New results on sub-Chandrasekhar mass explosions of White Dwarfs

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XXVIth IAP Annual Colloquium
Paris 28.06.-02.07.2010

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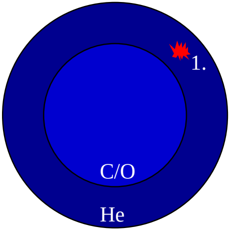
The double detonation scenario

- CO WD accretes He from a He-rich companion star
- He flash triggers a detonation in the shell



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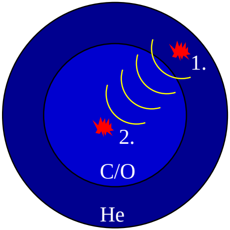

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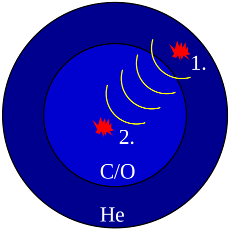

\+ WD mass direct parameter to explain range of observed ^{56}Ni yields

\+ Progenitors should be frequent

\+ Possible link to stellar population

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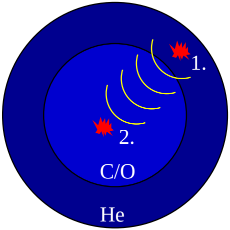

+ WD mass direct parameter to explain range of observed ^{56}Ni yields
+ Progenitors should be frequent
+ Possible link to stellar population
- Robustness of core ignition
- Problems in fitting observational data (Höflich & Khokhlov 1996, Nugent et al. 1997)

New hydro simulations

- Less massive helium shells than previously thought may detonate (Bildsten et al. 2007)
- Can these shell detonations trigger core detonations?

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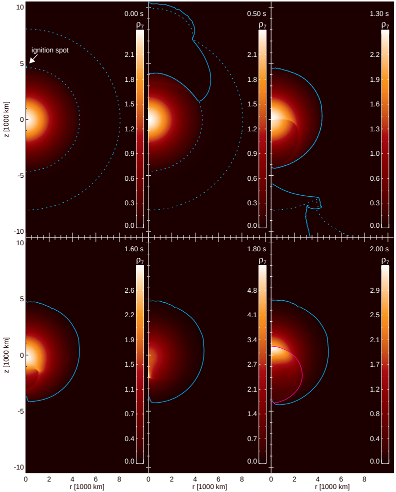
- Fink et al. (2010) investigate six models

Model	$M_{\mathrm{tot}}\,/\,M_{\odot}$	$M_{\mathrm{core}}\,/\,M_{\odot}$	$M_{\mathrm{shell}}\,/\,M_{\odot}$
1	0.936	0.810	0.126
2	1.004	0.920	0.084
3	1.080	1.025	0.055
4	1.164	1.125	0.039
5	1.293	1.280	0.013
6	1.389	1.385	0.004

New hydro simulations

- Less massive helium shells than previously thought may detonate (Bildsten et al. 2007)
- Can these shell detonations trigger core detonations?

- Fink et al. (2010) investigate six models
    - Surface reduction increases shock strength
    - All models successfully ignite a detonation in the C/O core

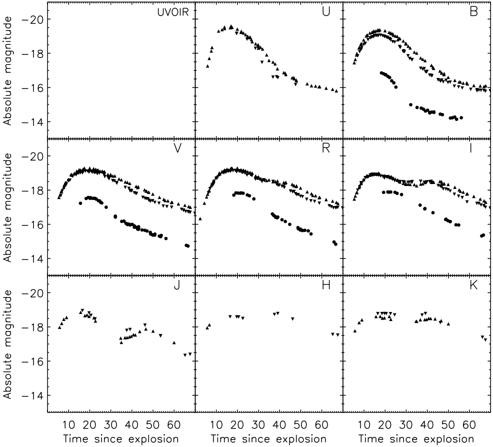


Now calculate synthetic observables for these models applying the ARTIS code (Kromer & Sim 2009, Sim 2007)

- Multi-wavelength: γ to NIR
- Time-dependent
- Fully 3D
- Detailed solution of ionisation and thermal balance equation
- Detailed treatment of radiation/matter interactions

⇒ Parameter-free prediction of synthetic observables

Synthetic observables (Kromer et al., ApJ in press)



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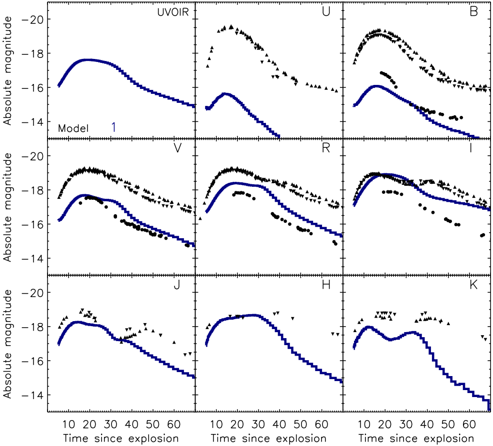
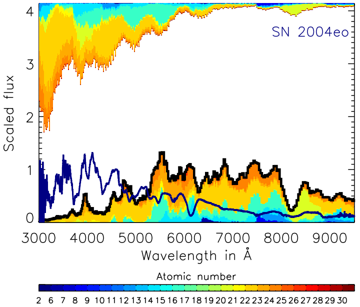


