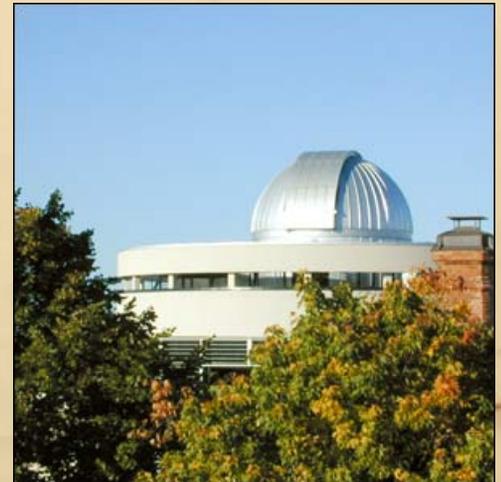


# Possible Circumstellar Interaction in SNe Ia and the Issue of Hydrogen

Peter Lundqvist

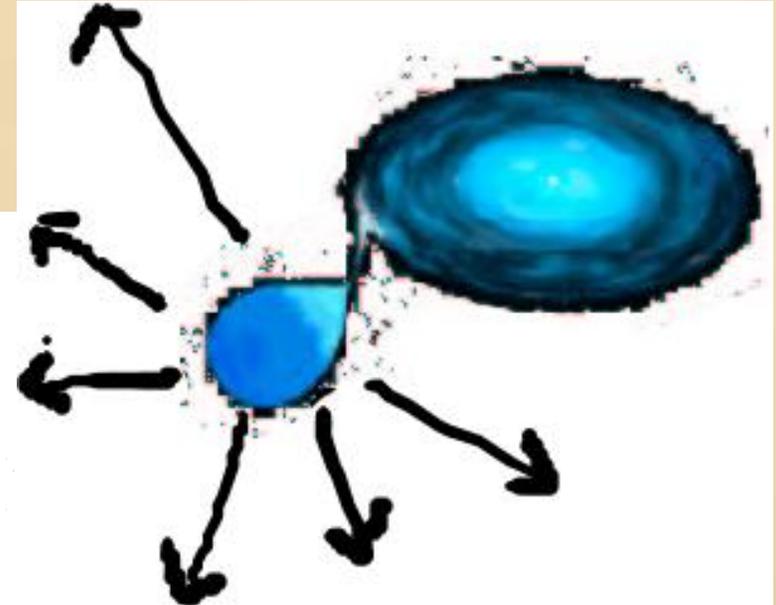
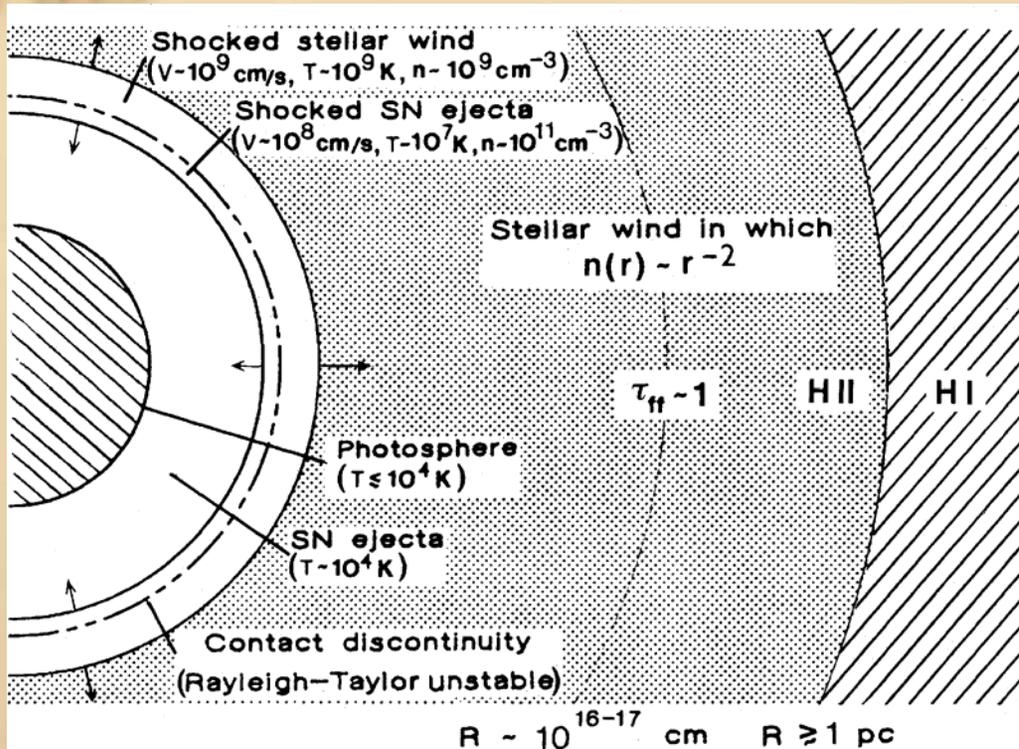
Stockholm Observatory,  
AlbaNova

