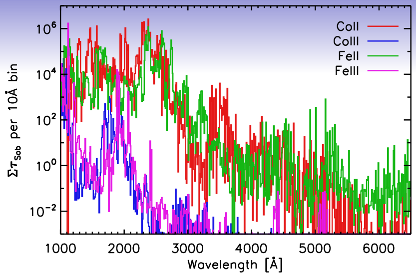
Effect on the photometry

- model flux integrated in WFPC2 filters
- change in m relativ to base model

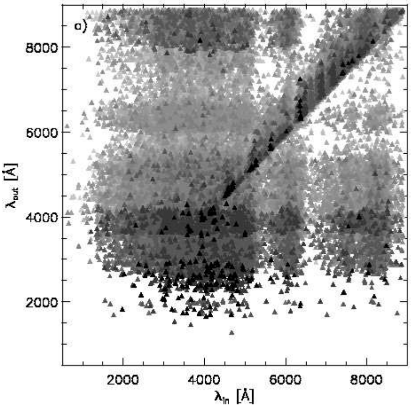
⇒ *L* can go both ways!



Interpretation



- reverse fluorescence red → 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)

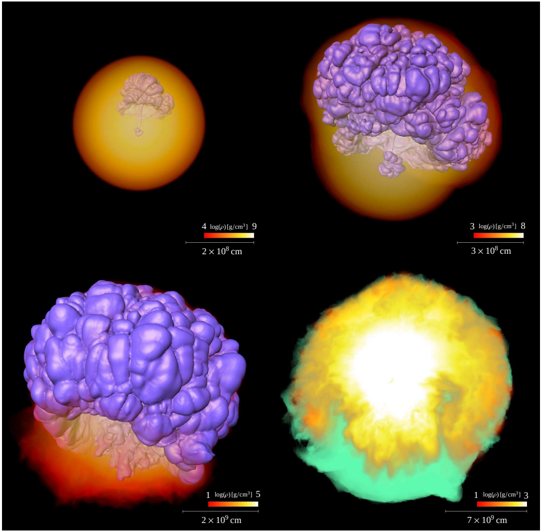
(→ Stuart Sim at the conference)

SNIa light curves from different viewing angles

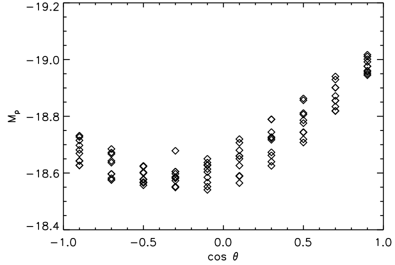
- Monte Carlo LC code ($\rightarrow$ Sim 2007)
- use Monte Carlo estimators to extract information needed for the formal solution as last step in the simulation (Lucy 2005)
- 3D time-dependent transport and energy deposition for γ-photons.
- gray bolometric treatment for optical photons. (composition dependence: $\kappa \propto 0.9 X_{\mathrm{FeGr}} + 0.1$)

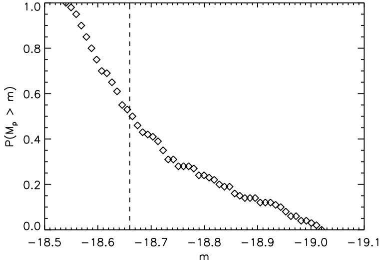
Off-center ignition SNIa

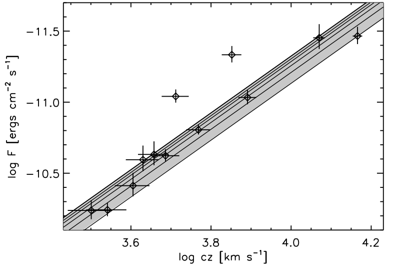
(Röpke et al. 2007)



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 intrisic scatter in the Hubble diagram
- effect unlikely to follow the known LC-width relation
- asymmetry of the probability distribution
  $\rightarrow$ potential observational bias

- …topic needs further investigation