Model 1	Core	Shell
M	0.810	0.126
$M(^{56}\mathrm{Ni})$	1.7×10^{-1}	8.4×10^{-4}
$M(\mathrm{Ti})$	3.9×10^{-4}	1.1×10^{-2}
$M(\mathrm{Si})$	2.7×10^{-1}	4.8×10^{-4}



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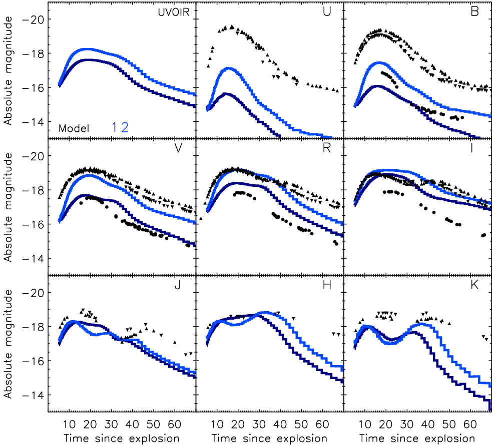
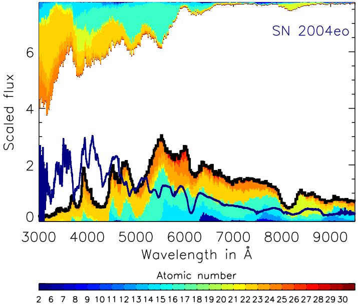


Model 2	Core	Shell
M	0.920	0.084
$M(^{56}\mathrm{Ni})$	3.4×10^{-1}	1.1×10^{-3}
$M(\mathrm{Ti})$	4.6×10^{-4}	7.8×10^{-3}
$M(\mathrm{Si})$	2.5×10^{-1}	2.5×10^{-4}



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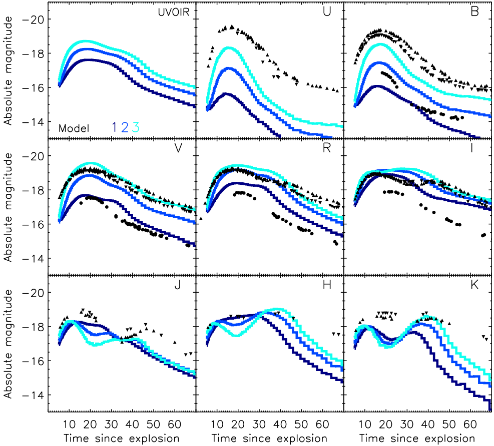
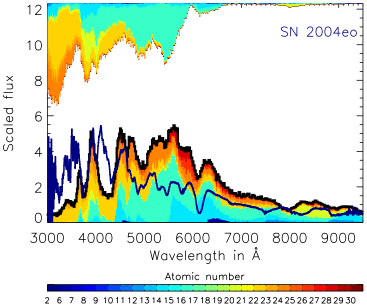


Model 3	Core	Shell
M	1.025	0.055
$M(^{56}\mathrm{Ni})$	5.5×10^{-1}	1.7×10^{-3}
$M(\mathrm{Ti})$	4.5×10^{-4}	4.4×10^{-3}
$M(\mathrm{Si})$	2.1×10^{-1}	1.4×10^{-4}



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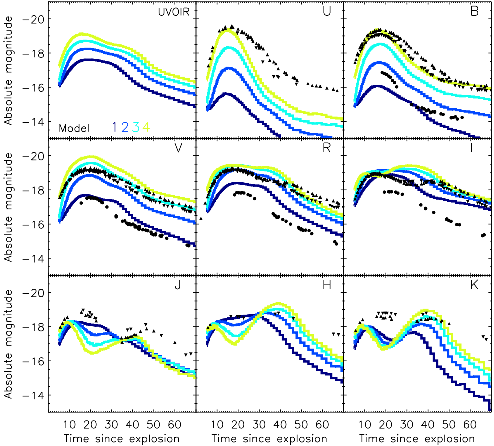
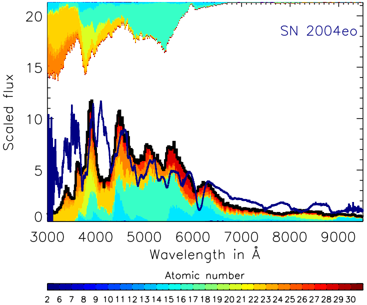


Model 4	Core	Shell
M	1.125	0.039
$M(^{56}\mathrm{Ni})$	7.8×10^{-1}	4.4×10^{-3}
$M(\mathrm{Ti})$	3.8×10^{-4}	2.2×10^{-3}
$M(\mathrm{Si})$	1.4×10^{-1}	4.7×10^{-4}