(Talk at KITP, February 15, 2007)



# Testing non-conservative mass loss

Some of the mass might escape from the binary system (see van den Heuvel's Monday talk)



**Fig. 1.** Schematic picture (not to scale) of a young Type II supernova interacting with a dense circumstellar medium, originating from presupernova mass loss. Typical values of the important physical parameters are shown, as well as the boundary of the region where the free-free optical depth to the radio emission is unity and the boundary of the ionized region

We might use the same model as for young core-collapse SNe

# Model for the circumstellar interaction

Numerical solution of shock structure  
for  $3 \times 10^{-5} M_{\odot}/\text{yr}$ ,  $v_{\text{wind}} = 10 \text{ km/s}$

## SELF-SIMILAR SOLUTIONS FOR THE INTERACTION OF STELLAR EJECTA WITH AN EXTERNAL MEDIUM

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## CIRCUMSTELLAR INTERACTION IN SN 1993J

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Assume power-law dependencies on density  
for the ejecta,  $\rho \propto r^{-n}$  and the CS gas,  $\rho \propto r^{-s}$ . The  
W7 model has roughly  $n=7$ , and the wind has  $s=2$ .

PROPERTIES OF THE SELF-SIMILAR SOLUTIONS

$s$	$n$	$R_1/R_c$	$R_2/R_c$	$A$	$\rho_2/\rho_1$	$p_2/p_1$	$u_2/u_1$	$M_2/M_1$
2	7	1.299	0.970	0.27	7.8	0.27	1.058	0.82
2	12	1.226	0.987	0.038	46	0.37	1.104	2.7

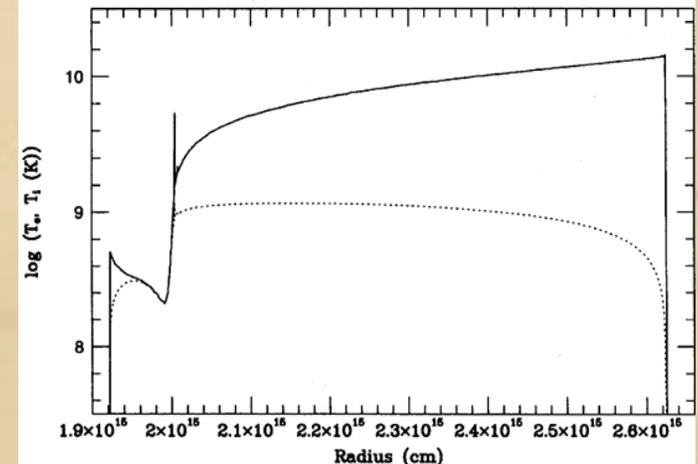
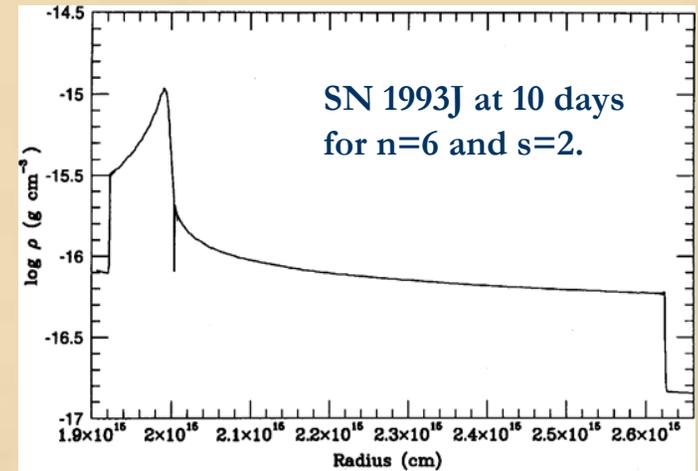


FIG. 3.—Density, electron temperature, and ion temperature for the  $s = 2$ ,  $n = 6$ ,  $M_{-5}/v_{w1} = 3$  model at 10 days. Only Coulomb heating of the electrons is assumed, leading to  $T_e \ll T_{\text{ion}}$  for the circumstellar shock.

