Non-LTE Time-Dependent Radiative Transfer of Supernova Ejecta

Luc Dessart

(Laboratoire d'Astrophysique de Marseille, France)

D. John Hillier

(University of Pittsburgh, USA)

PNPS

Synopsis

- ✓ Summary of supernova ejecta properties. Relevant quantities.
- ✓ Nature of the radiative transfer problem
- ✓ Step 1: non-LTE, D/Dt=0 Steady-State approach
- ✓ Step 2: non-LTE, De/Dt, Dn/Dt $\neq$ 0, but DJ/Dt = 0
- ✓ Step 3: non-LTE, De/Dt, Dn/Dt, & DJ/Dt $\neq$ 0
- ✓ Past, Ongoing and Future Projects

Summary of SN Ejecta Properties
Sequence of Events

- ✓ Dynamical phase:

  - Initial seconds: Sudden Release of Energy (shock and/or combustion) unbinds progenitor.

  - From seconds to days: acceleration to asymptotic velocity ($dP/dr \neq 0$; $P_{rad} >> P_{gas}$) and homologous expansion

- ✓ Kinematic Phase/Homologous Expansion:

  $Dv/Dt = 0$ - No Hydro (ignoring interaction).

  $V(m,t) = \text{const.}$

  $R(m,t) >> R(m,t_0)$

  $R(m,t) \sim V(m,t) \times t$

  $\rho(m,t) \sim \rho(m,t_0)\,(t_0/t)^3$

  Energy budget: **heating** (unstable isotopes + recombination)

  cooling (expansion + radiation)

Summary of SN Ejecta Properties
Connection to Light Curves

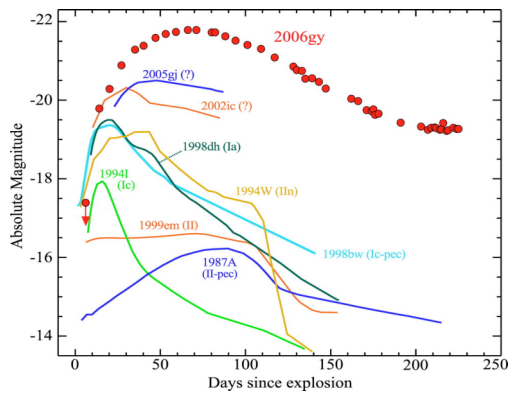
- Photosphere at ~8000K and 10^{15}cm => Large Luminosity L_{bol} (t)
- $\int dt\, L_{bol} << \int dm\, (e_{kin} + e_{th} + e_{rad})$: Radiation does work instead of escaping
- Radiative losses are key diagnostics of progenitor and ejecta properties

- ✓ Variations with R_{star}: ~10^8 (WD) to ~10^{13}cm (RSG). Impacts cooling losses due to expansion
- ✓ Variations with M_{star}: 1 to 10-20 Msun. Impacts <v(m)> for given $E_{explosion}$
- ✓ Variations in Composition: impacts κ_{es} (cm^2/g) through # of free electrons per baryon

➔Impacts $\tau = \kappa\, M/R^2$ and $t_{diffusion} \sim \tau\, R/c$; Light curve conditioned by the time it takes to release stored ejecta energy

- ✓ Variations in Explosion properties: $E_{explosion}$ impacts <v(m)> (modulo M_{star}); Radioactive isotope yields (half-life of weeks to months) affecs long-term ejecta thermal evolution

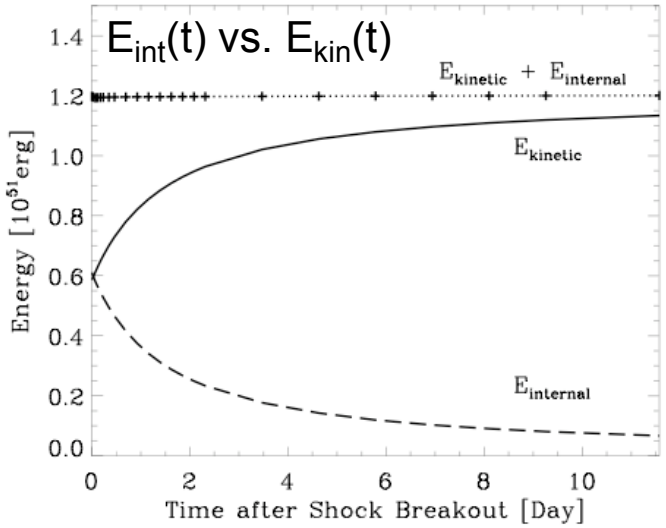
One non-spectroscopic SN classification:
Type I: Small star with little mass
Type II: Big star with Large mass



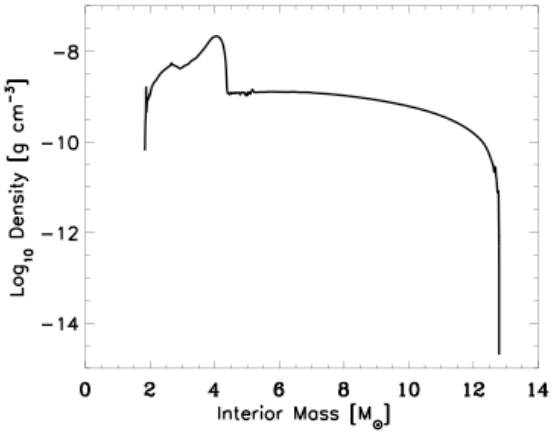
Summary of SN Ejecta Properties

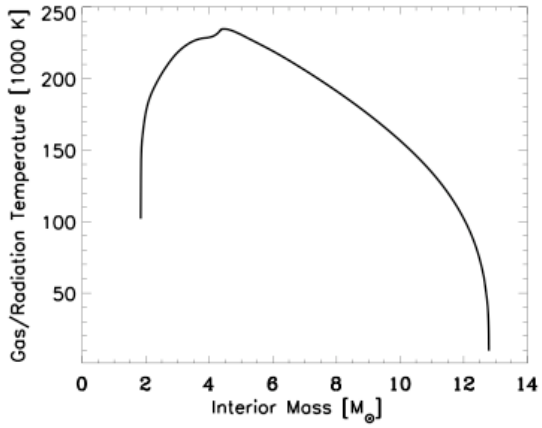
Illustration with a RSG Progenitor (Type II-P SN)

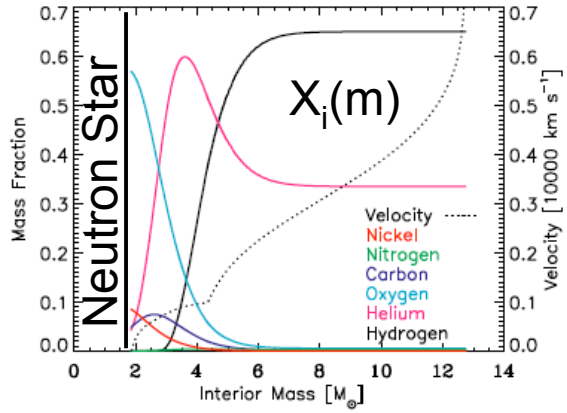
- ✓ E_{expl}=1.2 x 10^{51}erg; $\int dt\, L_{bol}$~10^{49}erg
- ✓ At shock emergence, E_{int}~E_{kin}
- ✓ Homologous Expansion reached after ~10d
- ✓ Chemical stratification: H, He, O (main shells).
- ✓ Radioactive isotopes at depth (v(m)<1000km/s)
- ✓ Fast Expansion => Low density => Dominance of scattering over collisional processes, non-LTE and time dependent effects.