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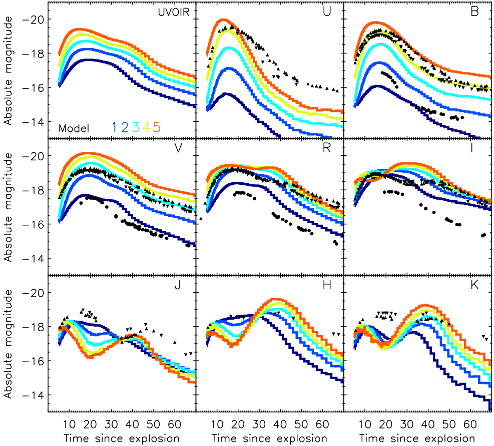
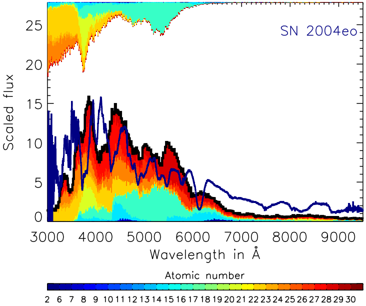


Model 5	Core	Shell
M	1.280	0.013
$M(^{56}\mathrm{Ni})$	1.05	1.5×10^{-3}
M(Ti)	2.1×10^{-4}	6.8×10^{-4}
M(Si)	6.1×10^{-2}	1.6×10^{-4}



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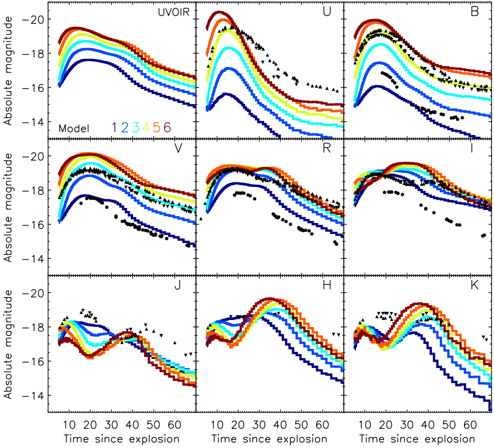
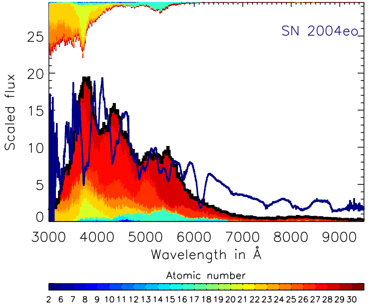


Model 6	Core	Shell
M	1.385	0.004
$M(^{56}\mathrm{Ni})$	1.10	5.7×10^{-4}
$M(\mathrm{Ti})$	7.1×10^{-5}	1.5×10^{-4}
$M(\mathrm{Si})$	1.5×10^{-2}	1.3×10^{-4}



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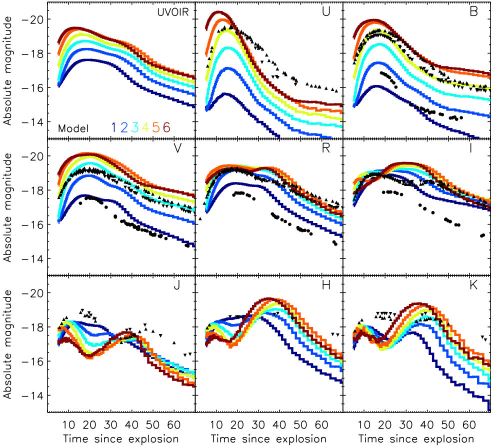
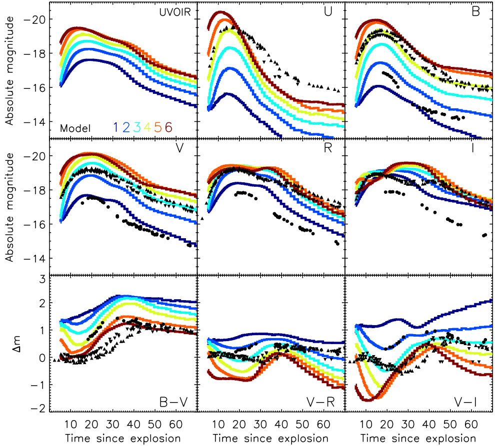


Promising models

- Populate a large range in brightness
- Despite low mass, time-evolution OK

Synthetic observables (Kromer et al., ApJ in press)