# Ionizing Radiation

## Consists of:

- Free-free emission from the shocked ejecta (important)
- Free-free emission from the shocked CS gas (not so important)
- Photospheric emission and inverse Compton scattering thereof (can be very important early on)
- Prompt emission from shock breakout (not important)
- Radioactive decay (unimportant)
- Precursor emission (unimportant)

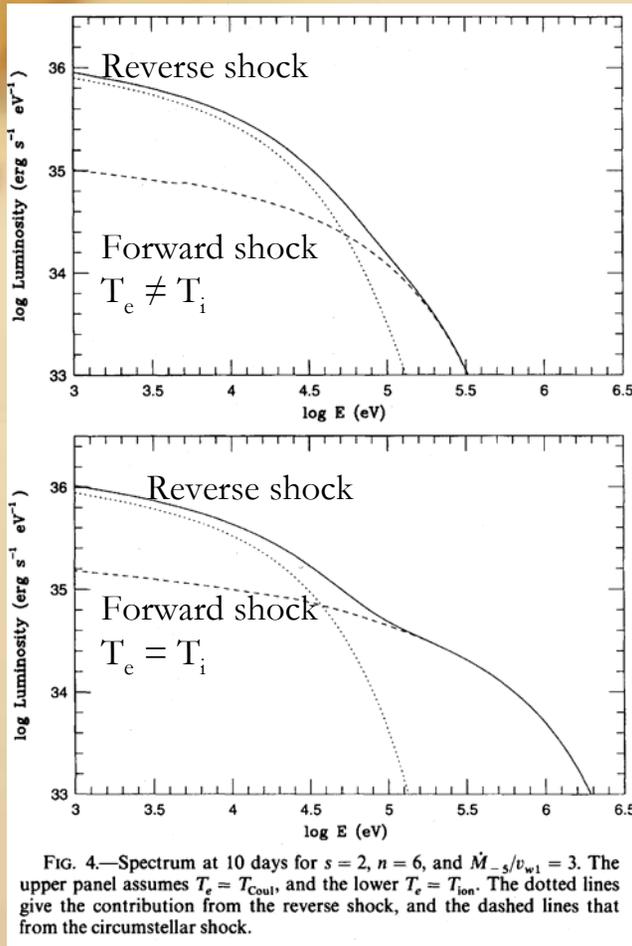


FIG. 4.—Spectrum at 10 days for  $s = 2$ ,  $n = 6$ , and  $\dot{M}_{-5}/v_{w1} = 3$ . The upper panel assumes  $T_e = T_{\text{Coul}}$ , and the lower  $T_e = T_{\text{ion}}$ . The dotted lines give the contribution from the reverse shock, and the dashed lines that from the circumstellar shock.

(Fransson et al. 1996)

