Understanding Photospheric Spectra of Core Collapse Supernovae

(Elmhamdi et al. 2006; A&A, 450, 305)

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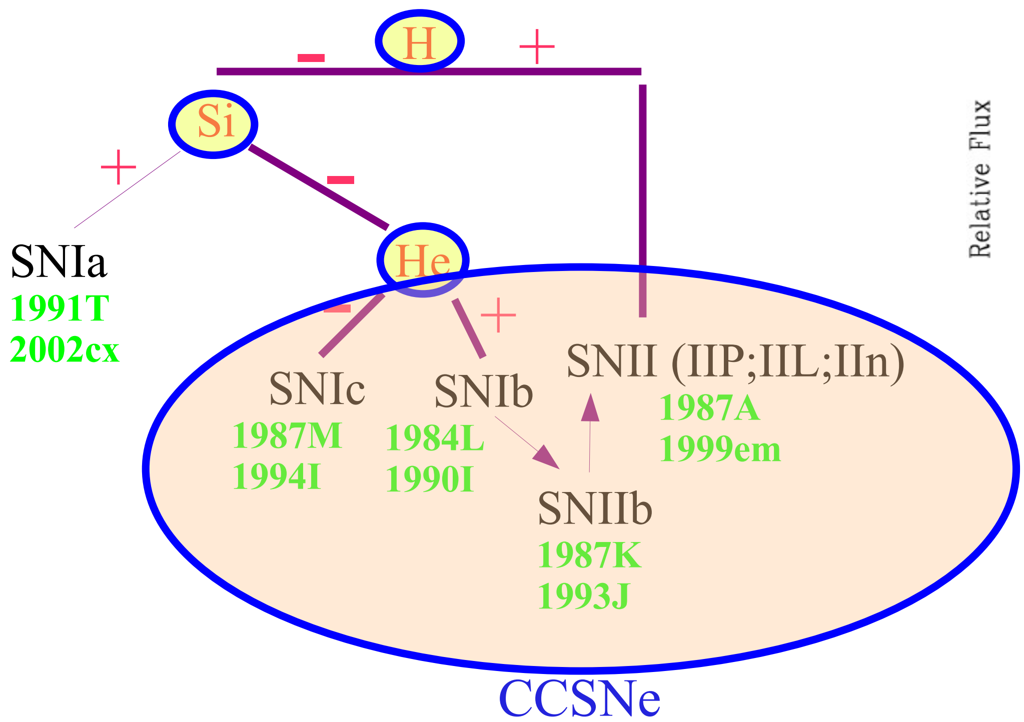
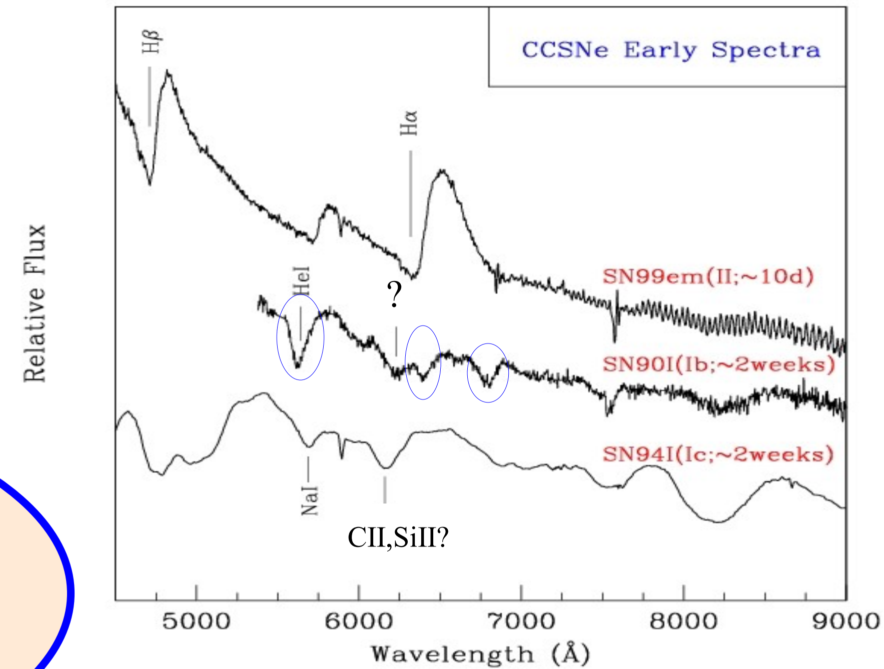
Outline

- Introduction
- Methodology analysis & The SNe sample
  - Fitting procedure : SYNOW code
  - Type Ib-Ic-IIb-II SNe sample
    (early photospheric spectra)
- Discussion
  - Manifestation of hydrogen in CCSNe spectra
  - Oxygen issue in CCSNe (work in preparation)
- Conclusions & Future investigations

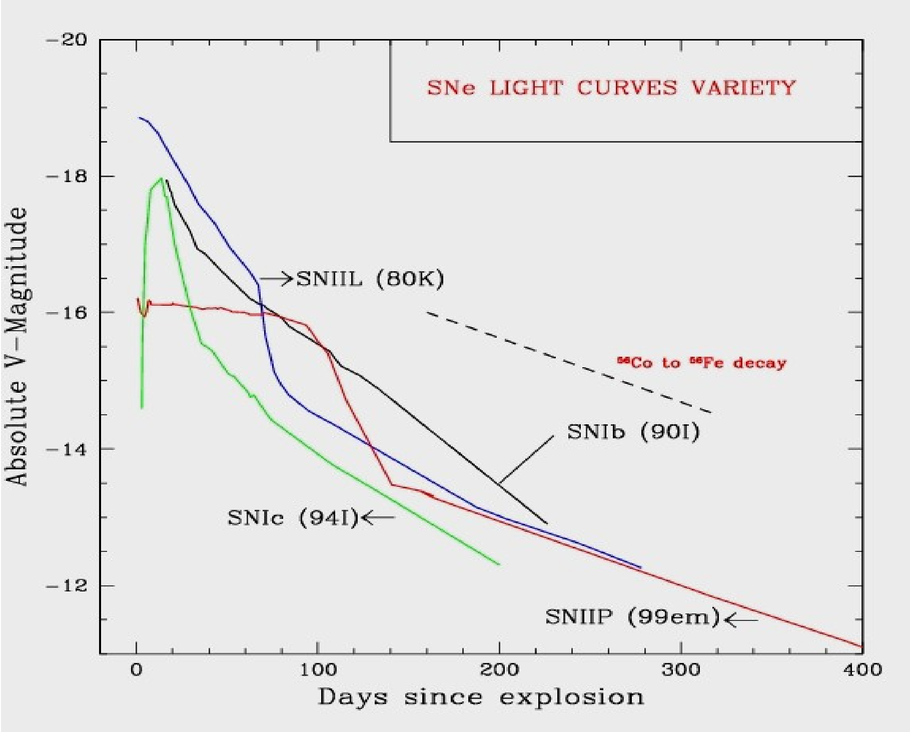
Basic Classification Scheme





Spectroscopy {
- **SNeII :** clear P-Cygni profiles of HI Balmer lines.
- **SNeIb :** clear evidence of optical HeI lines (no clear HI)
- **SNeIc :** No evidence neither for HI nor for HeI

Introduction

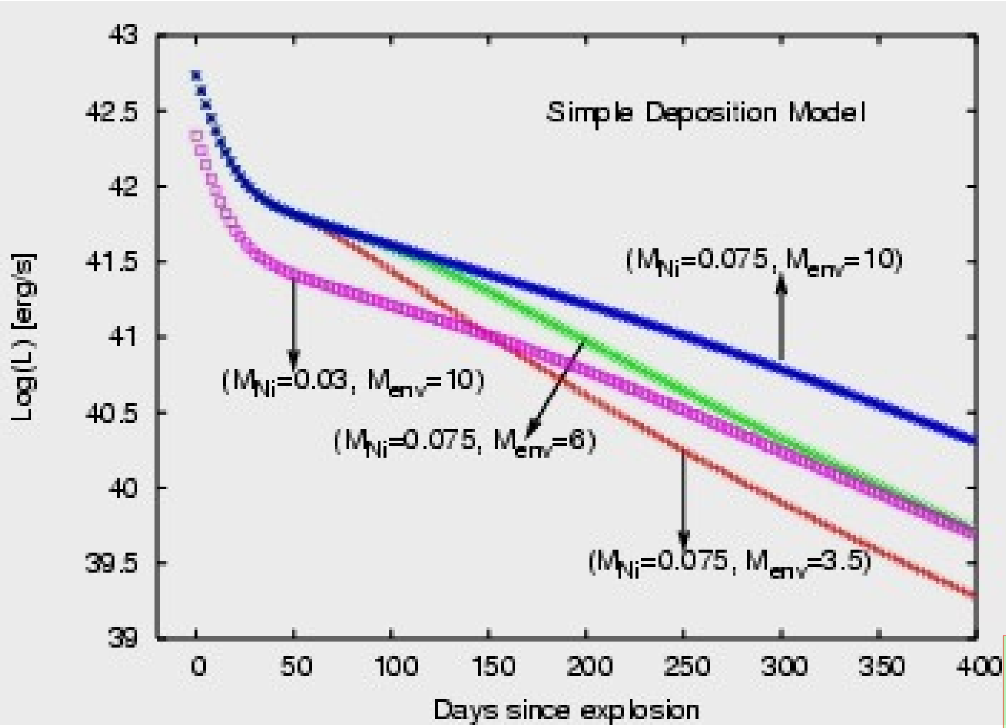


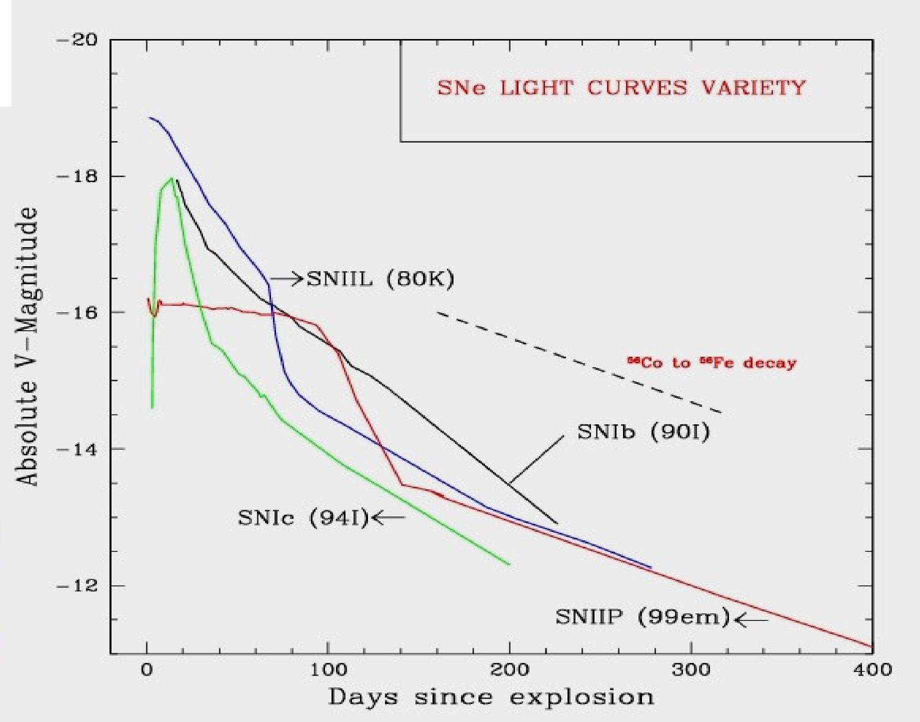
Light curves:

SNeIbc late LCs: *e*-folding time faster than the ^{56}Co decay (i.e. 111.23days)

The γ-rays escape with decreased deposition, owing to the low mass nature of the ejecta.

Introduction





SNeIbc late LCs: *e*-folding time faster than the ^{56}Co decay (i.e. 111.23days)

→ The γ-rays escape with decreased deposition, owing to the low mass nature of the ejecta.