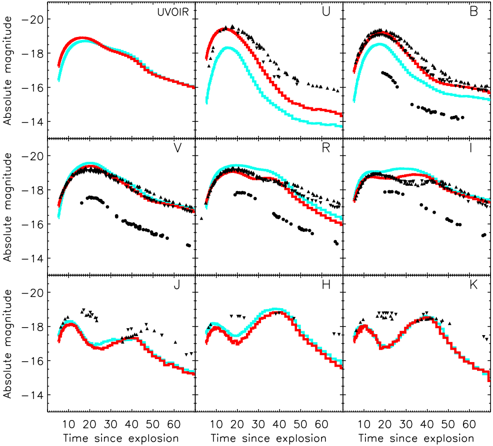
Promising models

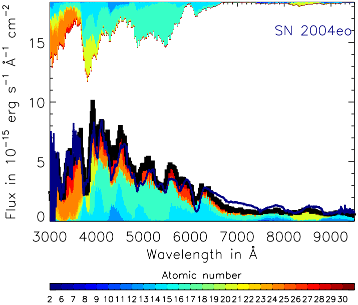
- Populate a large range in brightness
- Despite low mass, time-evolution OK

Problems

- Peculiar light curves and spectra
- Colours too red

Influence of the helium shell

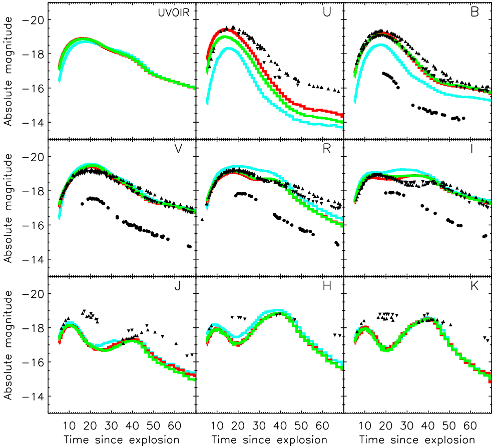


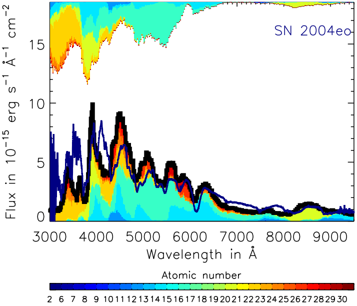


Model 3

Shell-less toy version of Model 3

Prospects: modifying the initial shell composition





Model 3

Shell-less toy version of Model 3

Model 3, initially 34 % ^{12}C in shell

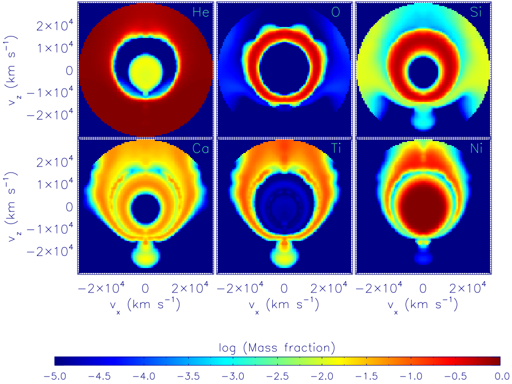
Summary

- Secondary core detonation ignites even for minimum helium shell masses (Fink et al. 2010)
- Models predict correct range of brightness and rise times (Kromer et al. arXiv:1006.4489)

- However, spectral features and colours do not agree
- Origin of this discrepancy is the helium shell material
- Tiny amounts of iron-group elements in outer layers cause severe problems

- Nucleosynthesis?
- Radiative transfer?

Model 3 as an example for line-of-sight effects



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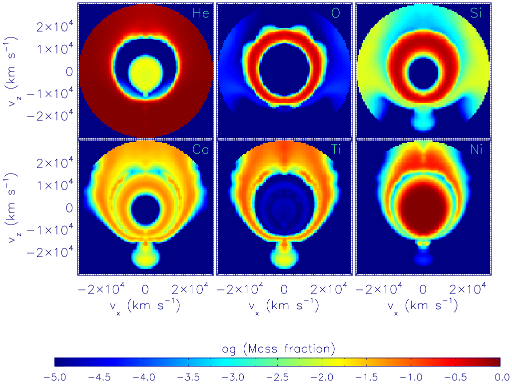

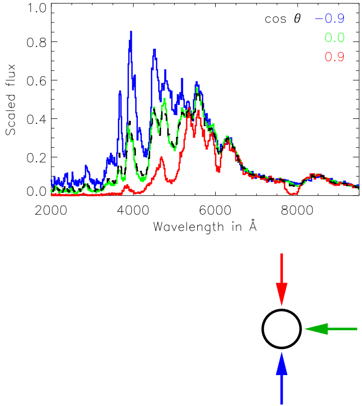

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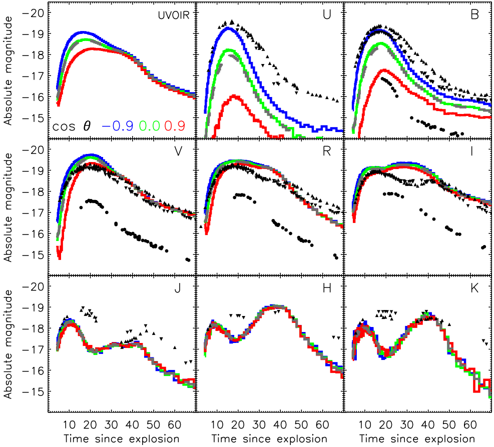
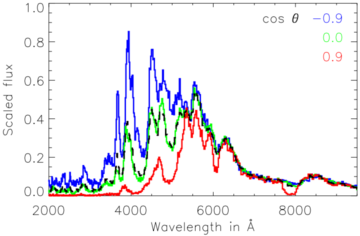
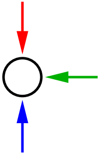