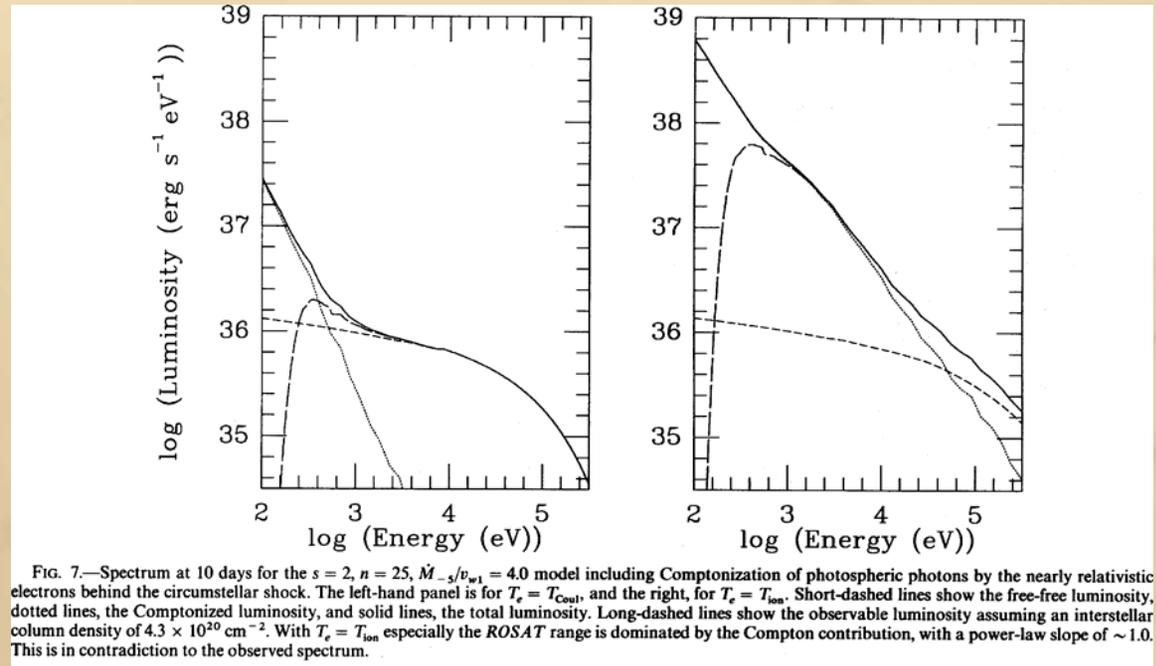
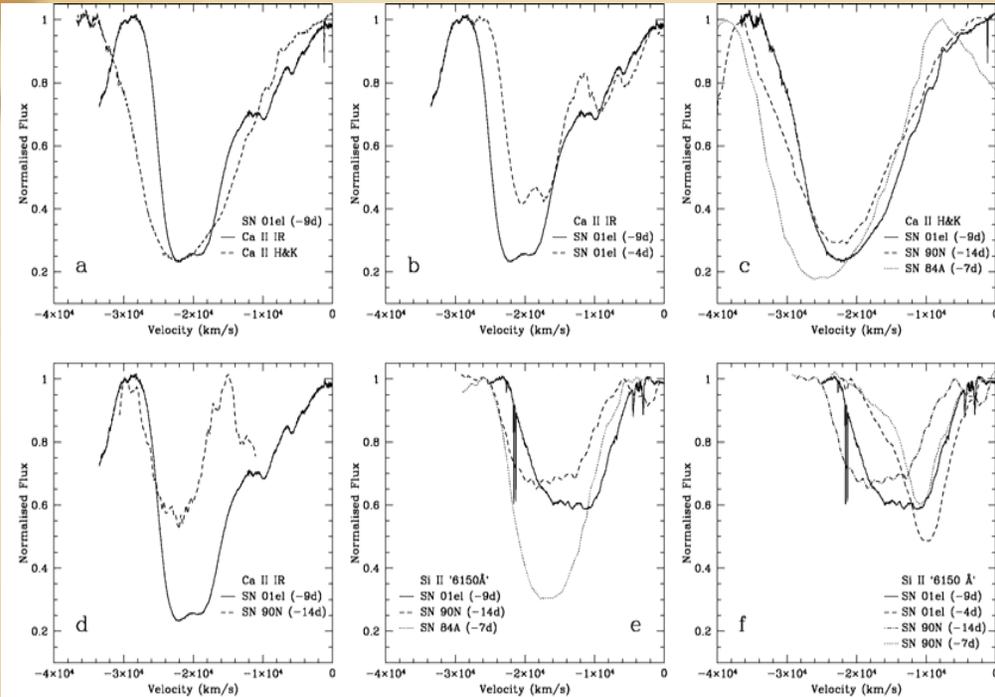


FIG. 7.—Spectrum at 10 days for the  $s = 2$ ,  $n = 25$ ,  $\dot{M}_{-5}/v_{w1} = 4.0$  model including Comptonization of photospheric photons by the nearly relativistic electrons behind the circumstellar shock. The left-hand panel is for  $T_e = T_{\text{Coul}}$ , and the right, for  $T_e = T_{\text{ion}}$ . Short-dashed lines show the free-free luminosity, dotted lines, the Comptonized luminosity, and solid lines, the total luminosity. Long-dashed lines show the observable luminosity assuming an interstellar column density of  $4.3 \times 10^{20} \text{ cm}^{-2}$ . With  $T_e = T_{\text{ion}}$  especially the ROSAT range is dominated by the Compton contribution, with a power-law slope of  $\sim 1.0$ . This is in contradiction to the observed spectrum.