Light curves:

$\rightarrow Simple\ \gamma - ray\ deposition\ model:$

★ Luminosity evolution in homogously expanding spherical ejecta

$$point\ source\ \gamma - ray\ deposition\ from.:\ ^{56}Ni. \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$$

$$v(r,t) = r/t;\ \rho(r,t) \propto r^{-n}(t),\ and.\ Cst\ opacity\ \kappa_{\gamma}\ throughout\ the\ ejecta$$

$$Total\ \gamma - ray\ opti.\ depth: \tau_{\gamma} \propto \kappa_{\gamma} \times M_{ej}^{2} / E \times t^{-2}$$

$$The\ emergent\ Luminosity: L(t) = L_0(t) \times [1 - \exp(-\tau_{\gamma}(t))]$$

Lo(t): computed on the basis of radioactive decay properties

The parametrized SN synthetic spectrum code "SYNOW"

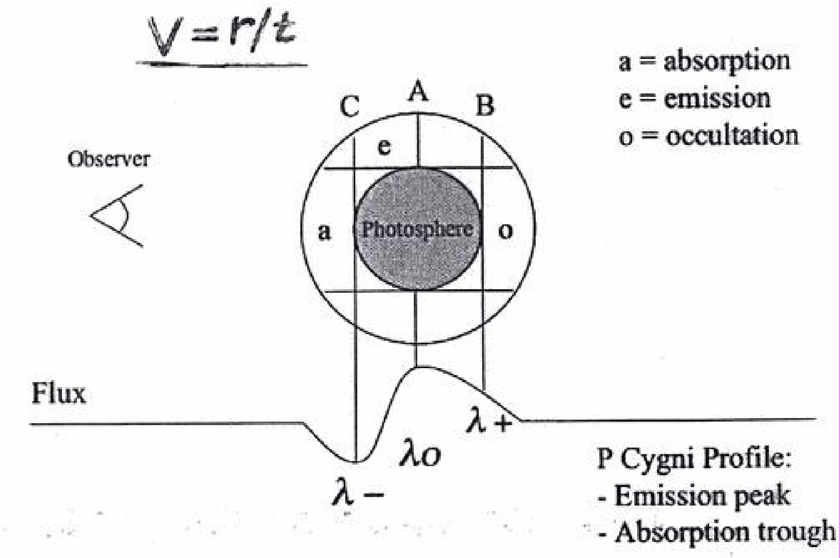
(Jeffery & Branch 1990; Branch 2001; Elmhamdi et al. 2006)

Descriptions:

P-Cygni profile formation in an expanding atmosphere

- Spherical symmetry & homologous expansion
- Sharp photosphere emitting blackbody continuum + region of line formation surrounding it.
- Line-photon interaction is pure resonnance scattering
- LTE-excitation for the relative strengths of lines of a given ion

SYNOW & Resonance Scattering



Input Parameters:

- $\tau(ref)$: Opt.depth of the strongest line, reference line, of the introduced ion.
- Tbb: The underlying blackbody continuum temperature
- Vphot : Velocity at the photosphere
- Radial dependence of the line Opt.depth:

Exponential : $\tau \propto \exp(-v/v_e)$

Power-law : $\tau \propto v^{-n}$

✯ SN Ib 1990I spectroscopic evolution:

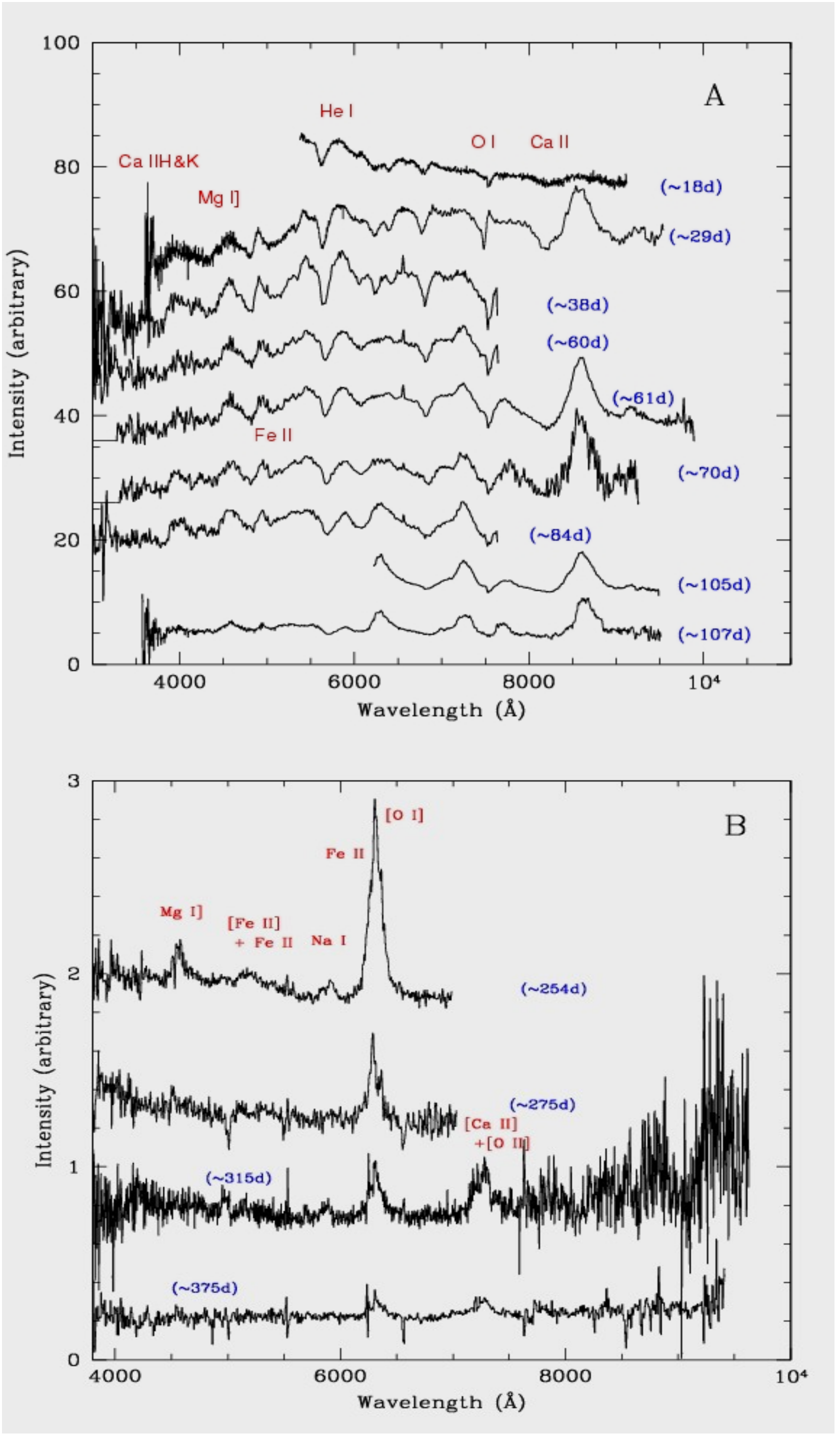
(Elmhamdi et al. 2004)

Photospheric phase

- No (SiII , H) + Blue continuum + Broad P-Cygni
  - → Expanding envelope V(HeI 5876)~13400km/s
  - → SN Ib + near Expl.
- ~10 days later : expansion & cooling
  - → Fainter continuum
  - → HeI, CaII H&K, MgI] and FeII + narrower P-Cygni profiles (lower Vexp)

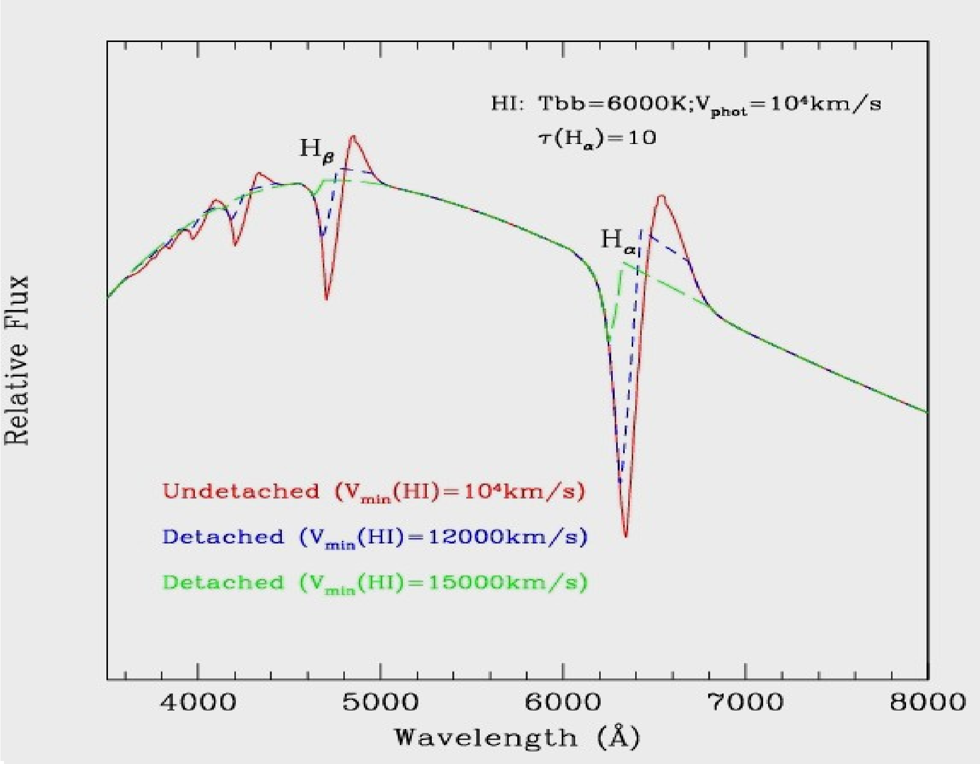
Nebular phase

- T decreases & Shift of the energy to the red
- Emergence of strong nebular emission of [O I]6300,64A
  - → Spectra dominated by strong and less broad lines of MgI],[OI],[CaII, FeII & [FeII] with low V.