Type II-Plateau SN ejecta at 4 days (RSG progenitor)







Radiative Transfer Problem

Aim: Model evolution of Gas+Radiation from explosion (large τ) until nebular phase (small τ) with 1D non-LTE model atmosphere code CMFGEN

Track:

1. Changes in the radiation (I, J, H)
2. Changes in the gas (e, N_i, N_e, κ) + sources (decay)
3. Coupling between gas and radiation
4. Changes in composition ($X_i(t)$ through decay)

Use Comprehensive Atomic dataset for microphysics (κ, η, κ_{th} vs. κ_{scat})

Non-LTE Time-Dependent Radiative Transfer Problem

Gas

Rate Equation: $$\frac{\partial n_i}{\partial t} + \nabla.(n_i \vec{V}) = \sum_{j \neq i} (n_j R_{ji} - n_i R_{ij})$$

Lagrangian Form: $$\rho \frac{D(n_i/\rho)}{Dt} = \frac{1}{r^3}\frac{D(r^3 n_i)}{Dt} = \sum_{j \neq i} (n_j R_{ji} - n_i R_{ij})$$

Coupling

Energy Equation: $$\rho \frac{De}{Dt} - \frac{P}{\rho}\frac{D\rho}{Dt} = 4\pi \int_0^\infty \chi_\nu (J_\nu - S_\nu)\, d\nu$$ + De_{decay}/Dt

where e = internl energy/unit mass

$$= \frac{\frac{3}{2}kT(n + n_e)}{\mu m_H n} + \frac{\sum n_i E_i}{\mu m_H n}$$ (Excitation + Ionization)

Radiation

RTE 0th moment: $$\frac{1}{cr^3}\frac{D(r^3 J_\nu)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 H_\nu)}{\partial r} - \frac{\nu V}{rc}\frac{\partial J_\nu}{\partial \nu} = \eta - \chi J_\nu$$

RTE 1st moment: $$\frac{1}{cr^3}\frac{D(r^3 H_\nu)}{Dt} + \frac{1}{r^2}\frac{\partial(r^2 K_\nu)}{\partial r} + \frac{K_\nu - J_\nu}{r} - \frac{\nu V}{rc}\frac{\partial H_\nu}{\partial \nu} = -\chi H_\nu$$

Step 1: Non-LTE Steady-State Approach

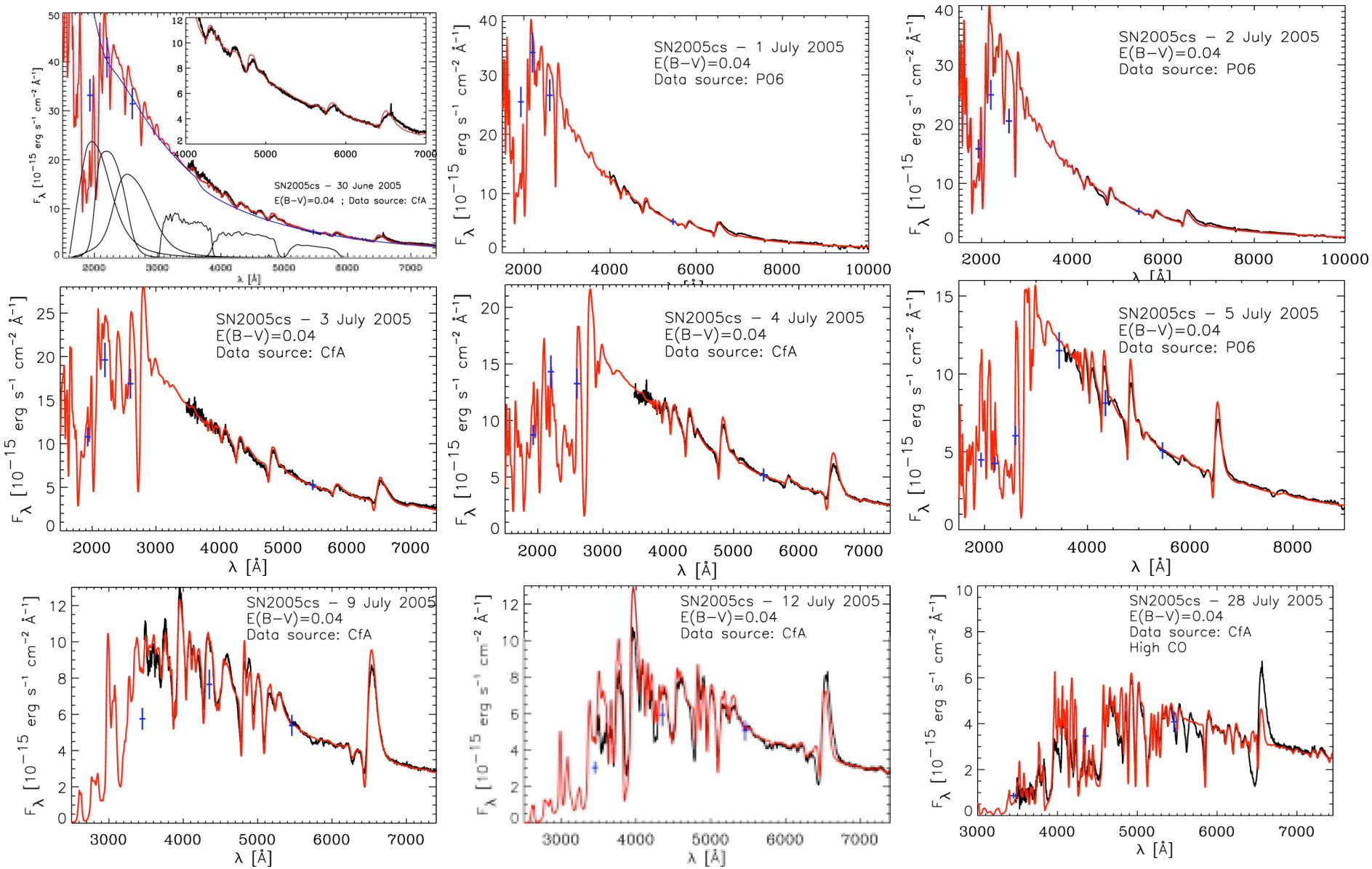
- ✓ Non-LTE treatment
- ✓ Ignore all D/Dt terms
- ✓ Focus on Decoupling region: $\tau \in [10^{-8}, 10^{2}]$
- ✓ Assume Diffusion Approximation at base (CMF flux)
- ✓ Analytical Description of SN Ejecta: $L_{0,CMF}$, R_0, $\rho(R)$, $v(R)$
- ✓ Chemical Homogeneity: $X_i(R) = X_i$
- ✓ Approach: Guess and check parameters describing SN ejecta properties until sensible fit (stellar approach)