# Constraints on the models

Maximum velocity of the ejecta must exceed observed ones



**Fig. 8.** a) Comparison between the Ca II IR triplet (solid line) and the Ca II H&K velocity profiles (dashed line) at  $-9$  days. b) Spectral evolution of the Ca II IR triplet from  $-9$  days (solid line) to  $-4$  days (dashed line). c) The Ca II H&K profiles in SNe 2001el at  $-9$  days (solid line), 1984A at  $-7$  days (dotted line), and SN 1990N at  $-14$  days (dashed line). d) Comparison between the Ca II IR triplet profiles of SNe 2001el (solid line) and 1990N (dashed line). Note that due to the limited wavelength coverage in SN 1990N spectrum the normalisation of its Ca II IR profile is unreliable in the red part. e) Comparisons between the Si II “6150 Å” profiles in SNe 2001el at  $-9$  days (solid line), 1984A at  $-7$  days (dotted line), and SN 1990N at  $-14$  days (dashed line). f) Spectral evolution of the Si II “6150 Å” profile in SNe 2001el (solid and dashed lines) and 1990N (dotted and dotted-dashed lines). The flux calibrated ( $f_{\lambda}$ ) spectral features have been normalised and converted to velocity space w.r.t. to the rest wavelengths assuming  $V_{\text{rec}} = 1180, 1010,$  and  $-261 \text{ km s}^{-1}$  for SNe 2001el, 1990N, and 1984A, respectively. For this we used the rest wavelengths of the bluest components of the Ca II triplet/doublet lines viz.  $8498 \text{ \AA}$  and  $3934 \text{ \AA}$ , and the Si II “6150 Å” profile of  $6347 \text{ \AA}$ .

**Table 4.** Maximum velocities for SNe 1984A, 1990N, and 2001el as indicated by the blue edges of the Ca II H&K and IR triplet and Si II “6150 Å” profiles (see Fig. 8).

SN	Epoch (days)	$V_{\text{Ca II,H\&K}}$ ( $\text{km s}^{-1}$ )	$V_{\text{Ca II,IR}}$ ( $\text{km s}^{-1}$ )	$V_{\text{Si II}}$ ( $\text{km s}^{-1}$ )
1984A	$-7^a$	38 000	–	26 000
1990N	$-14^b$	36 000	$\sim 28\,000$	26 000
2001el	$-9$	34 000	28 000	23 000

<sup>a</sup> Date of observation 1984 Jan. 10 (Wegner & McMahan (1987). The epoch adopting Jan. 17 for the *B*-band maximum light (Barbon et al. 1989).

<sup>b</sup> Date of observation 1990 June 26.2 UT (Leibundgut et al. 1991).

We require:  $V_{\text{ej,max}} \geq 4.5 \times 10^4 \text{ km/s}$  at 1 day  
(decays with time as  $\propto t^{-0.2}$ )