Detachment concept:

- A line is said deatched when its "Vmin" is greater than "Vphot" → has a non-zero opt.depth only down to "Vmin".
- The profile of a detached line has a flat-topped & the absorption minimum is blueshifted by the detachment velocity

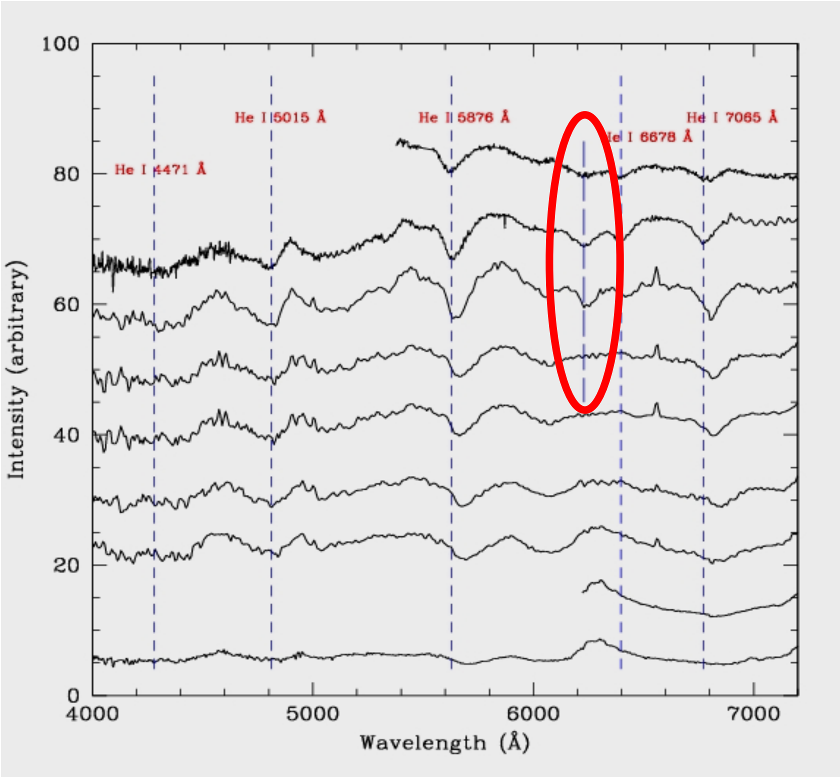


The sample

- Consists of 20 SNe: 16 Type Ib; 2 Type Ic, 1 Type IIb and 1 Type II.
- Analysis of 45 spectra: Photospheric Phase

Main goals: *Traces of hydrogen in Ib and Ic SNe; H_alpha ~ 6250A*
How hydrogen manifests its presence compared to IIb & II

Type Ib: SN 1990I
(Elmhamdi et al. 2004 A&A, 426, 963)

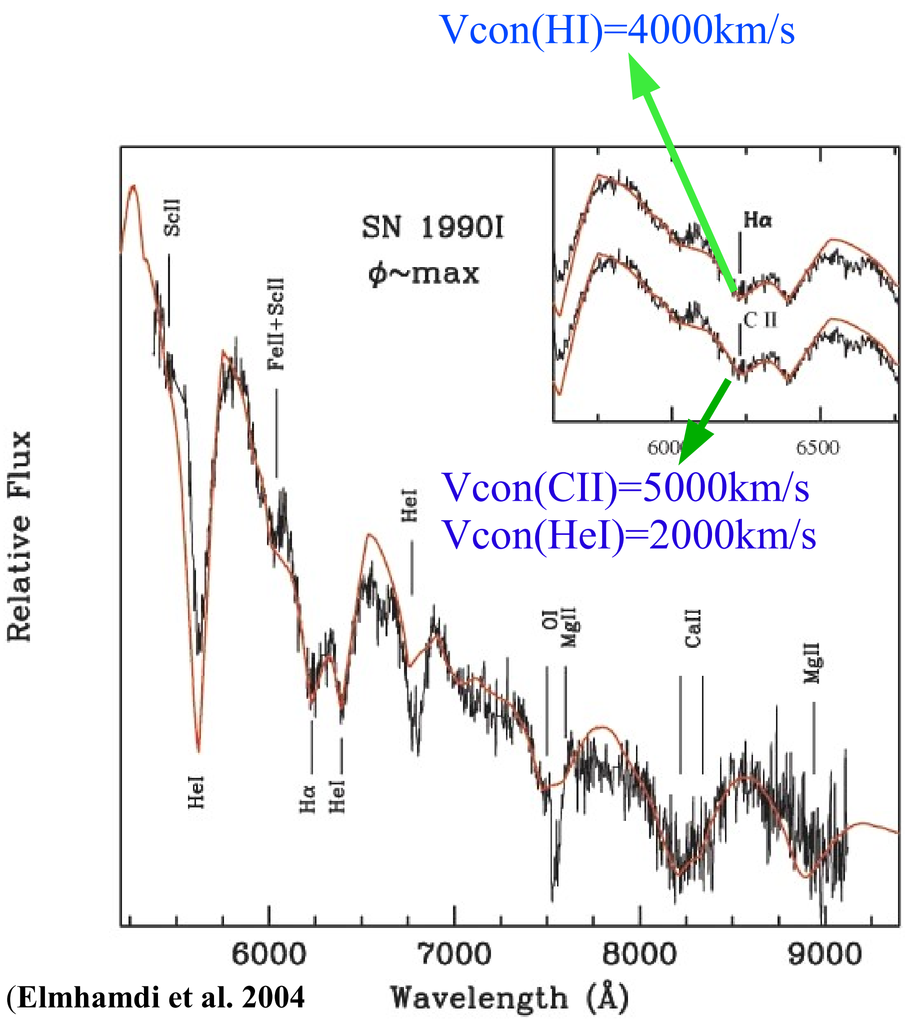


SN Ib 1990I:

Synthetic spectrum near max: Vph=12000km/s,Tbb=14000K

Contains 7 lines: HeI, FeII, MgII, OI, CaII, ScII and ~6250A feature attributed to H_α

The "~6250A" feature: Ambiguity with SiII 6355A, NeI 6402A and CII 6580A



(Elmhamdi et al. 2004

Selection criteria to decide on H

- Undetached NeI 6402A is rejected once it produces too blue absorption for the 6250A trough or/and various unwanted optical lines.
- Similar reasoning applies to Si II 6355A.
- CII 6580A: excluded if higher velocity than He I (i.e. When Vcont(CII)>Vcont(HeI))

Rk: We define a parameter called contrast velocity of the line defined as:

Vcont(line)=V(line)-Vphot

Undetached case: Vcont(line)=0 km/s

Evolution from early to later phases

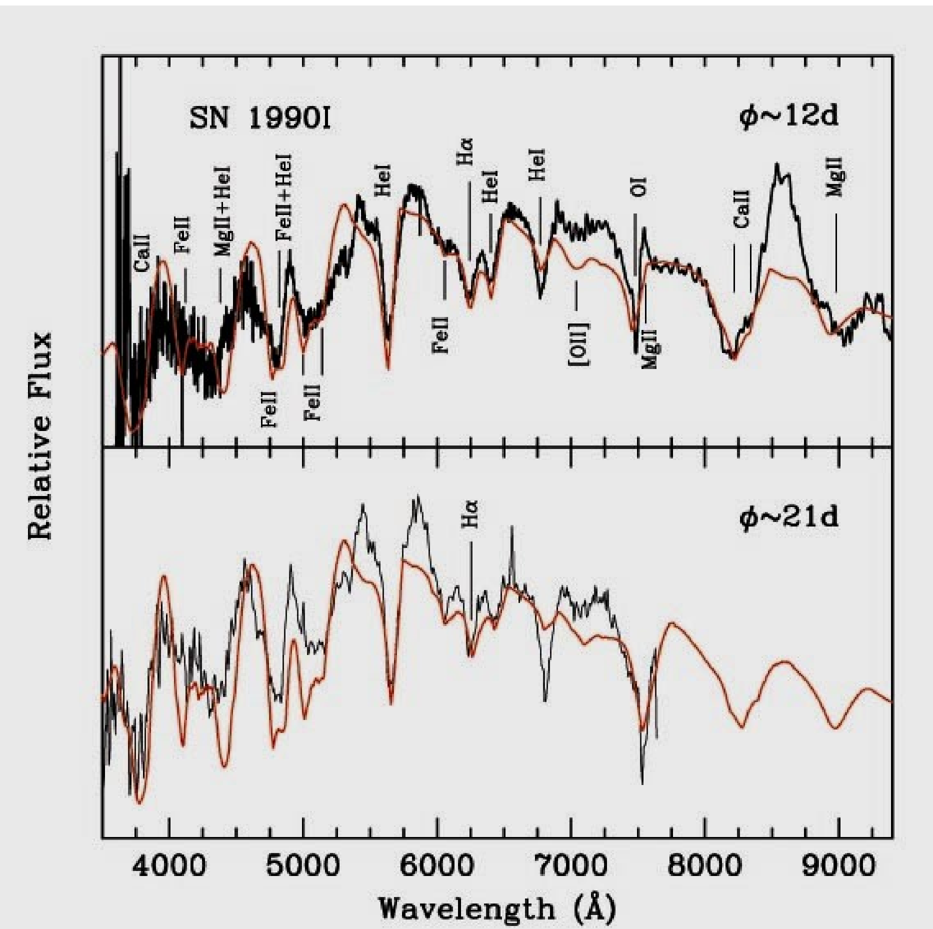
typically the velocities decrease

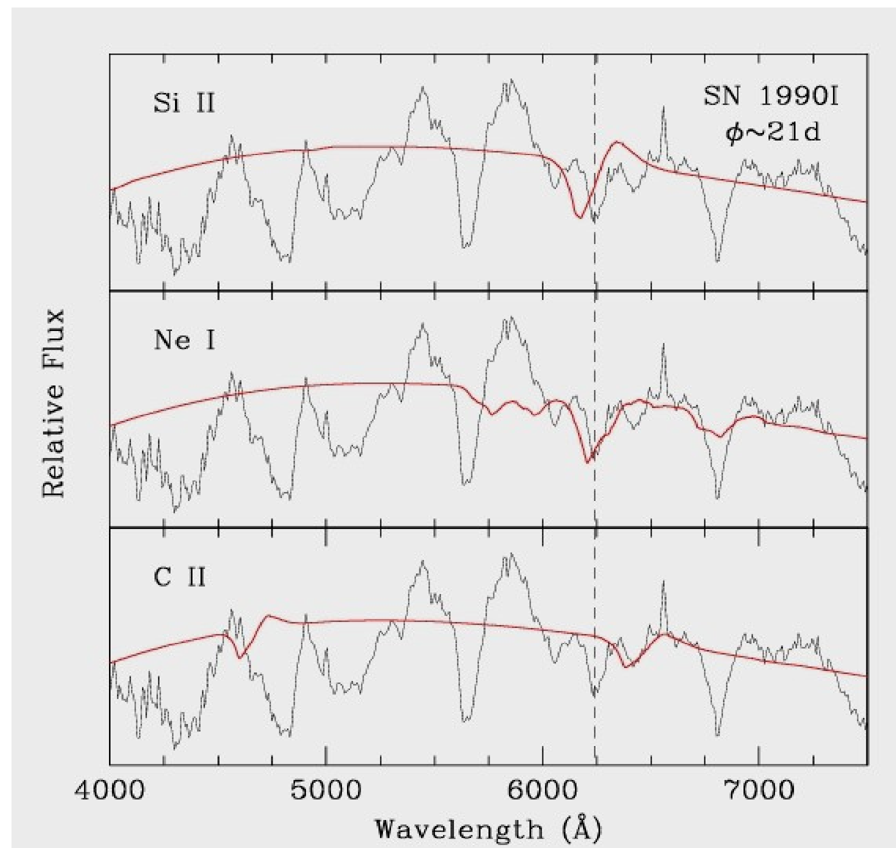
the lines become even less prominent

At 12d: Vph=10000km/s;Tbb=5500K;Vcon(HI)=5500;Vcon(HeI)=3000km/s

At 21d: Vph=9500km/s;Tbb=5400K;Vcon(HI)=5500;Vcon(HeI)=2500km/s

The other introduced lines are all undetached

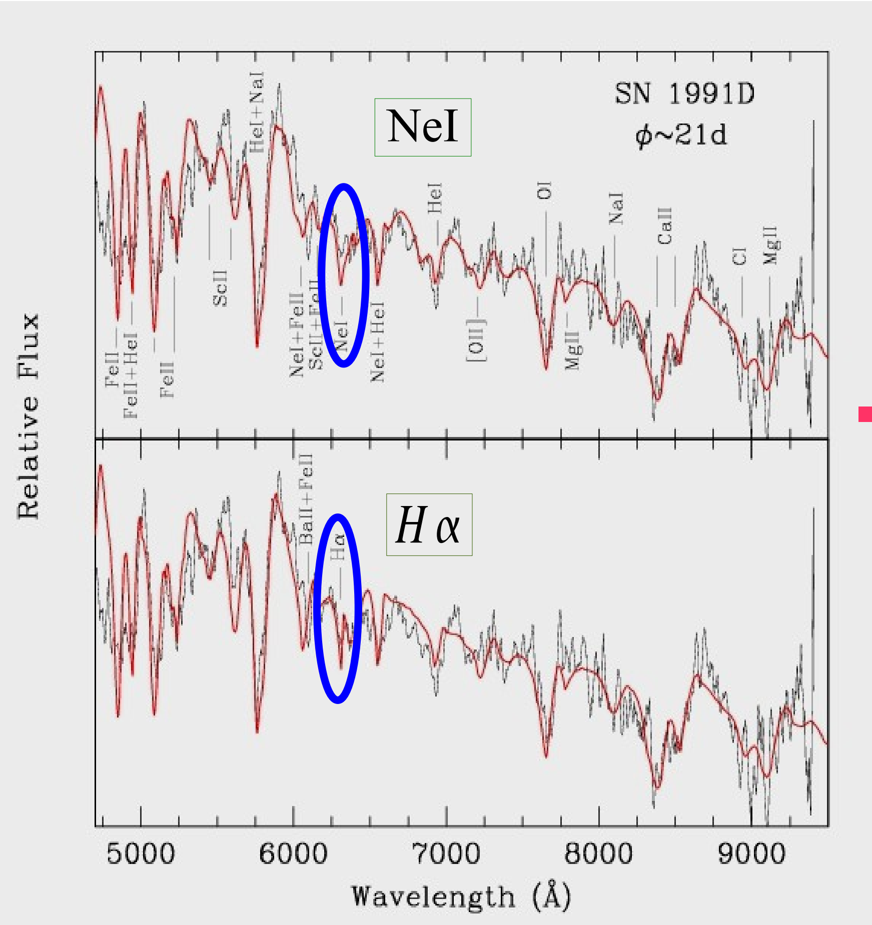




Particular Ib events

SN 1991D

Particular case: hard to decide
between H_α and NeI:
Vph=4600km/s (low velocity SN); 11 elements in the fit
HeI lines: Vcon=1400km/s; τ (HeI)=1.8
Top: undetached NeI; τ=2
Bottom: Vcon(H_α)=7400km/s; τ= 0.46