- ✓ Focus on Type II SNe because well-defined diffusing inner boundary, massive homogeneous hydrogen shell, little ^{56}Ni

Step 1: Non-LTE Steady State Approach

Application: Modeling of Young Type II SNe

The case of the Type II-P SN 2005cs in NGC 5194 (Dessart et al. 2008)



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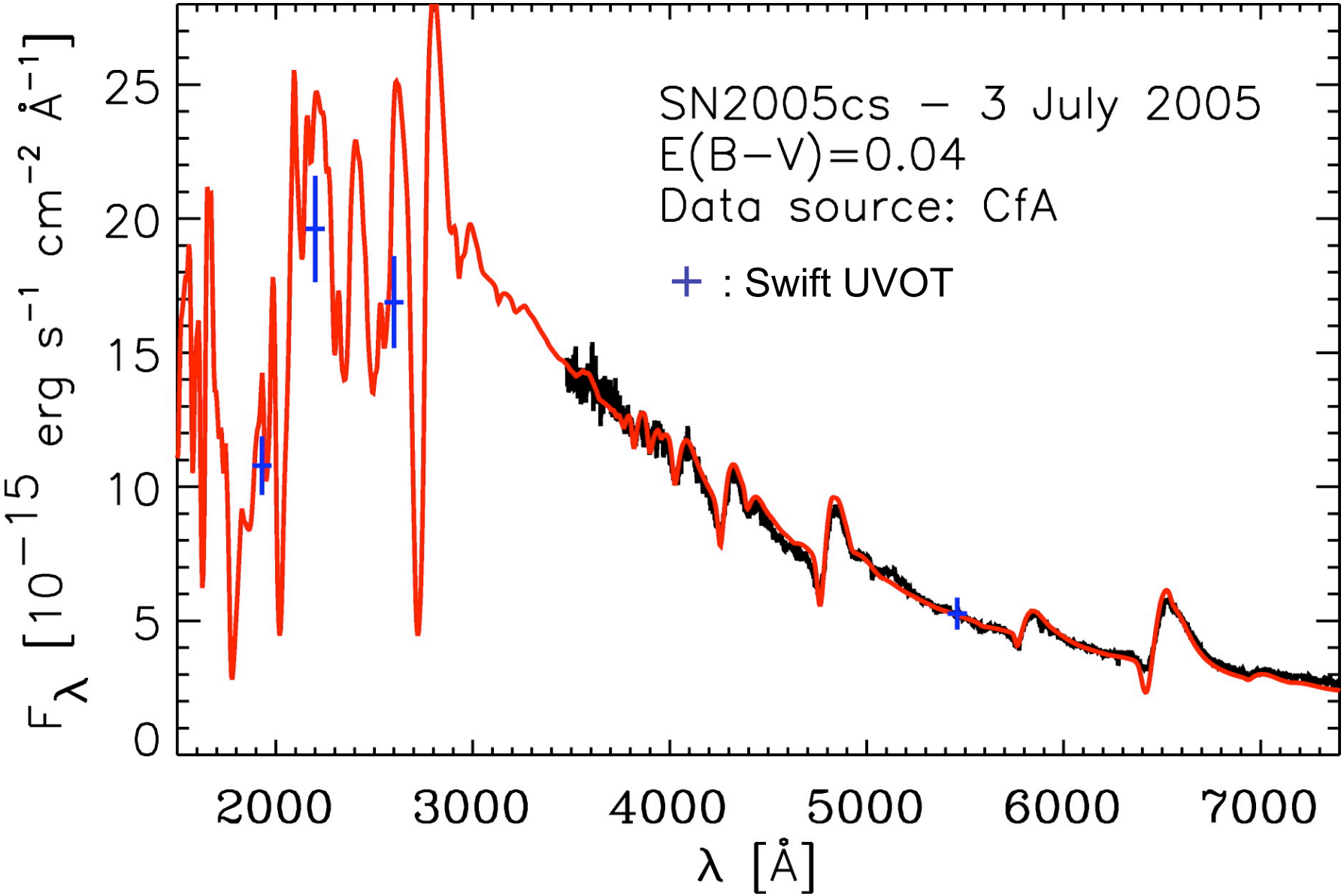
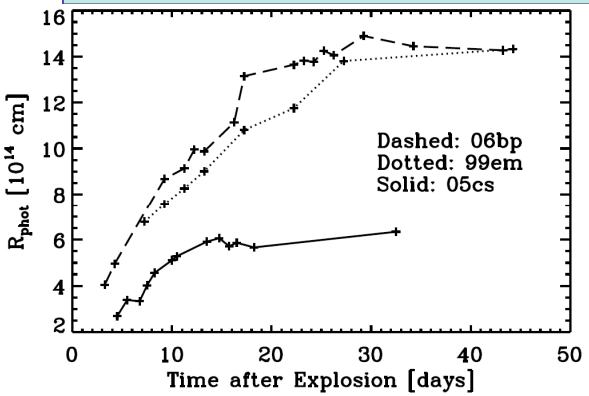
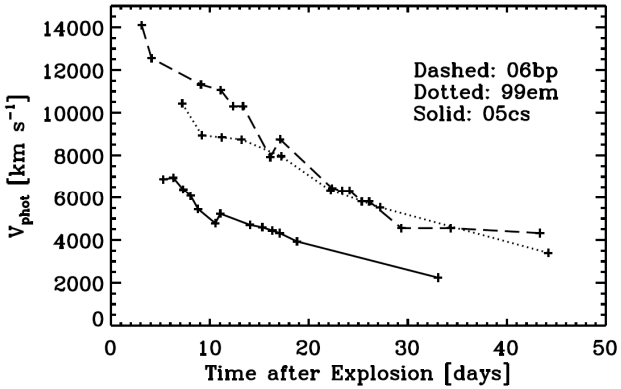