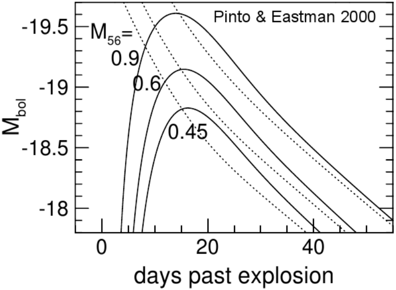
Model 3 as an example for line-of-sight effects

Sim et al. (2010) investigated pure detonations of naked sub-Chandrasekhar mass WDs

- Set of 1D models (0.88 – 1.15 $M_\odot$)
- Hydrodynamics, nucleosynthesis and radiative transfer

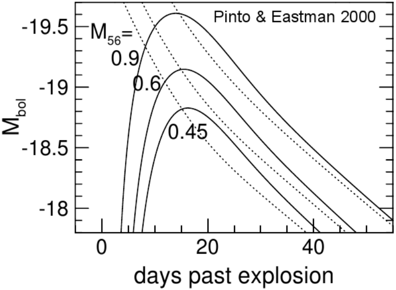
- Compared to observed SNe Ia the models explain
  - Range of brightness
  - Rise times
  - Colours
  - Silicon-line ratio
  - Velocity evolution of silicon lines
  - Width-luminosity relation

Outline of the problem



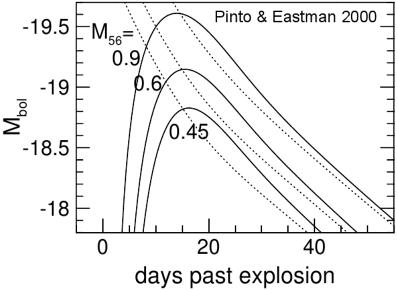
Outline of the problem

- Multi-wavelength



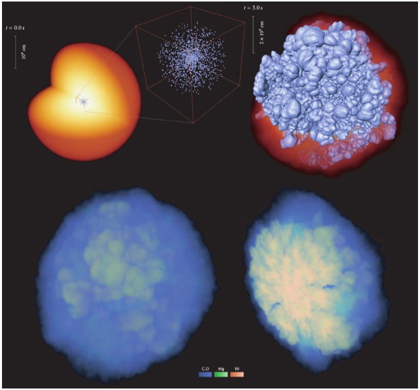
Outline of the problem

- Multi-wavelength
- Time-dependent



Outline of the problem

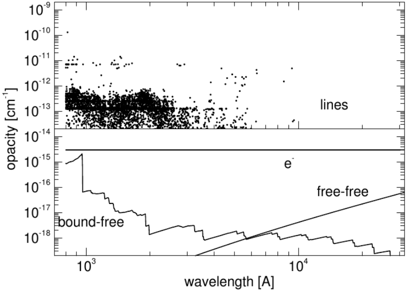
- Multi-wavelength
- Time-dependent
- Multi-dimensional



Röpke et al. 2007

Outline of the problem

- Multi-wavelength
- Time-dependent
- Multi-dimensional
- Opacity dominated by lines



Pinto & Eastman 2000

Outline of the problem

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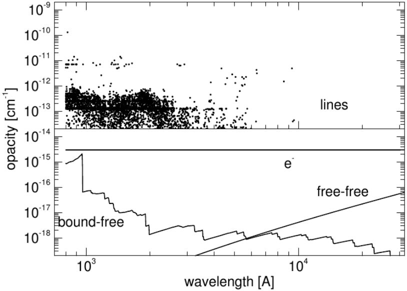
- Non-LTE effects important



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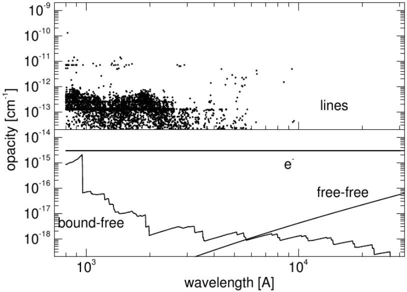