H_alpha provides slightly better fit to the weak 6250A trough, compared to NeI, however the HI-case fit does not account for some observed features especially near 6630A and 6840A

Ne I remains hence a strong candidate in this Tyep Ib object

Particular Ib events

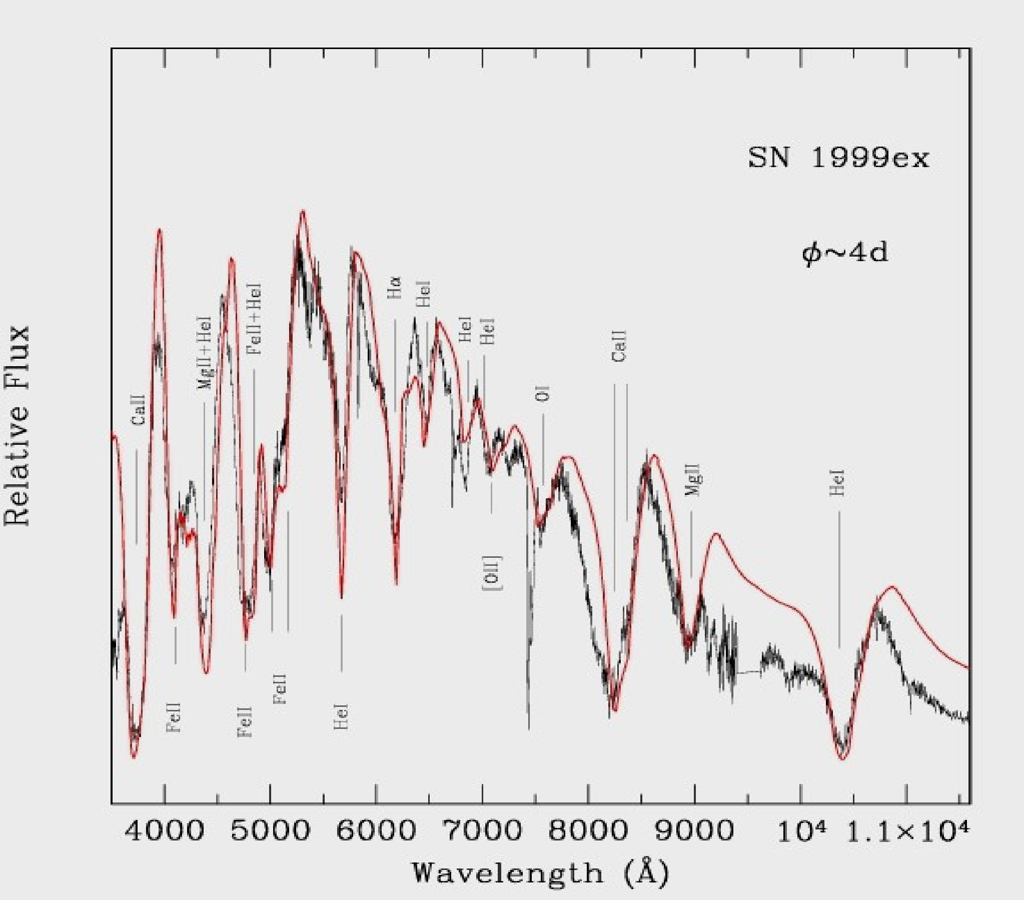
SN 1999ex

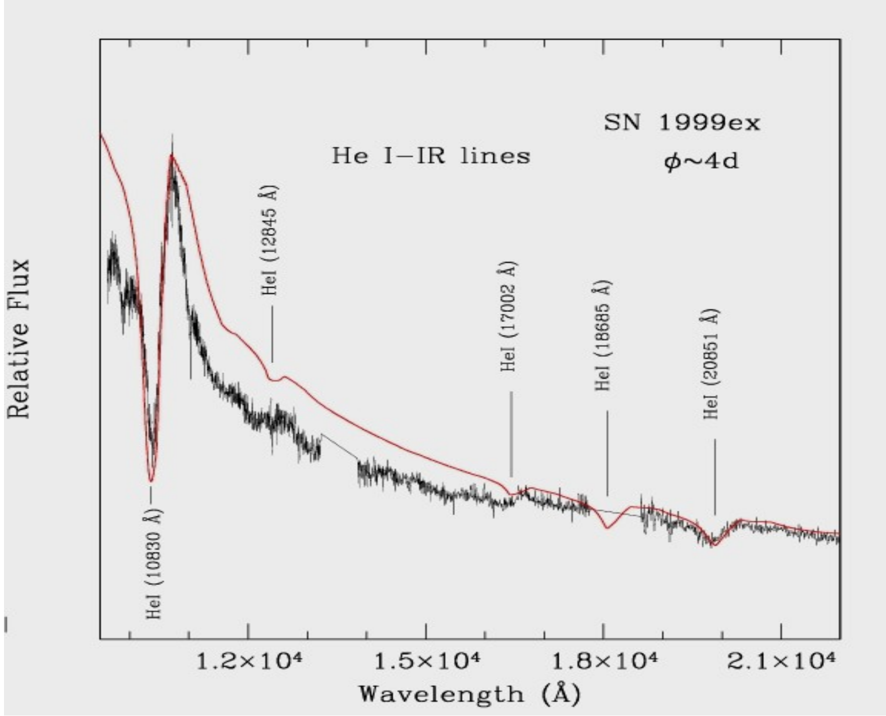
Was classified as Ic and then as intermediate Ib/c rather than a pure Ib (**Hamuy et al. 2002**):

- Weak HeI lines; feature around 5700 attributed to NaI
- The deep 6250A trough was attributed to SiII 6355A

By means of synthetic sp: He I optical lines are well reproduced by $Vph = 10000 km/s$; $Tbb = 5800K$

$$\tau(HeI) = 2.5 \; ; Vcont(HeI) = 1000 km/s$$





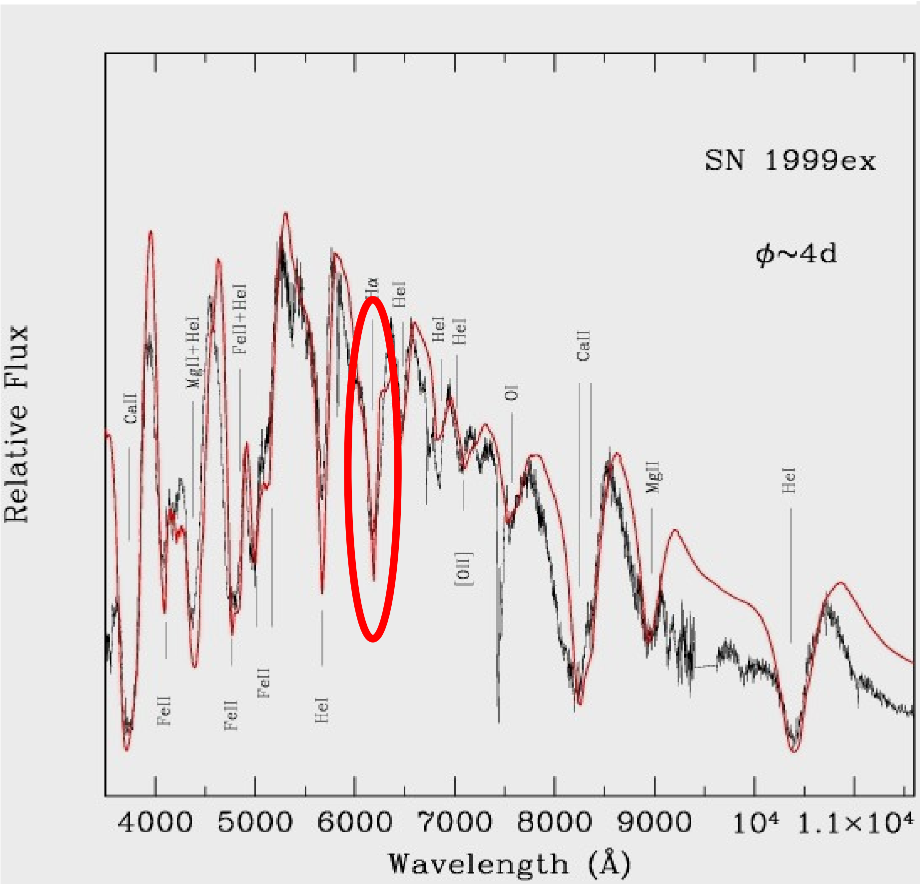
Good match: Optical-IR HeI lines

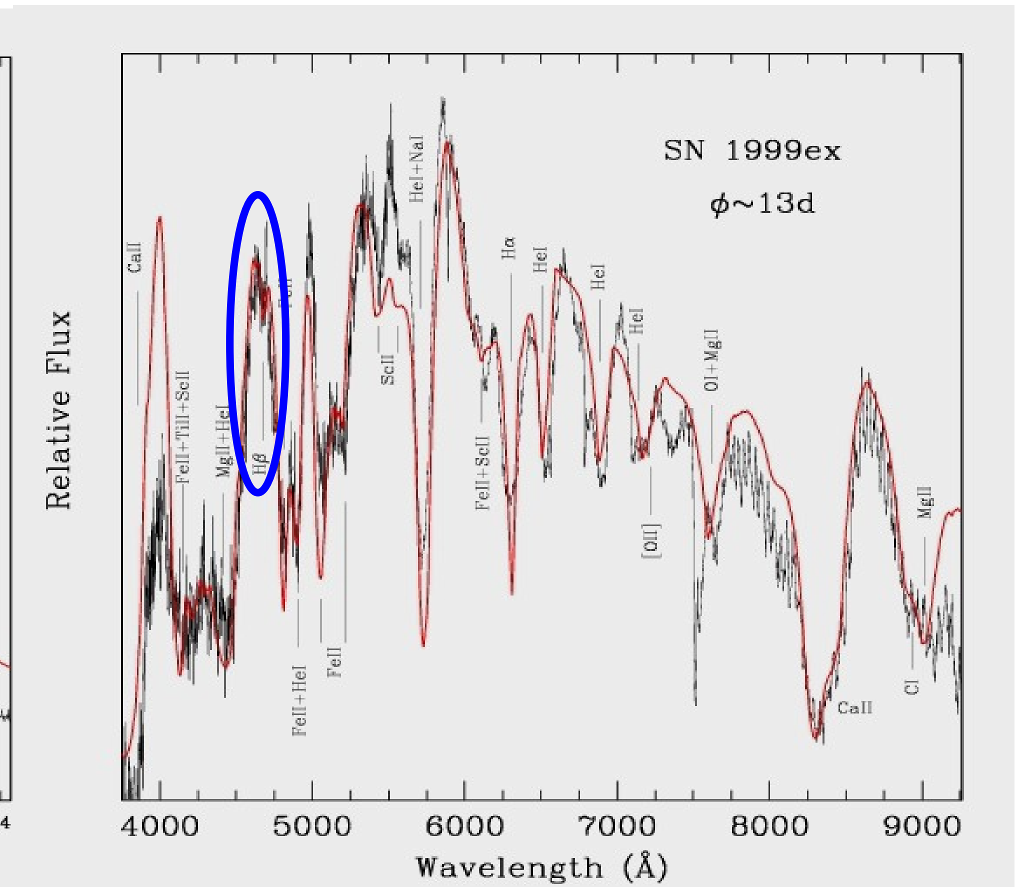
Type Ib object

As far as the trough around 6250A is concerned:

- NeI, SiII, CII are ruled out (criteria)
- Best fit remains H_α: Vcont=8000km/s; τ =1.5

<u>13d spectrum:</u> Vph=7000km/s;Tbb=5600K
HeI lines: Vcont=1000 km/s; Opt.dep=3.4
HI: Vcont=5000 km/s; Opt.dep=1.6





Particular Ib events

SN 2000H

- Considered one of the more interesting Ib-c objects.
- The 6250A trough is very deep!.