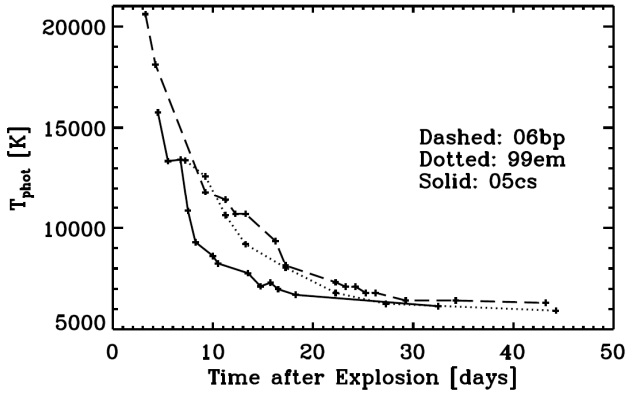
Step 1: Non-LTE Steady-State Approach

Application: Modeling of Young Type II SNe

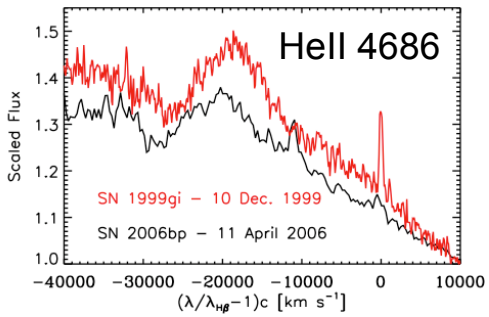
Properties of the Type II-P SNe 1999em, 2005cs, and 2006bp (Dessart et al. 2008)

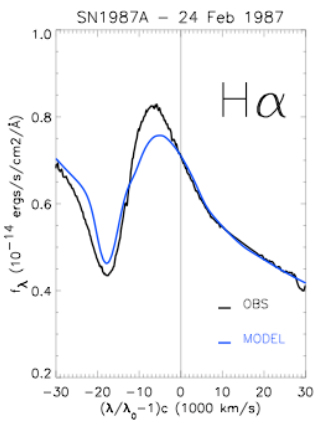




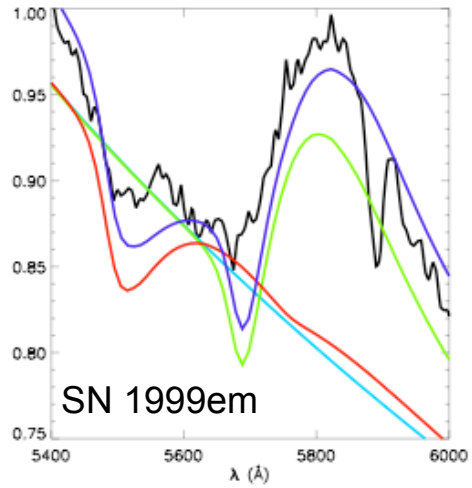


- ✓Inferrences on evolution of R_{phot}, T_{phot}, V_{phot}, reddening, chemistry (He/CNO; non-LTE effects)
- ✓Line identification (HI, HeI/HeII, CNO (I,II), FeII etc.)
- ✓Peculiar Line formation (e.g.: peak blueshift)
- ✓Correlation v_{phot}/L_{bol}
- ✓Typically: $R_{phot} \sim 10^{15}$cm, $T_{phot} \in [7,20]$kK, $L \sim 10^{8\text{-}9} L_{sun}$





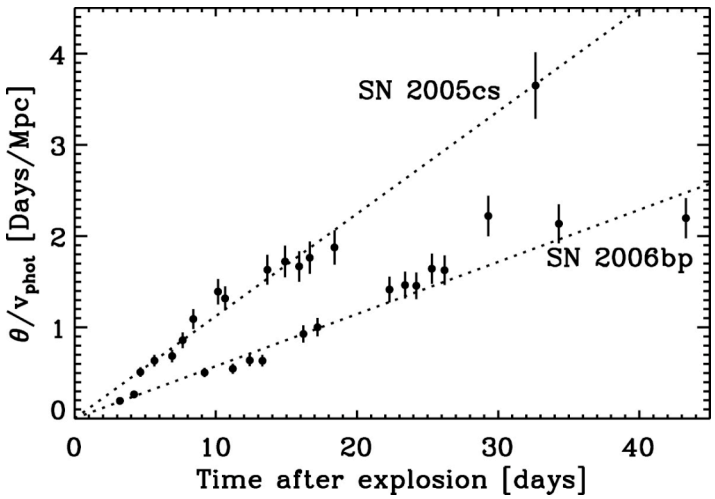
Obs. All HI HeI NII



Step 1: Non-LTE Steady State Approach

Application: ~10% Accurate Distance Determination to Type II SNe

- ✓ Modeling of multi-epoch spectroscopic & photometric observations yields $T_{phot}(t)$
- ✓ Modeling of brightness evolution for homologous expansion yields $R_{phot}(t)$ and distance
- ✓ Methods: Expanding Photosphere Method (EPM; Kirshner & Kwan 1974) and Spectral-fitting Expanding Atmosphere Method (SEAM; Baron et al. 2000)
- ✓ Application to cosmology: Independent determination of the Hubble Constant.



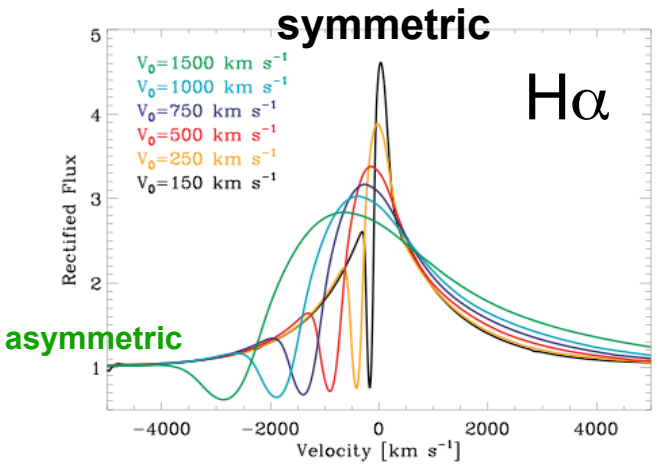
JD (+2,453,000)	Day	Angular Size (10^8 km Mpc^{-1}) θ_{BV}	θ_{BVI}	θ_{VI}
552.25	2005 Jun 30	3.006	3.028	3.028
553.25	2005 Jul 01	3.778	3.822	3.822
554.50	2005 Jul 02	3.645	3.778	3.822
555.25	2005 Jul 03	4.505	4.527	4.527
556.00	2005 Jul 04	5.139	5.139	5.104
557.75	2005 Jul 05	5.783	5.748	5.692
558.25	2005 Jul 06	5.982	5.960	5.872
561.25	2005 Jul 09	6.599	6.643	6.709
562.50	2005 Jul 10	6.776	6.820	6.864
563.50	2005 Jul 11	6.291	6.423	6.555
564.25	2005 Jul 12	6.445	6.577	6.754
566.00	2005 Jul 14	6.291	6.379	6.423
580.25	2005 Jul 28	7.084	7.084	7.216
D (Mpc)		9.0 + 0.5	8.9 + 0.5	8.7 + 0.5
$t_{explosion}$ (JD)		2,453,547.6 ± 0.5	2,453,547.6 ± 0.5	2,453,547.7 ± 0.5