## Early and late time VLT spectroscopy of SN 2001el – progenitor constraints for a type Ia supernova\*

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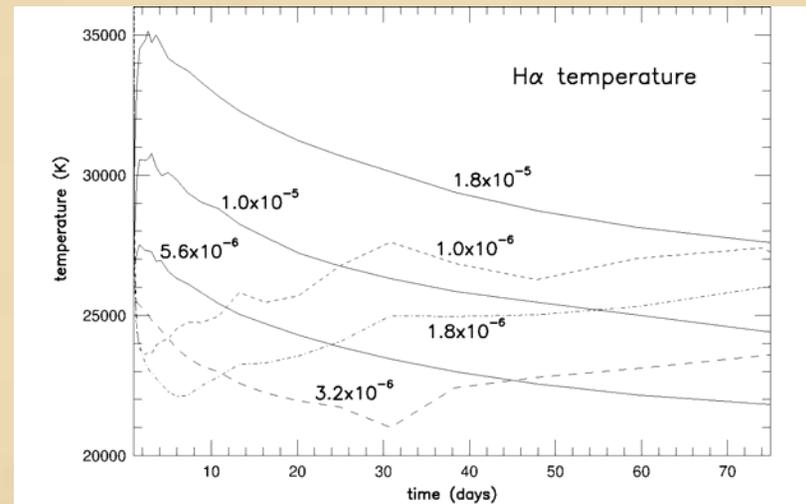
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<sup>4</sup> Department of Astronomy and Research Center for the Early Universe, University of Tokyo, Bunkyo-ku, Tokyo, Japan

# The modeling involves:

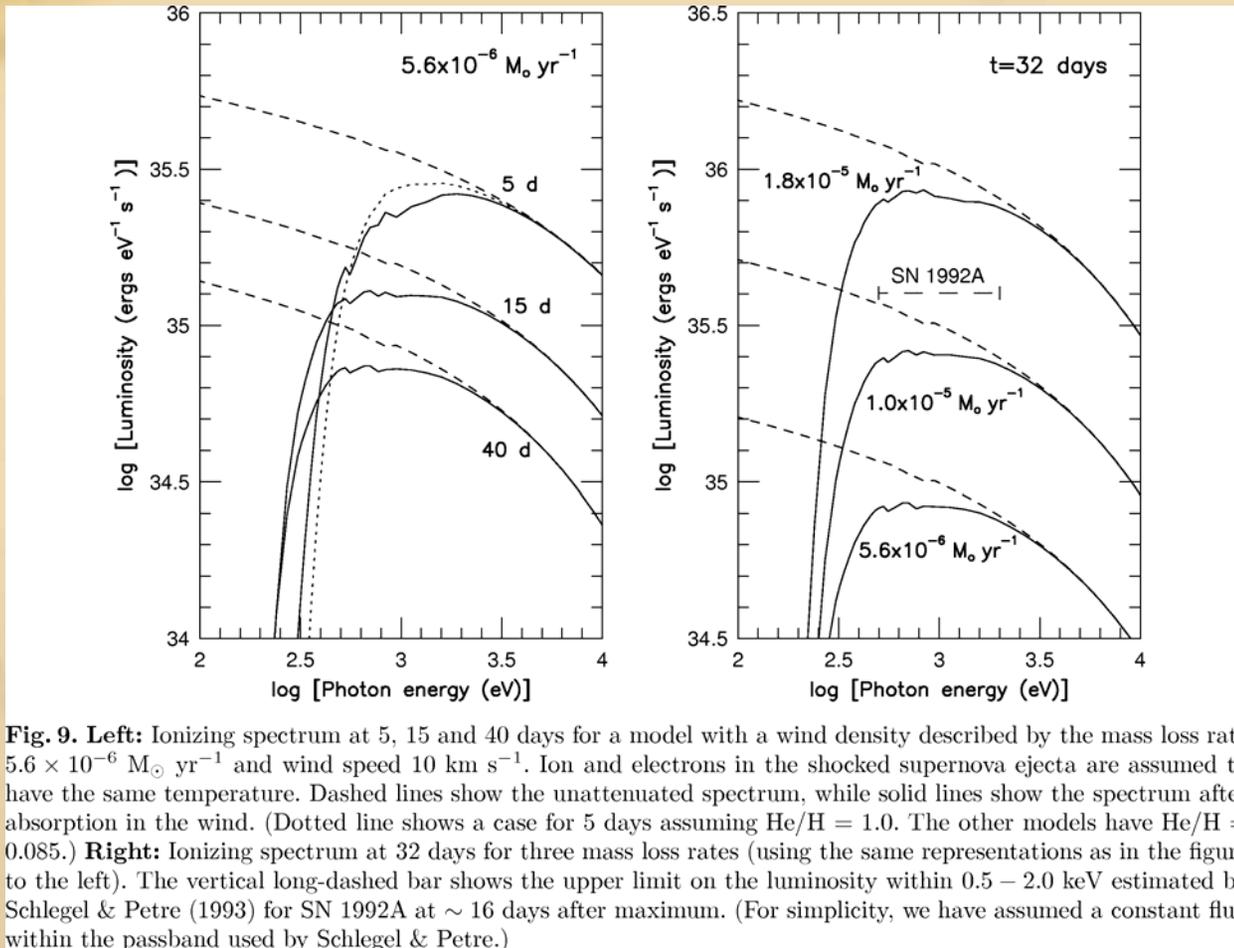
- Calculating the ionizing radiation from the reverse shock in detail, and in some models including the photospheric emission (from Blinnikov & Sorokina). Other contributions omitted. Models for  $T_e = T_i$  and  $T_e \neq T_i$  of the reverse shock have been made.
- Calculating the temperature and ionization structure of the unshocked circumstellar gas time dependently. (Elements included are H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca and Fe. Most of the ions are treated as multilevel atoms.)
- Calculating the emission of the escaping line photons.