Pinto & Eastman 2000

But some simplifications

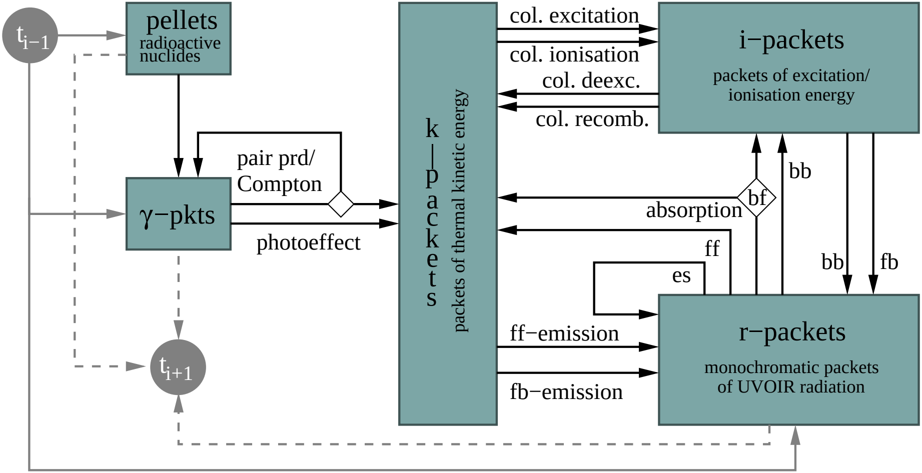
- Homologous expansion
- Sobolev approximation
- Statistical and thermal equilibrium

Monte Carlo method

- Based on quantized energy flow: energy packets
- Follow the packets propagation through the ejecta
- Microphysical description of radiation/matter interactions
  - ⇒ Purely local
  - ⇒ Suitable for complex geometries & time-dependence
- Extract spectra and light curves by binning of escaping packets

- Use indivisible energy packets (Abbott & Lucy 1985; Mazzali & Lucy 1993; Lucy 1999, 2005)
  - ⇒ Implicit energy conservation
  - ⇒ Statistical and thermal equilibrium enforceable (Lucy 2002, 2003)

The framework of ARTIS (Kromer & Sim 2009)



Calculation of transition probabilities requires

1. Specification of atomic data

2. Population numbers (excitation/ionization state of the plasma)

3. Local radiation field J_ν

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   - CD23: 4×10^5 bound-bound transitions
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    - Complete set of NLTE rate equations too expensive
    - Instead approximate NLTE treatment (detailed)
        - Consistent solution of photoionization and thermal balance
        - Boltzmann excitation formula
    - For comparison: LTE treatment (simple)
        - Saha ionization formula
        - Boltzmann excitation formula

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3. Local radiation field J_ν
    - Extractable from MC simulation, but computationally prohibitive
    - Nebular approximation for detailed treatment: $J_\nu = WB_\nu(T_\mathrm{R})$
    - Black body approximation for simple treatment: $J_\nu = B_\nu(T_\mathrm{J})$

Excitation/ionisation treatment

- detailed solution of the ionisation balance
  - assume photoionisation equilibrium

$$\frac{N_{j,k}}{N_{j+1,k}n_\mathrm{e}} = \frac{\alpha^\mathrm{sp}_{j,k}}{\Gamma_{j,k}}$$

  - derive $\Gamma_{j,k}$ from Monte Carlo simulation

$$\Gamma_{j,k} \equiv \frac{g_{0,j,k}}{U_{j,k}n_{0,j,k}} \cdot \sum_{i=0}^{\mathcal{N}_{j,k}} n_{i,j,k}\gamma_{i,j,k}$$

- simultaneous solution of the thermal balance equation $\Rightarrow T_\mathrm{e}$
  - heating rates from Monte Carlo simulation
  - cooling rates evaluated at T_e
- use Boltzmann formula evaluated at $T_\mathrm{J} = \frac{\pi}{\sigma^4}\langle J\rangle$ for excitation

Radiation field

- exact radiation field extractable by Monte Carlo estimators

$$J_\nu \mathrm{d}\nu = \frac{1}{4\pi \Delta t V} \sum_{\mathrm{d}\nu} \epsilon_\nu^{\mathrm{cmf}} \mathrm{d}s$$

- *but*: computationally prohibitive

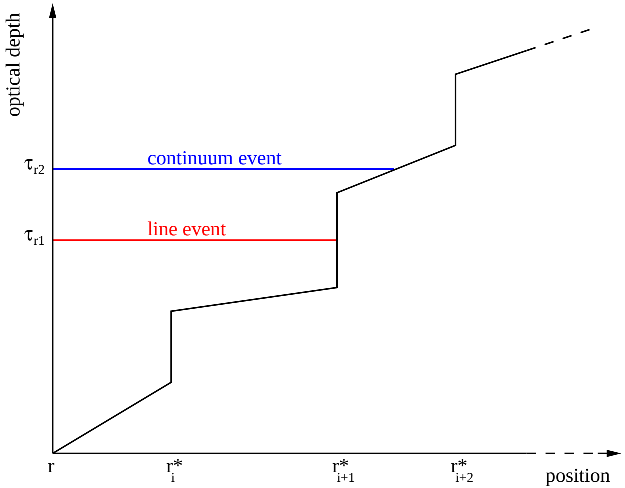
⇒ parameterise local radiation field in nebular approximation

$$J_\nu = W \cdot B_\nu (T_R)$$

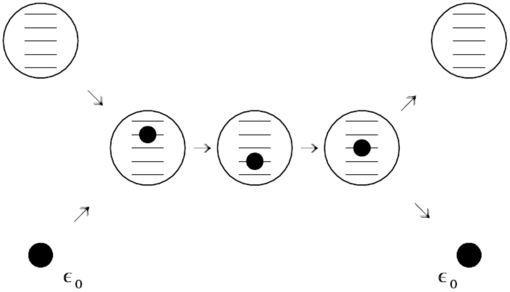
dilution factor W and radiation temperature T_R defined as

$$W = \frac{\pi}{\sigma T_\mathrm{R}^4} \langle J \rangle \qquad T_\mathrm{R} = \frac{h \langle \nu \rangle}{3.832 k_\mathrm{B}}$$