SN	EPM	SEAM	Other
1999em	11.5 ± 1.0 (D06)	12.2 ± 2.0 (D06)	11.7 ± 1.0 (Cepheid; L03)
2005cs	8.9 ± 0.5 (D08)	8.9 ± 0.7 (D08)	7.7 ± 1.0 (SBF; T01)
2006bp	17.5 ± 0.6 (D08)	17.1 ± 0.4 (D08)	17.0±? (TF; T88)

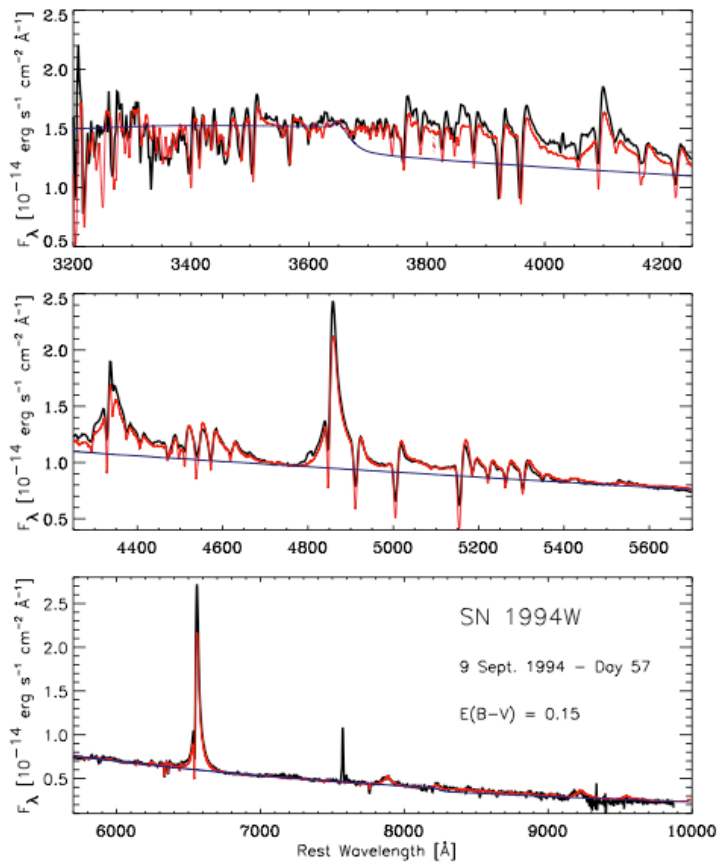
Step 1: Non-LTE Steady State Approach

Application: Modeling of the Interacting SN 1994W

- In Interacting SNe, the photosphere forms at large distances where the SN ejecta rams into a pre-SN ejected shell.
- Interaction leads to conversion of kinetic into internal energy.
- Large mass of resulting ionized material cools on diffusion time scale
- For large τ, thermalization ensues and allows the modeling of the optically-thick shell.
- Good fits for SN 1994W
- Key finding: Line broadening dominated by non-coherent scattering with thermal electrons rather than expansion

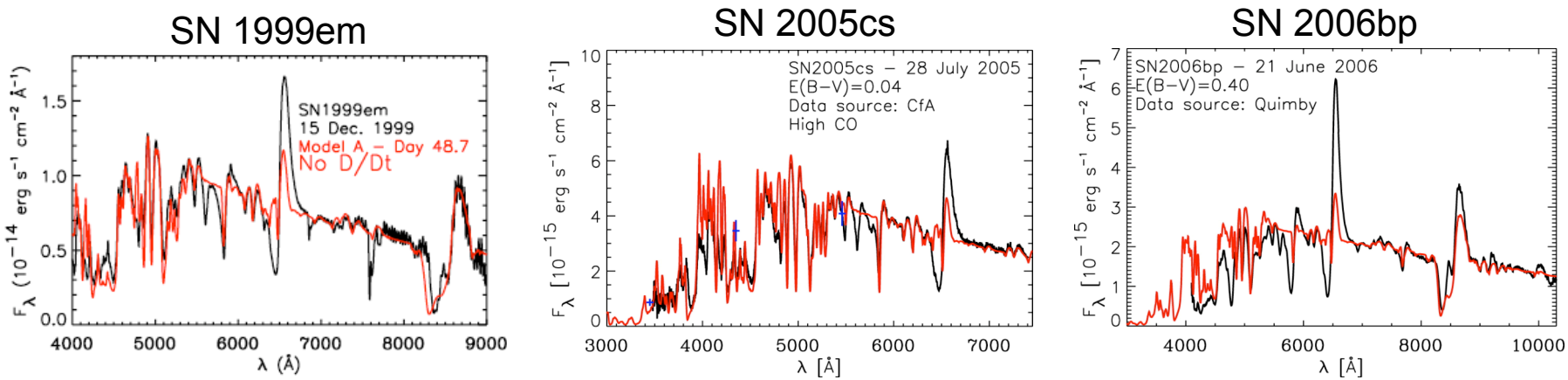


Variation in expansion rate.
P-Cygni profile for high V_0
Symmetric profile for small V_0