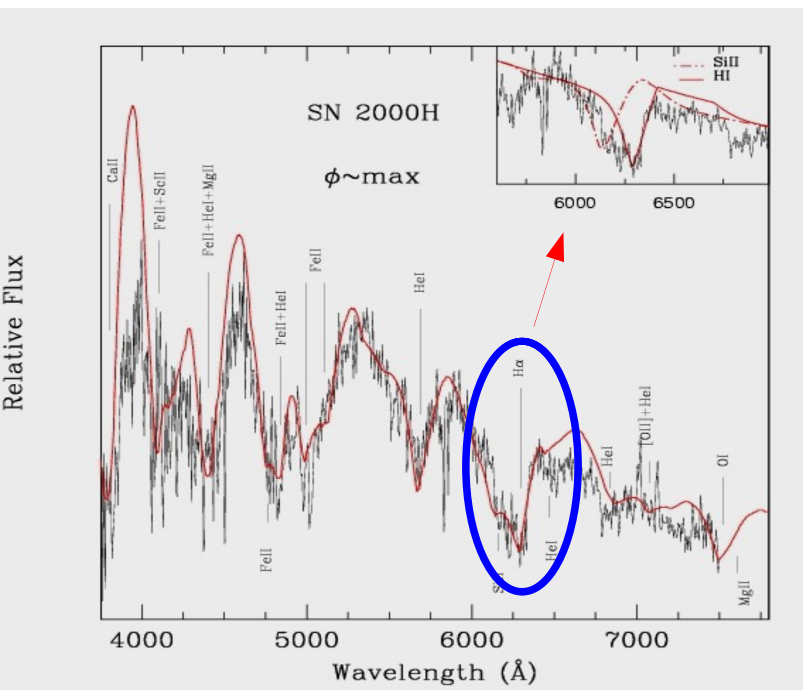
$$\mathit{Best\ fit\ at\ max\ with: Vph} = 11000 km/s; \mathit{Tbb} = 10000K$$
$$\mathit{Undetached\ HeI\ lines\ with}\ \tau(\mathit{HeI}) = 2$$

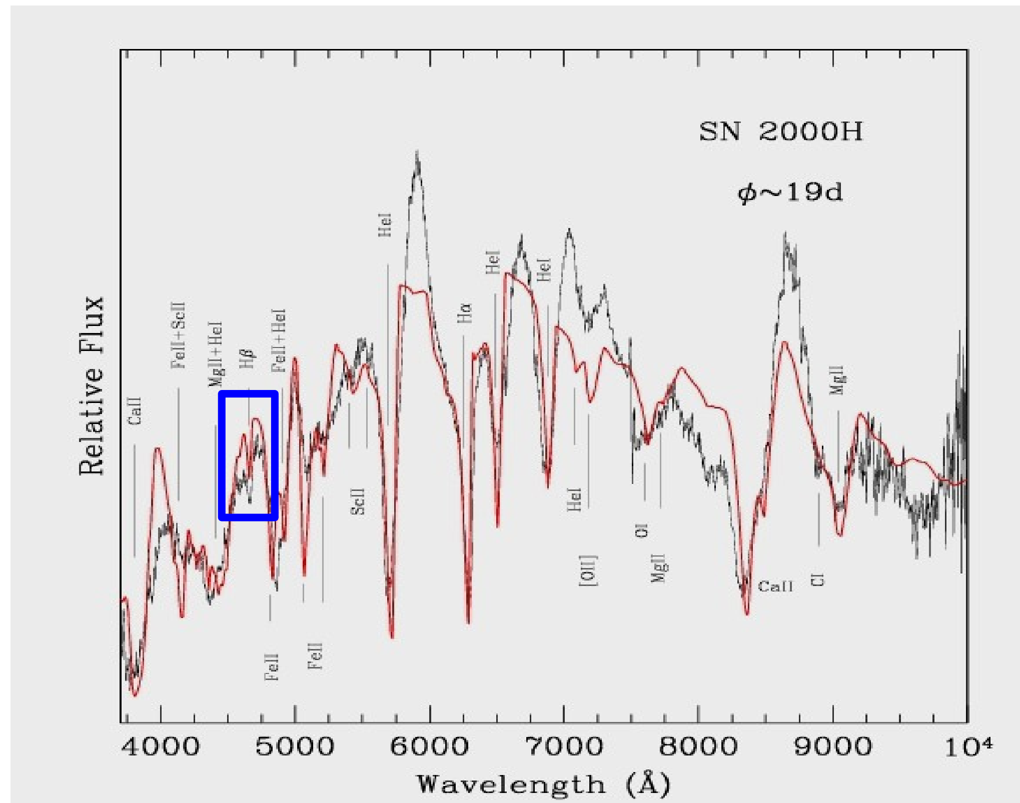
- The 6250A trough is exceptionally broad

$$\mathit{Best\ combination: detached\ H\alpha\ at}\ 13000\,km/s\ (\tau = 5.3) + \mathit{undetached\ SiII}$$

- The trough remains deep at later phases

- Noticeable change: development of He I lines at 6678A and 7065A
  Vph=6000km/s
  HeI: Vcont=2000km/s; Opt.dep=5
- HI: Vcont=8000km/s;Opt.dep=1.5
- Strong support from other HI.





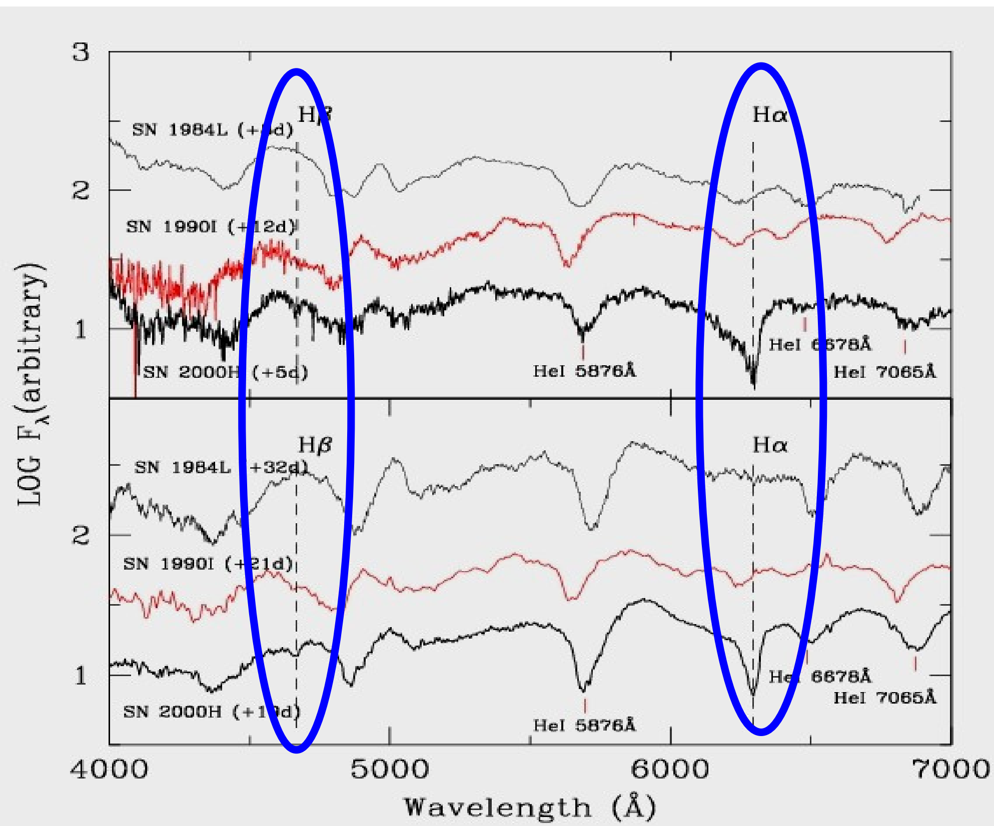
If H_α present what about H_β then?

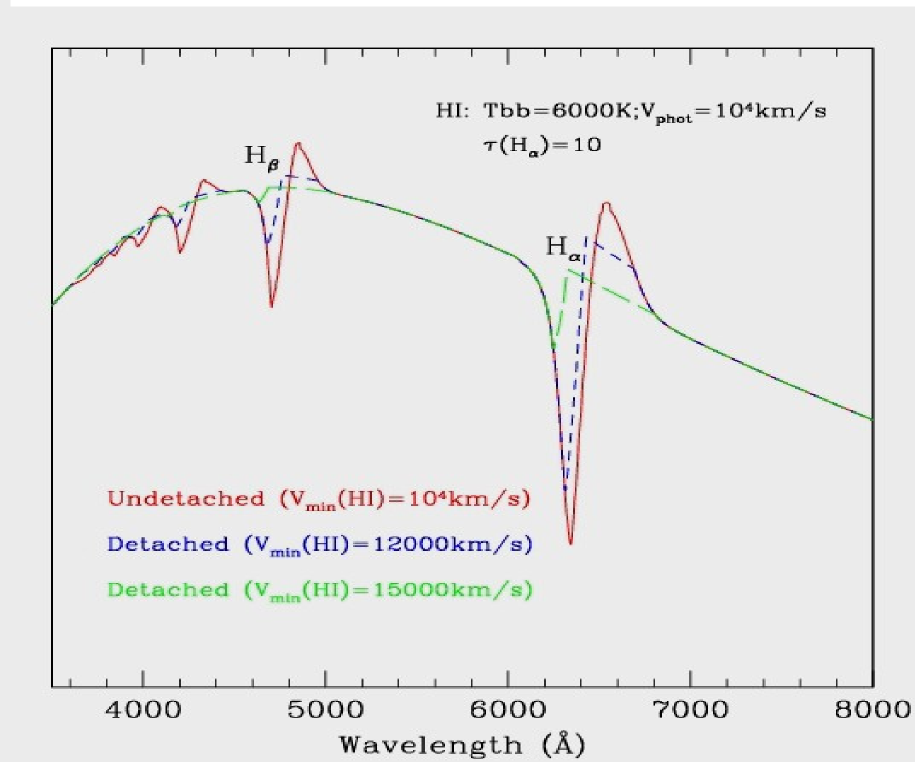
Two factors make H_β barely discernable in type Ib:

1- the optical depth sufficient to fit H_α trough is so small that the other Balmer features are too weak to be unambiguously detectable.

→ $\tau(H\alpha)$ *is about a factor 7 greater than* $\tau(H\beta)$

2- the contrast velocity of H_α is high.