Selecting the next event

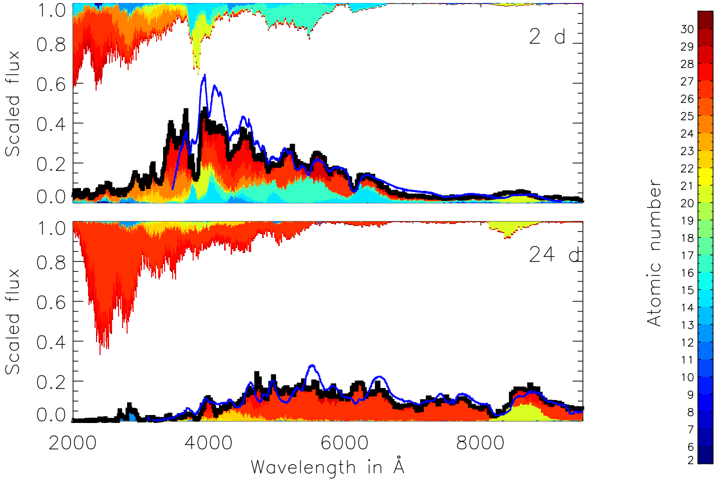


Macro atom formalism

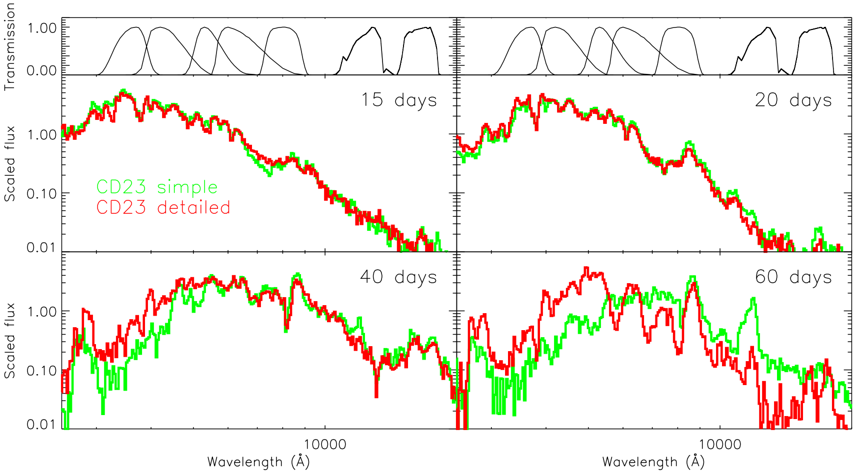


Lucy 2002

Spectral evolution



Influence of ionisation treatment



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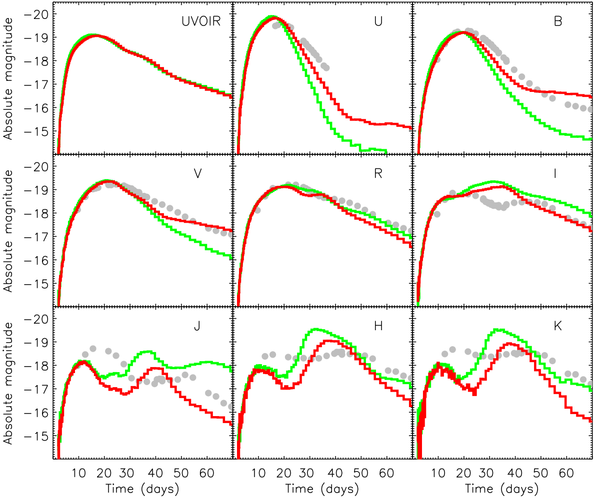
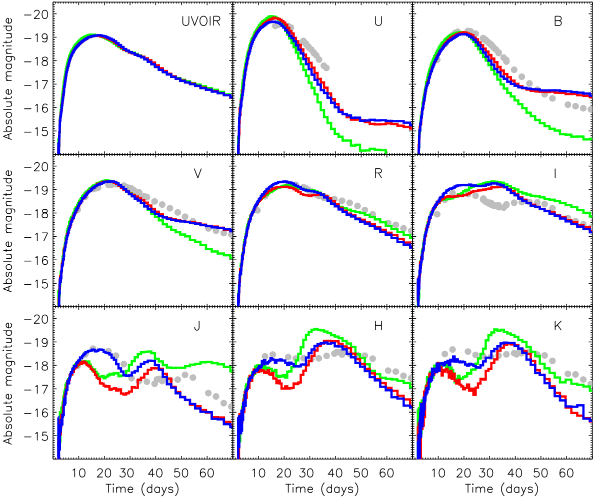