Step 1: Non-LTE Steady State Approach

Shortomings: Problem at recombination epoch in Type II SNe

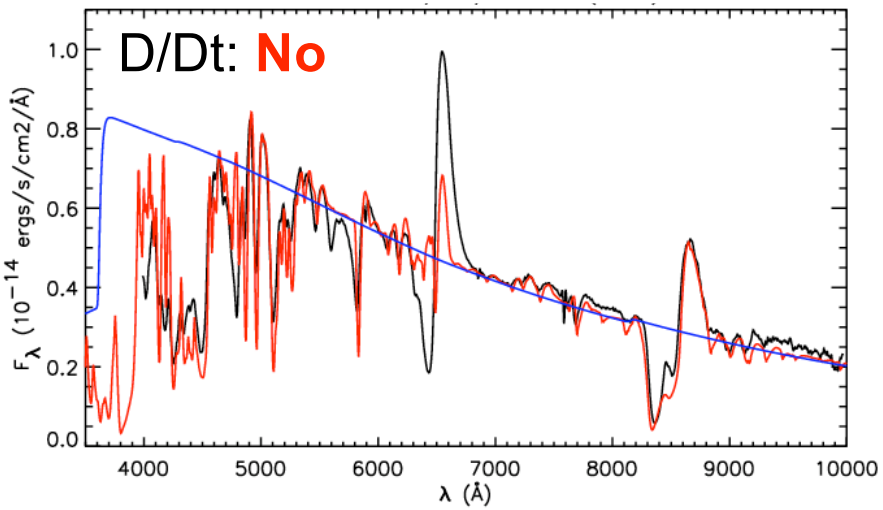


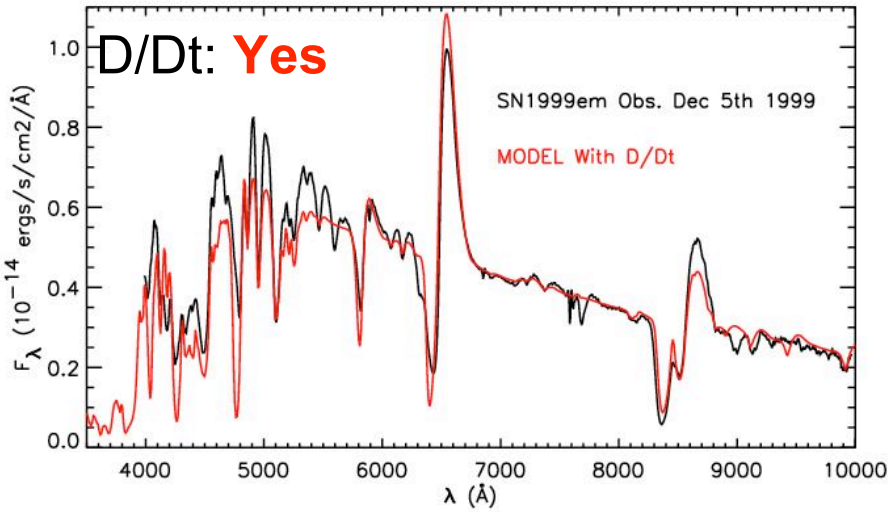
- ✓ Synthetic Balmer line profile shapes systematically too narrow and weak
- ✓ Problem encountered in all Type II SNe (low/high L_{bol}, E_{expl}, or ^{56}Ni)
- ✓ Origin: **Recombination** and **expansion** time scale comparable: **$R/V \sim 1/\alpha N_e$**
- ✓ Solution: Include <u>time-dependent terms in statistical and gas energy equation</u>

Step 2: Non-LTE, Dn/Dt and De/Dt≠0, but DJ/Dt=0

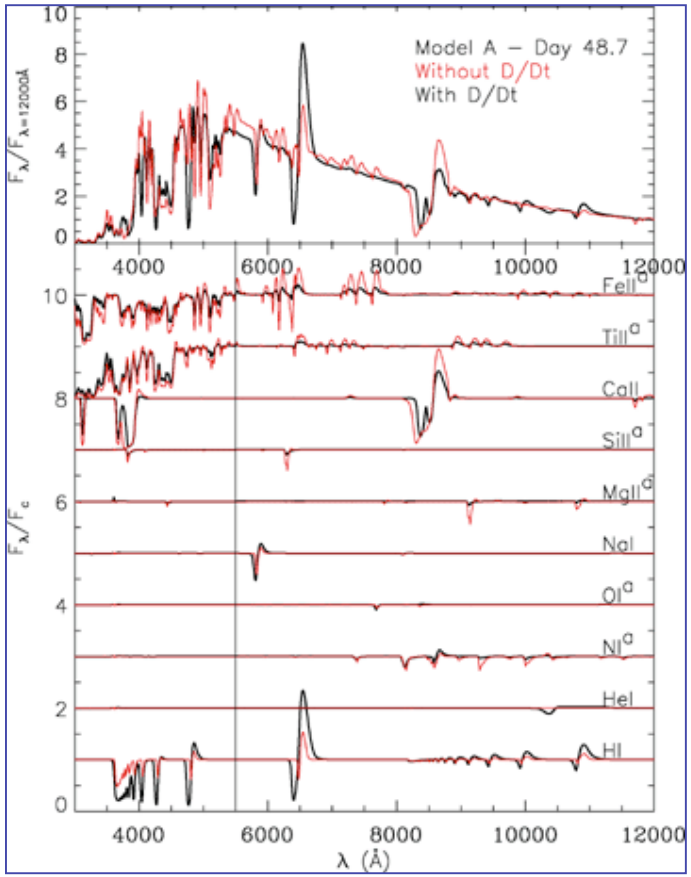
- ✓ Non-LTE treatment
- ✓ Include Dn/Dt and De/Dt terms in statistical and energy equations.
- ✓ Evolve outer ejecta layers: $\tau \in [10^{-8}, 10^{4}]$
- ✓ Assume Diffusion Approximation at base (CMF flux)
- ✓ Analytical Description of SN Ejecta: $L_{0,CMF}(t)$, R_0, $\rho(R)$, $v(R)$
- ✓ Chemical Homogeneity: $X_i(R) = X_i$
- ✓ Approach: Adopt initial SN ejecta properties and evolve, adjust $L_{0,CMF}(t)$ to follow the typical SN $L_{bol}(t)$

Step 2: Non-LTE, Dn/Dt and De/Dt≠0, but DJ/Dt=0
Results for Type II SNe



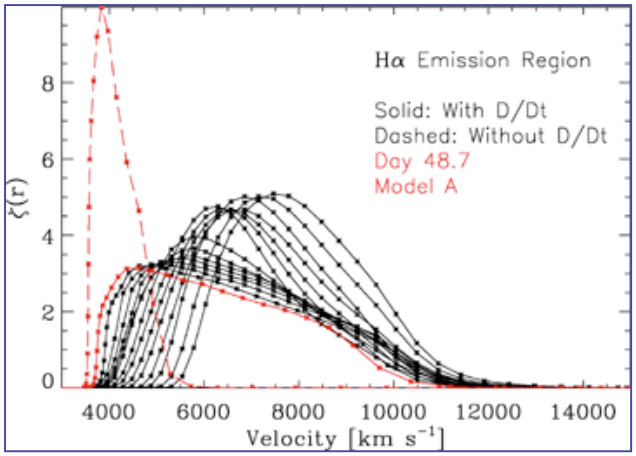


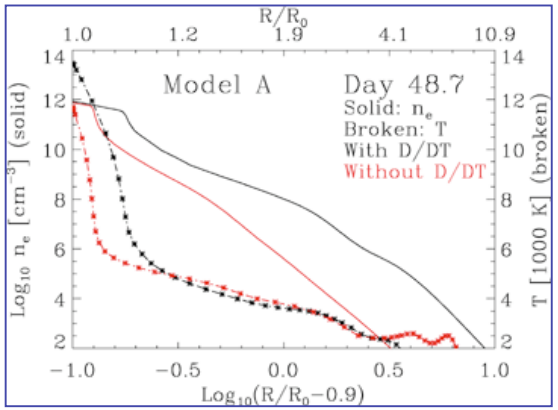
- ✓ Balmer line strength and width reproduced
- ✓ All lines affected