Type Ic events:

SN 1994I

- Compare the spectrum at max with SSp

  → good match: Vphot=12000km/s; Tbb=7500K
- No evidence for HeI lines. The ~5800A trough: NaI
- Concerning ~6200A feature:

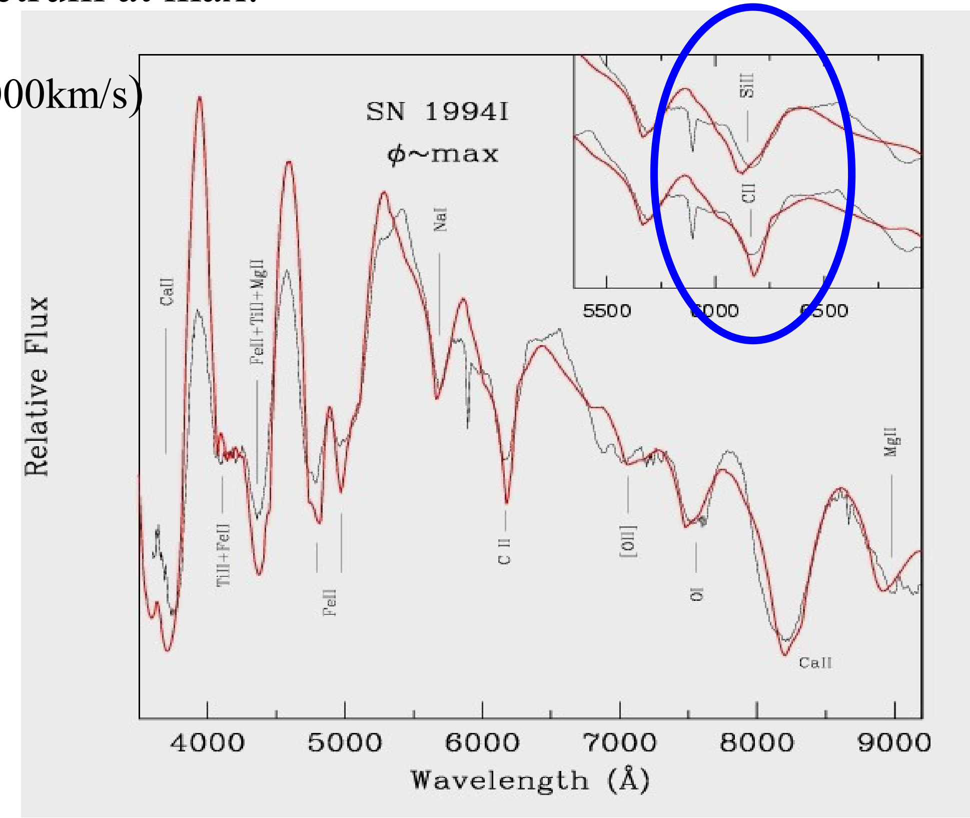
  → Millard et al early spectra: it was difficult to decide between SiII 6355A and CII6580A.

  We test the two possibilities for the spectrum at max:

  → 1- undetached Si II : somewhat blue

  2- detached high-velocity CII (Vcont=8000km/s)

We prefer detached CII as the more probable



Type IIb events:

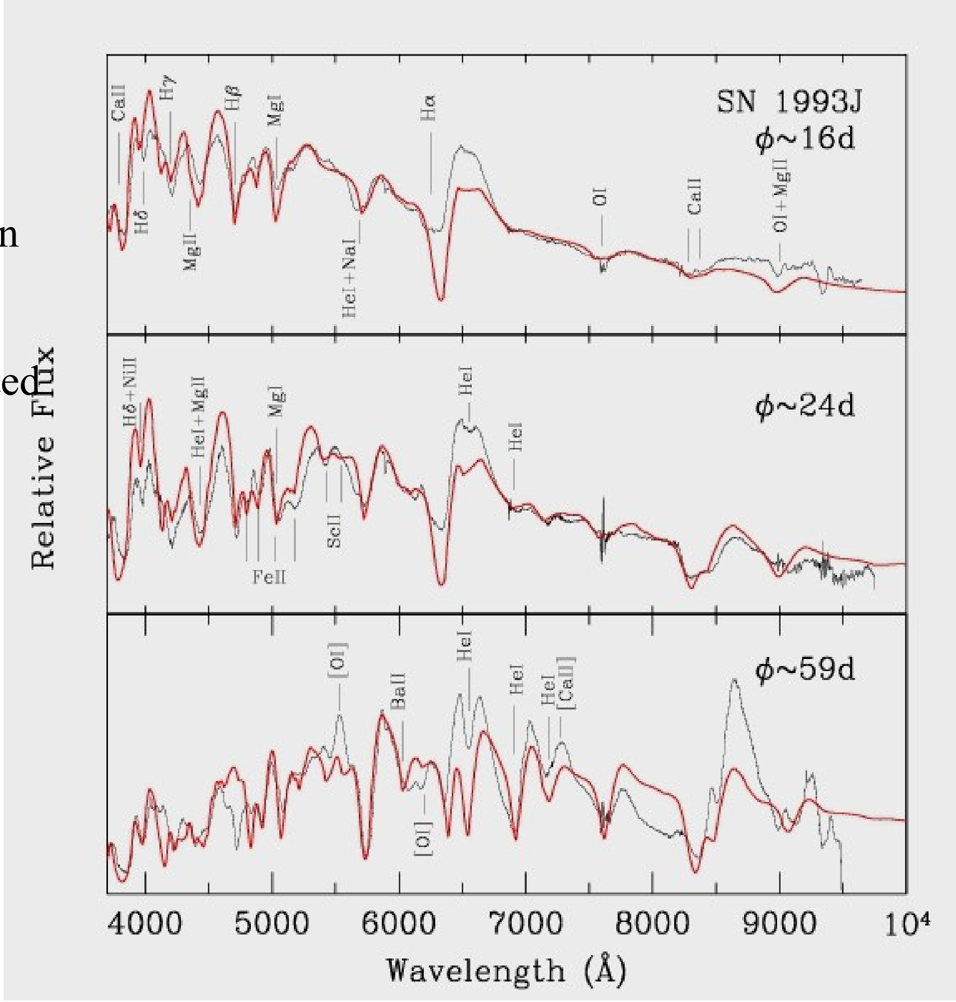
SN 1993J

- Hybrid SNe: link between Ib-c and II SNe.
- 3 epochs:

16d: Vph=9000km/s;Tbb=7800K
good match, except the strong H_α P-Cygni profile
SYNOW uses resonance scatterig source fct.
Vcont(HI)=1000km/s;Opt.dep(HI)=20
H_β, H_γ and H_δ are clearly discernible
HeI 5876A undetached with small NaI contribution

24d: Vph=8000km/s;Tbb=7000K
the notch on the H_α emission component is attributed
to HeI 6678A. HeI are still undetached.

59d: Vph=6000km/s;Tbb=5000K
HeI lines are prominent and undetached
HI Balmer lines becomes weak at this phase
Forbidden emission lines develop: transition to
the nebular pahse



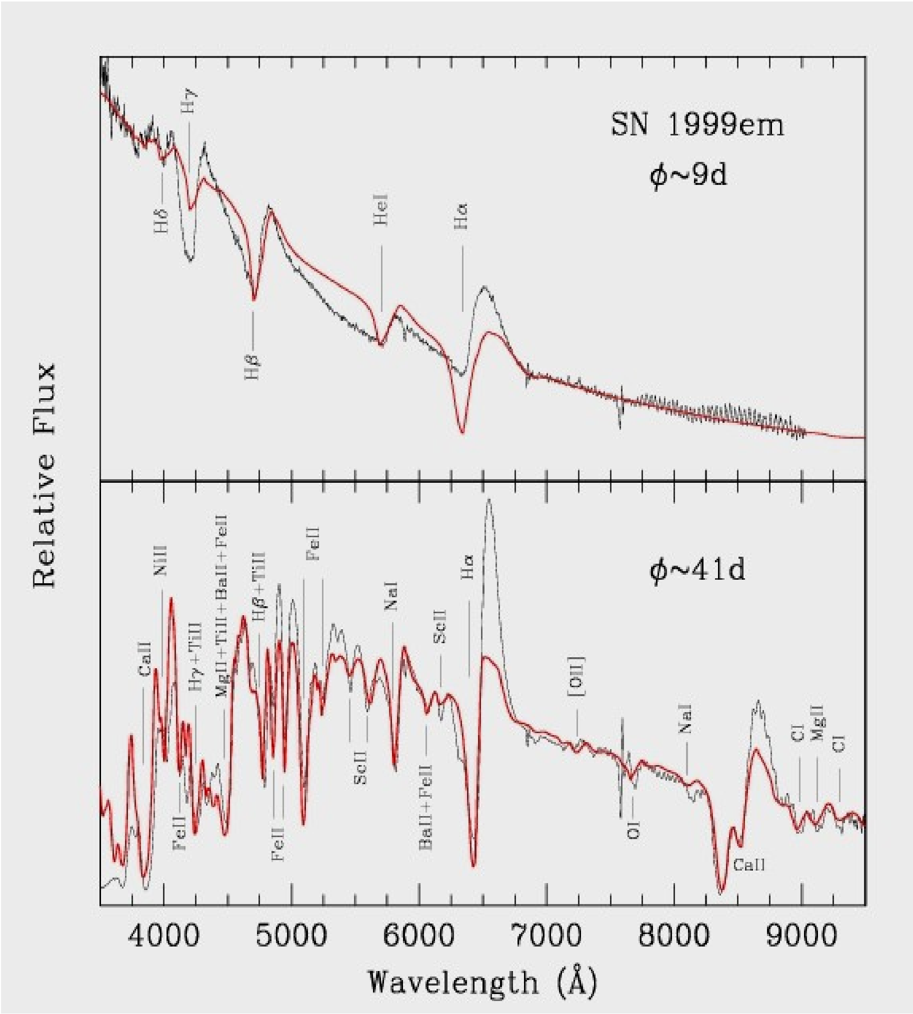
Type II events:

SN IIP 1999em

- Typical IIP features: broad HI Balmer P-Cygni profiles.
- Two photospheric phases:

9d: Vph=10000km/s;Tbb=10000K
Undetached HI Balmer and He I reproduce the most conspicuous features superimposed on the "hot" continuum.
Opt.dep(HI)=15.
As for the case of 1993J, SYNOW can not reproduce the full observed H for same reasons.
α

41d: Vph=4600km/s;Tbb=6000K
decrease in the expansion velocity → HI P-Cygni get narrower.
HI slightly detached: Vcont(H)=1000km/s;   = 20
All other lines are undetached.
α τ



Spectroscopic mass estimates

Approximate method:

The hydrogen mass required to fill an uniform-density sphere of radius 'vxt' at an epoch 'td' since explosion :

$$M(Msun) \simeq (2.38\text{x}10^{-5}) v_4^3 t_d^2 \tau(H\alpha) \quad \text{(eq .1)}$$

td in days; V4 in 10^4km/s

eq.1 is based on the equation for the Sobolev optical depth for an expanding envelope (e.g. Castor 1970; Jeffery & Branch 1990)

→ eq. 1 is applied to estimate the amount filling a spherical shell corresponding to the FWHM of the H_α absorption trough.