- circles: SN 2001el (Krisciunas 2003)
- CD23 simple
- CD23 detailed

Influence of atomic data



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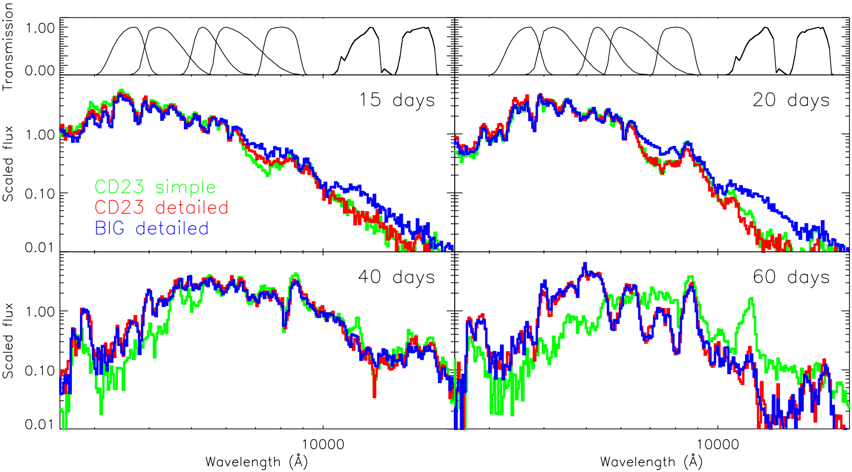
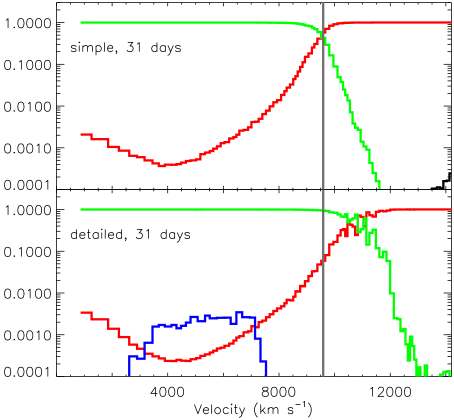


Influence of ionisation treatment

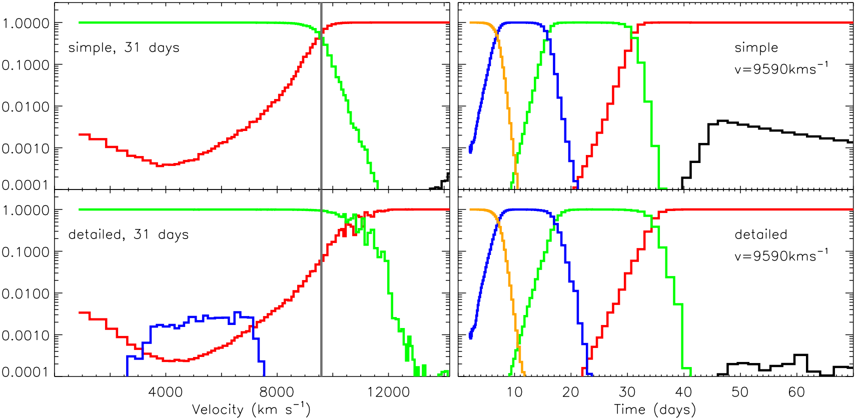
Ionisation fractions of Fe I, II, III, IV, V
versus radial velocity



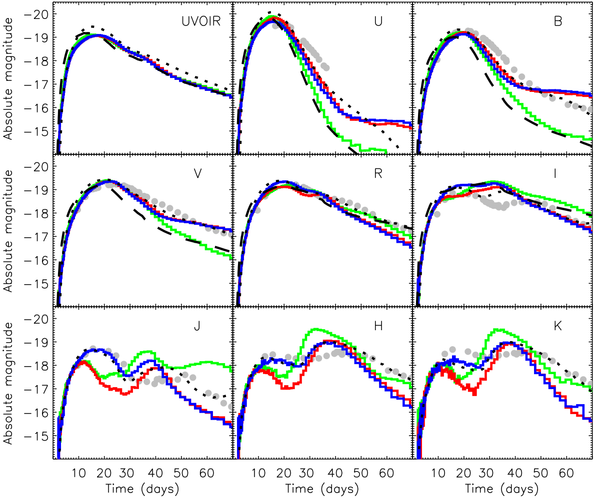
Influence of ionisation treatment

Ionisation fractions of Fe I, II, III, IV, V

versus radial velocity versus time



Broad-band light curves



- blue: big detailed
- red: CD23 detailed
- green: CD23 simple
- dashed: STELLA (Blinnikov 1998)
- dotted: SEDONA (Kasen 2006)
- circles: SN 2001el (Krisciunas 2003)

Flux redistribution