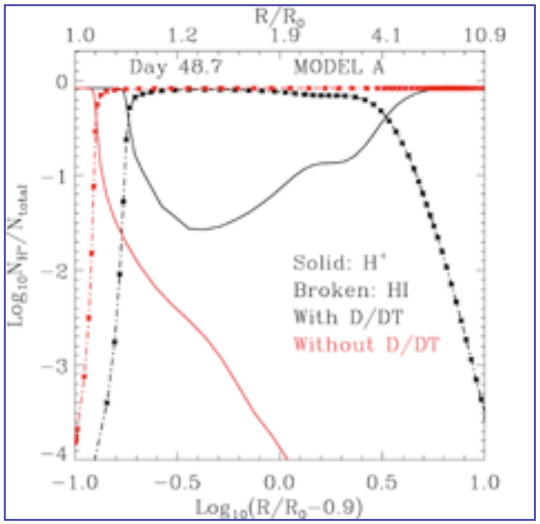


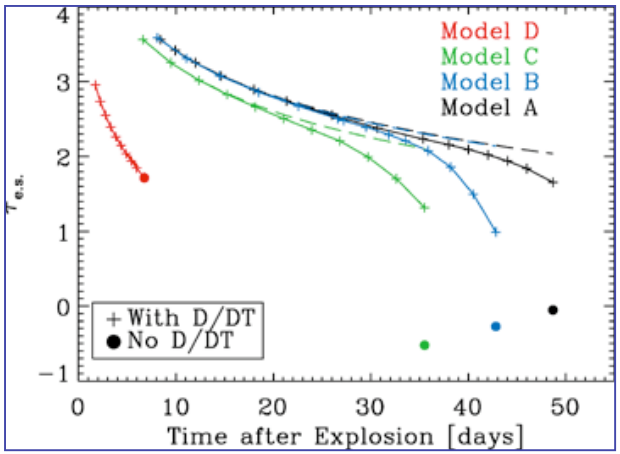
Step 2: Non-LTE, Dn/Dt and De/Dt≠0, but DJ/Dt=0
Results for Type II SNe

- ✓ Impacts ejecta ionization (N_e, N_i, ∀ ion), with freeze-out in low density (high velocity) regions.
- ✓ Impacts τ_{line}: broader line formation region, broader/stronger lines; impacts inferred chemistry/stratification
- ✓ Impacts $\tau_{cont,\ ejecta}$: ejecta optically-thick longer



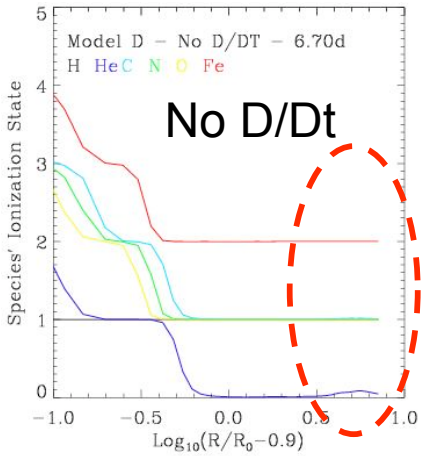


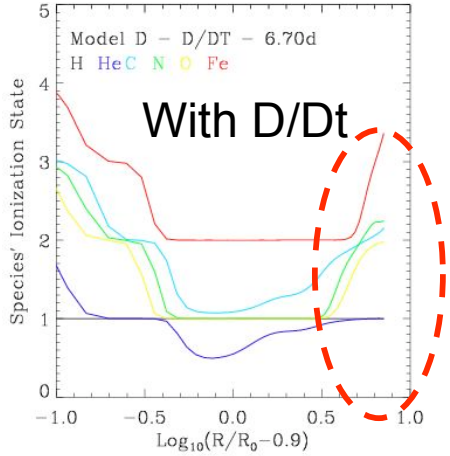


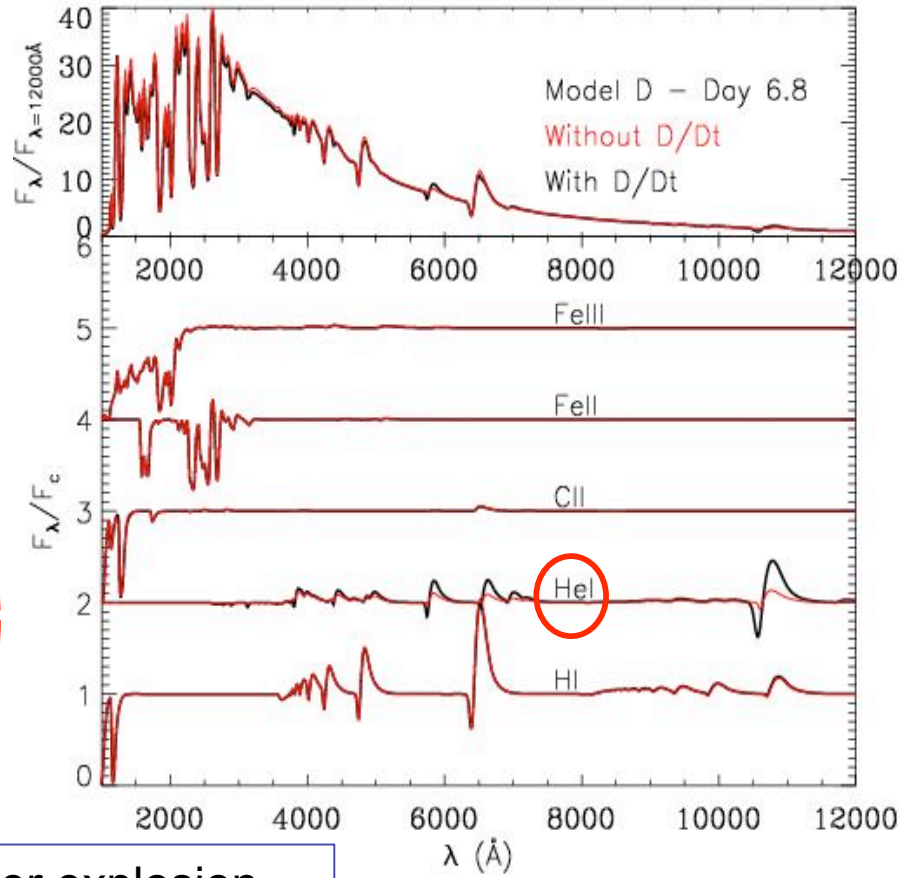


Step 2: Non-LTE, Dn/Dt and De/Dt≠0, but DJ/Dt=0
Results for an early-time Type II SN ejectum

D/Dt effects present even at **early times**







- ✓ HeI lines strongly affected 1-2 weeks after explosion
- ✓ Effect present at early time so not due to ^{56}Ni
- ✓ Effect present under fully-ionized conditions so not fundamentally linked to recombination energy