Results:

SN Ib 1990I: ~ 0.02 Msun
SN Ib 1983N : ~ 0.008 Msun
SN Ib 2000H : ~ 0.08 Msun

→ SN Ib: For a representative Opt.dep of 0.5 at day 20 with A hydrogen mass of 0.015 Msun is estimated

Although non-thermal excitation & NLTE effects may be also important for hydrogen, this simple approach seems to give reasonable and LOW estimates

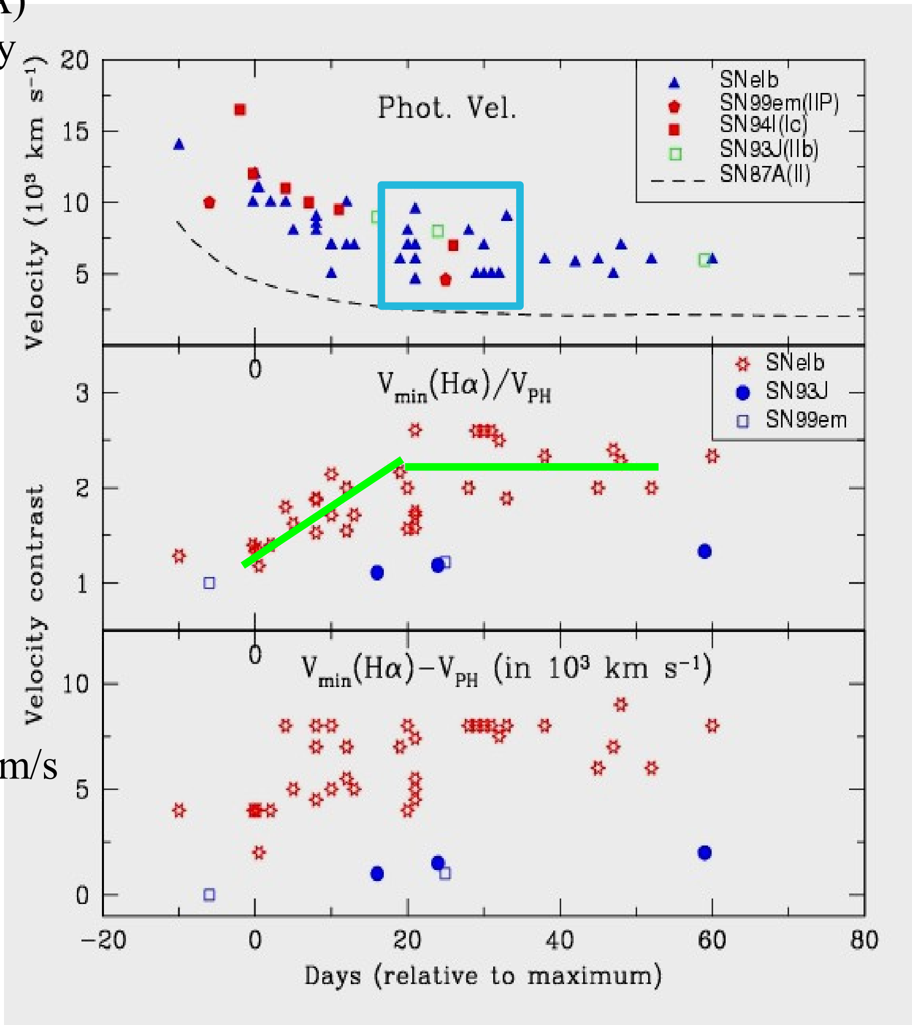
Discussion:

Velocity behaviour:

Phot. Vel (upper panel):

- Best fit results + 1987A data for comparison (FeII 5018A)
- Low velocity behaviour of SNe II (87A & 99em) at earlly and intermediate epochs
- SN Ic 94I & IIb 93J: follow similar high vel. Behaviour
- SNe Ib: display different velocity evolution.

→ The scatter increases at intermediate phases around ~20d: as high as 5000 km/s can be due to data paucity outside that time range



Contrast Vel. (middle & lower panels):

- SNe II&IIb: HI slightly detached
- SNe Ib: HI highly detached

→ Vcont increases within the first ~15d, reaching values as high as 8000km/s. Then follows almost canstant evolution.

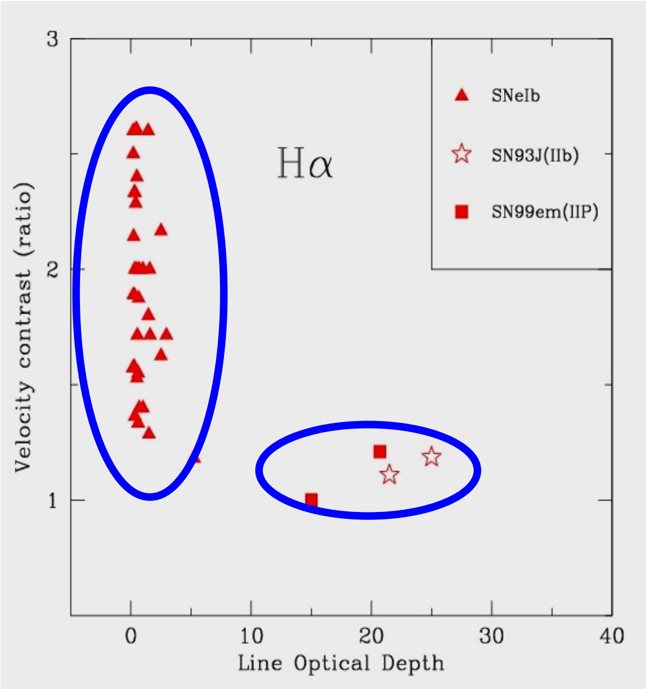
→ Up to ~60d: SNe Ib have HI down to 11000-12000km/s SNIIb 93J has HI down to 8000km/s SNe II appear to have HI down to even lowe Vel. (~5000km/s for SN 99em)

Discussion:

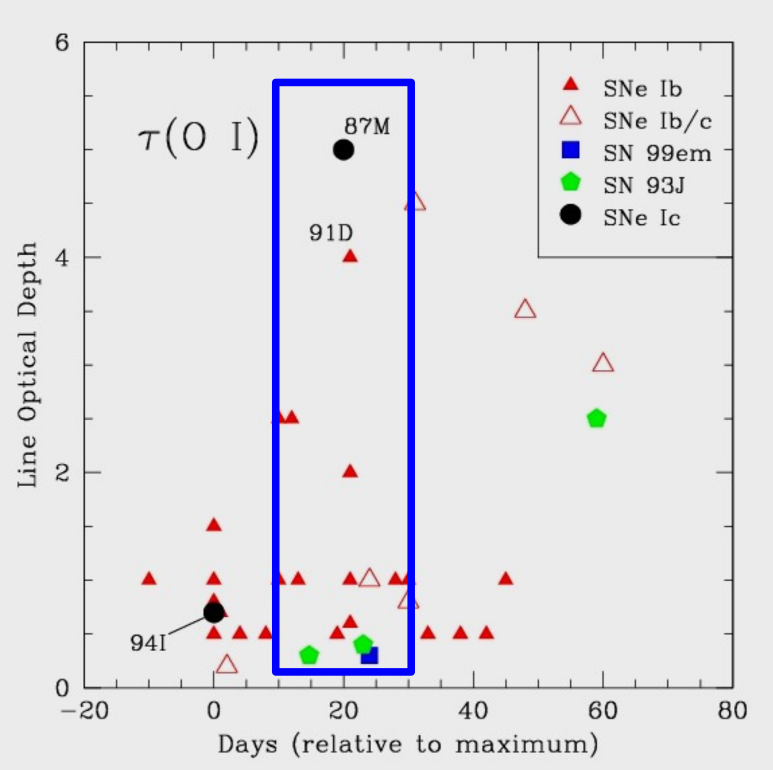
Optical depths:

H_α 6563A:

- H_α in Ib SNe: very small optical depths independently of "Vcont" and the phase
  → contrary to SNe IIb 93J & II 99em



OI 7773A



- Not easy to draw conclusions. Need for example to populate with more Ic objects.
- At intermediate epochs however, SNeIb tend to concentrate in low opt.dep region. SNIc 87M displays the deepest profile. SNe 93J&99em are events with the lowest opt.dep.

Stonger & deeper permitted oxygen: might indicate SNeIc are less diluted by the presence of He envelope.

Discussion:

Oxygen issue in CCSNe:

- Oxygen lines: more prominent for a "naked" C/O progenitor core.
- Two observational facts reinforce this belief:

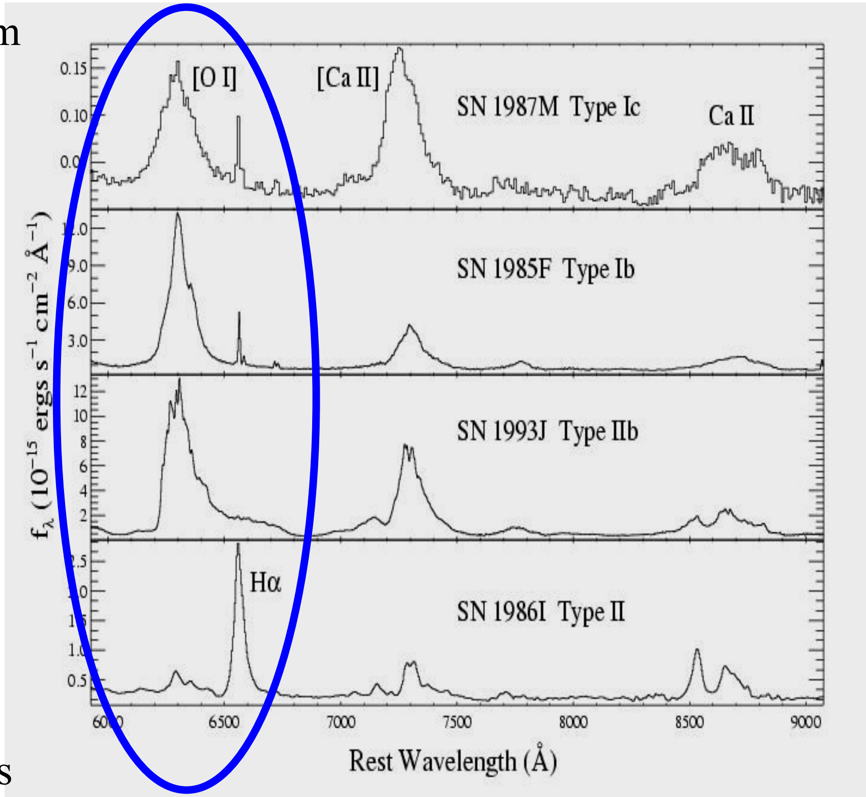
1/- Forbidden lines, especially [OI]6300,64A, seem to emerge following the sequence: **"Ic-Ib-IIb-II"**

Ic SNe: 87M&94I ~1-2 months
(Filippenko 97; Clocchiatti et al. 1996)

Ib SNe: 90I ~ 70 days (Elmhamdi et al. 2004)
& earlier in other Ib objects

IIb SNe: ~62 days in 93J (Barbon et al. 1995)
& ~80 days in 96cb (Qiu et al. 1999)

II SNe: ~150days in 87A (Catchpole 1988)
& ~ 130 days in 92H and 99em
(Clocchiatti et al 1996; Elmhamdi et al. 2003)



(Matheson et al. 2001)

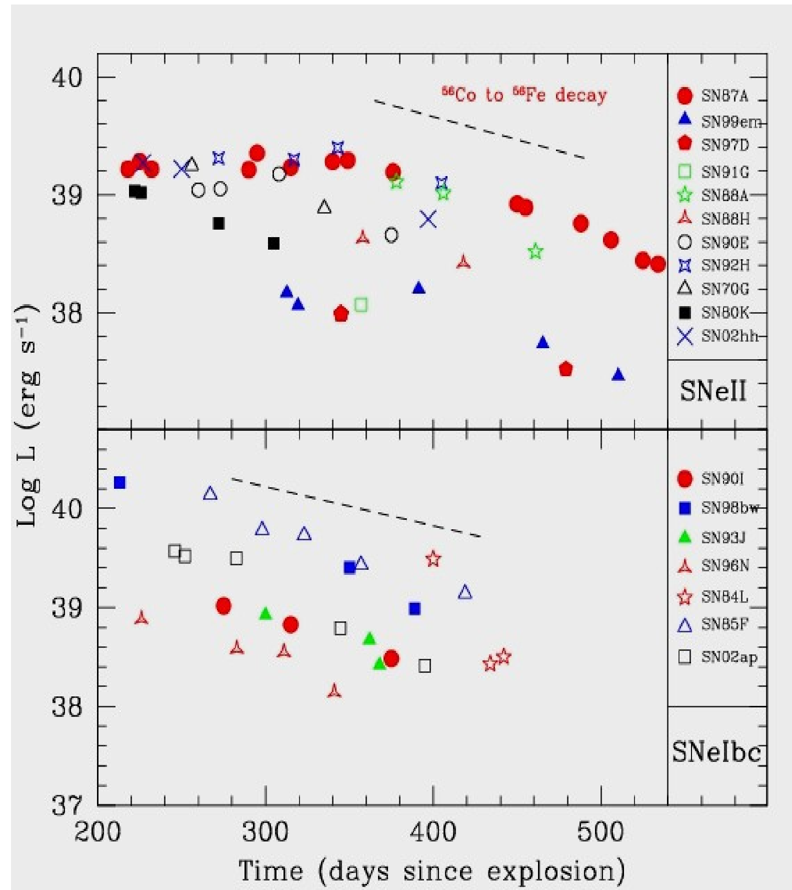
2/- The nebular emission line [OI]6300,64A looks decreasing in breadth following the above SNe order.