  => Dn/Dt effects likely important in **all** SN ejecta

Step 2: Non-LTE, Dn/Dt and De/Dt≠0, but DJ/Dt=0
Shortcomings

- ✓ Inner boundary flux must be set: Tricky tuning
- ✓ Diffusion approximation potentially faulty: low τ, weak thermalization
- ✓ Analytical description of ejecta not globally consistent; no chemical stratification

Step 3: Non-LTE, Dn/Dt, De/Dt, and DJ/Dt≠0

Combination of Non-LTE and full time dependence

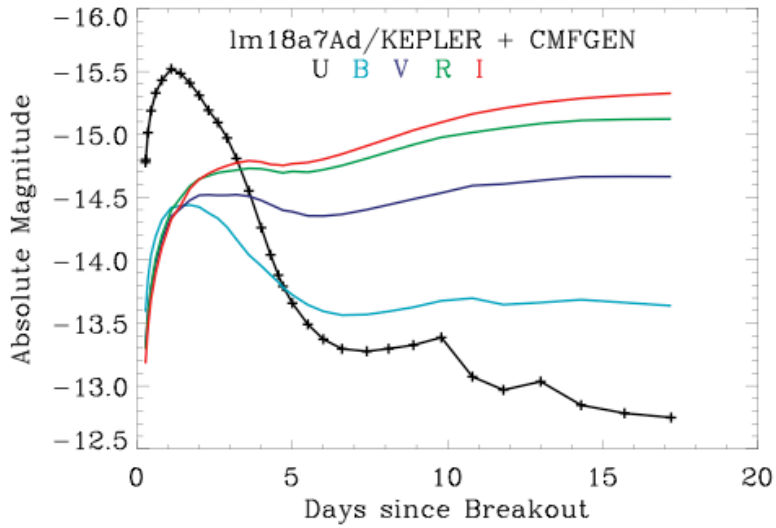
- ✓ Non-LTE treatment
- ✓ Include Dn/Dt and De/Dt terms in statistical and energy equations.
- ✓ Include DJ/Dt and DH/Dt terms in RTE
- ✓ Evolve ENTIRE ejecta: $\tau \in [10^{-8}, \sim 10^{5}]$
- ✓ Zero Flux adopted at inner boundary
- ✓ Initial SN ejecta conditions taken from a **physical model** of the progenitor star exploded with a "piston" (KEPLER, Woosley & Weaver)
- ✓ Chemical Stratification; Profile taken from evolved progenitor star
- ✓ Approach: **Initial Value problem**. No boundary input.
- ✓ Disadvantage/Advantage: No adjustable parameter to "fit" observations once a time sequence is started. Global consistency rather than fine tuning

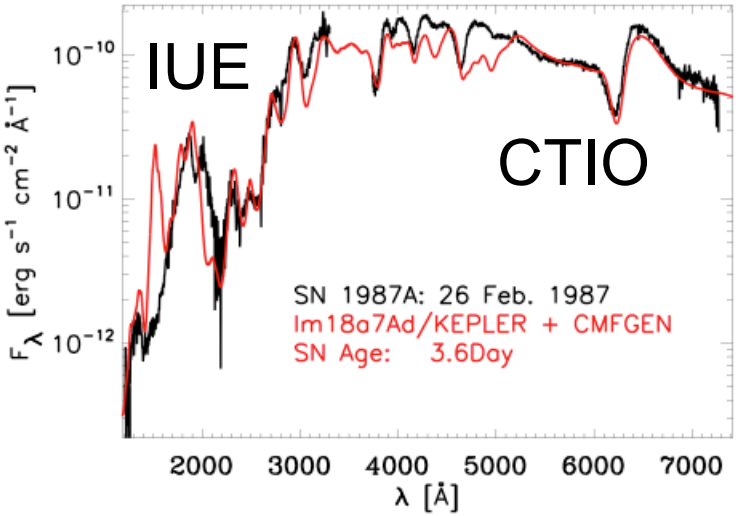
Step 3: Non-LTE, Dn/Dt, De/Dt, and DJ/Dt≠0

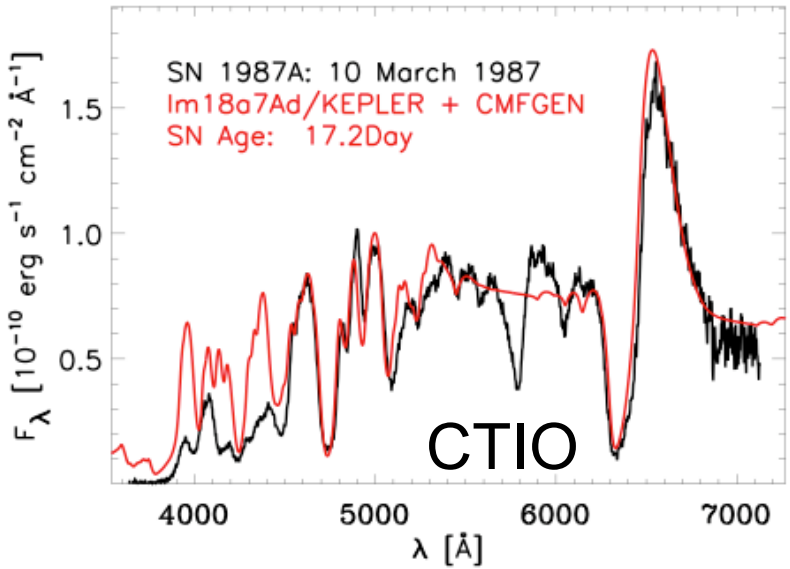
Application: Time Evolution of SN ejecta + emergent radiation

- ✓ Initial model: lm18a7Ad (Woosley) at 0.1day
- ✓ Evolved with steps Δt=1.1t
- ✓ Chemical Stratification
- ✓ Energy deposition from isotopes

Results: non-LTE light curve, sensible fits to spectra (although some discrepancies), Ionization freeze-out (as in step 2), recombination fronts (HI,HeI,HeII)







Summary and Ongoing/Future Projects

- ✓ Various approaches possible for quantitative spectroscopy of SNe.
- ✓ Non-LTE and steady state adequate at early times in Type II SN. Needs further checking. Allows “good fits” through tuning parameters.
- ✓ Modeling of recombination phase (changes in ionization at low-density high velocity) requires time-dependent terms (Dn/Dt, De/Dt)
- ✓ Better physical consistency with “Full-Ejecta” simulations based on hydrodynamical inputs of pre-SN evolution and explosion and NO artifical boundary condition.

Future Projects

- ✓ Parameter study of core-collapse SN ejecta (II, Ib/c), width-luminosity relation of Type Ia SN light curve
- ✓ Application to cosmology: systematic errors with Type Ia SNe, use of Type II for distance determinations and Hubble constant (EPM, SEAM, SCM)
- ✓ Application to stellar evolution and structure: Quantitative spectroscopy of SN ejecta to infer properties of progenitor (M, R, Ω, shell structure) and explosion (yields, morphology)