Discussion:

Oxygen issue in CCSNe:

(Elmhamdi & Danziger 2006, in preparation)

- CCSNe sample study: the evolution of L([OI]) at the nebular phase
  - → approximately follow the bolometric light curves (in IIP decays later than Ibc SNe)
  - → direct evidence that the dominant source of ionization and heating is γ-rays from the radioactive decay of ^{56}Co



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→ Translate this into Oxygen mass:

$$L([O\,I]) = \eta\,(Moxy/Mex) \times L(^{56}Co)$$ (eq. 2)

(Elmhamdi et al. 2003)

η : efficiency of transformation of energy deposited in Oxygen into the [OI] radiation.

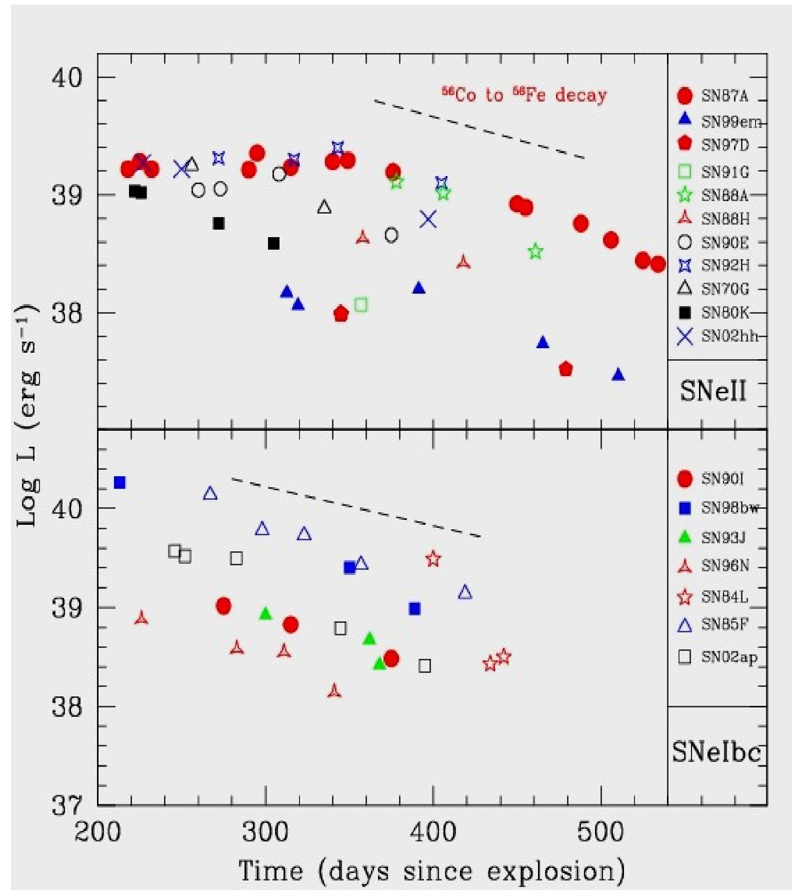
Moxy : mass of Oxygen.

Mex : the "excited" mass in which the bulk of radioactive energy is deposited

L(Co): radioactive energy input $(. \propto M_{Ni.}\, e^{-t/111.23d})$

Moxy/87A=1.5-2 Msun **(Fransson et al. 93)**

IIP SNe $\rightarrow Similar: \eta\,, Mex$



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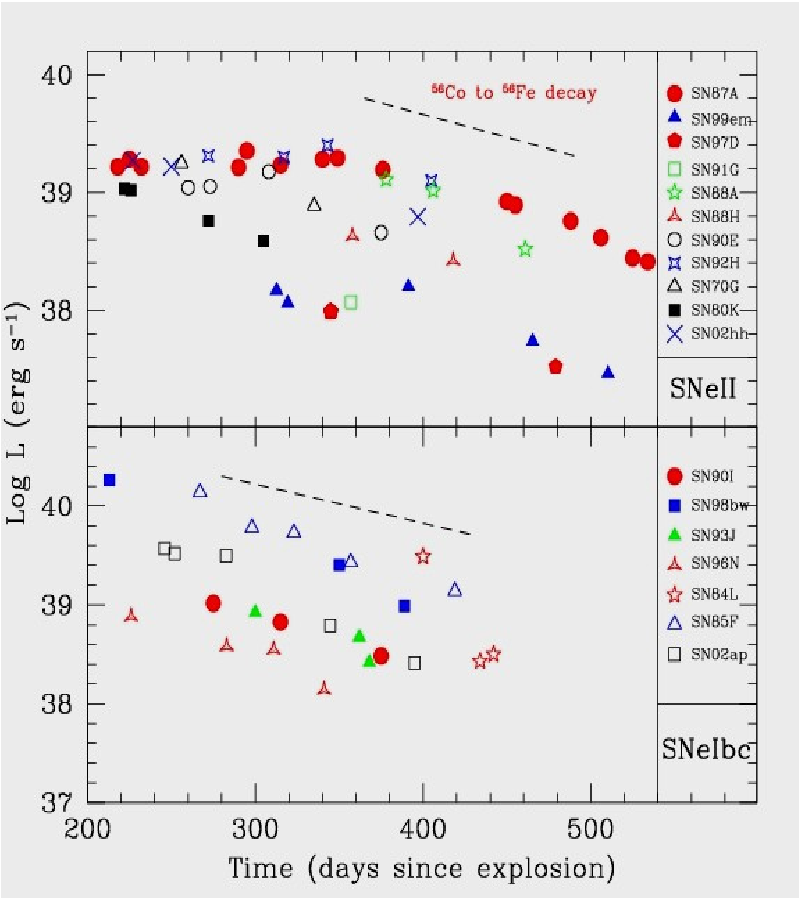
Ibc SNe

$$M_{Ox} = 10^{8} \times D^{2} \times F([O\,I]) \times \exp(2.28/T4) \quad \text{(eq. 3)}$$

(Uomoto 1986)

T4: temperature of the oxygen-emitting gas (in 10^4 K)



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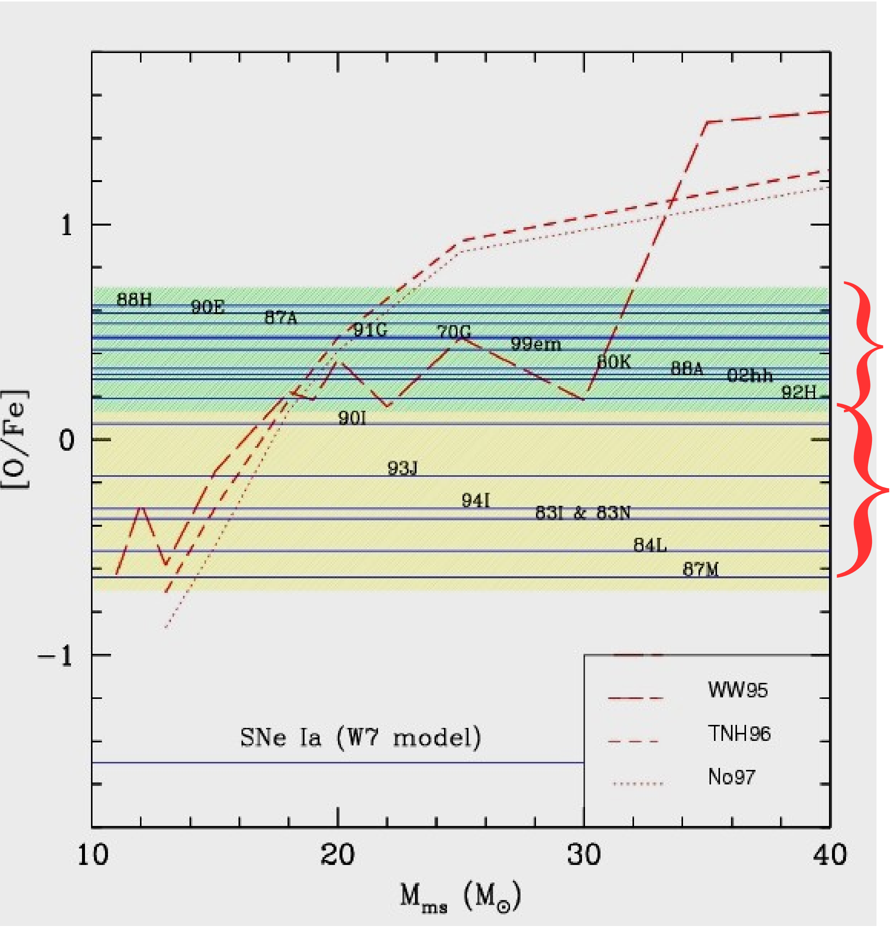

SNeII

SNeIbc

- Having in hand estimates of oxygen and iron (basically from light curves analysis)
  → use them as indicative of the CCSNe progenitors ?
  By means of: **[O/Fe]**

- Compared to initial mass according to CCSNe models:
  WW95 : Woosley & Weaver 1995
  TNH95 : Thielemann, Nomoto & Hashimoto 1996
  No97 : Nomoto et al. 1997

- Observation-based results:
  → Two separate concentration regions
  → Lower masses for SNeIbc

[O/Fe]=log10(O/Fe)_star – log10(O/Fe)_sun
log10(O/Fe)_sun=0.82; **Andres & Grevesse (1989)**

Main Conclusions:

- Hydrogen is present in "almost" all type Ib objects:
  - "almost" because: Ne I remains a possibile alternative in only 2 cases
  - Low optical depths of H_{α}
  - Low masses ~ $10^{-2} - 10^{-3}\, Msun$
  - H_{β} hardly discernible in type Ib: low $\tau(H\alpha)$ & high contrast velocity.

- Hydrogen manifests its presence in different ways within CCSNe:
  - Always confined to a detached high-velocity shells in Ib SNe + incomplete P-Cygni profiles + low τ + increasing contrast velocity in time contrary to what found for type IIb & II events.

- We describe some interesting properties related to oxygen in CCSNe:
  - Optical depths, from our fits, of the OI 7773A.
  - Appearance of the [OI] 6300,64A following the order: **Ic-Ib-IIb-II**
  - L([OI]) evolution & the possibility to recover oxygen masses.
  - Combined with Ni estimates → [O/Fe] .vs. Mms using empirical theoretical models for yields in CCSNe.
    → We found two separate regions (for SNeII & SNeIbc)

<u>Open Questions</u>

1/- Why we have imprints from hydrogen always once helium is identified ?
(question to people dealing with stellar evolution theory!!!)

2/- SNe 1994I, 1996aq, 1999ex & recently the Ic-hypernova 2005bf: presence of hydrogen?
Did type Ic SNe have hydrogen too?
How we may explain situations where the events have traces of hydrogen and no clear helium lines?
Can this be related to differences in HeI excitation? Ni distribution? Mixing?
Could these excitation conditions be the main raison for spectroscopic differences between type Ib and Ic SNe?

Surely more observations and more interest to type Ibc SNe, especially sample studies, NLTE treatement are needed ......