Example of model output:



**Fig. 10.** Calculated temperature of the CS gas emitting  $H\alpha$ . (The temperature at each epoch was weighted by the luminosity of  $H\alpha$ .) We have assumed  $T_e = T_i$  behind the reverse shock, no photoionizing radiation from the photosphere, and  $He/H = 0.10$  for the CS gas. Models were made for different mass loss rates of the progenitor system, as marked in the figure in  $M_{\odot} \text{ yr}^{-1}$  for a wind speed of  $10 \text{ km s}^{-1}$ . Although the temperature is in general higher in the models with high wind density, the  $H\alpha$  temperature is rather insensitive to wind density, and also remains rather constant with time.

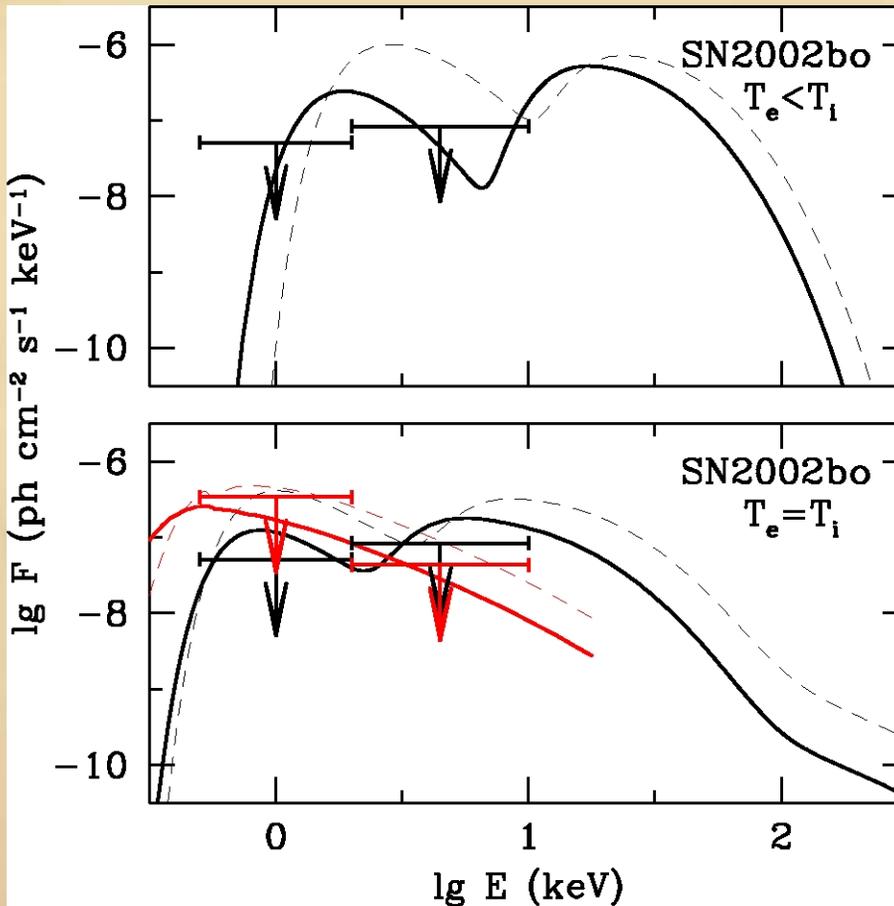
# X-ray emission and absorption



**Revised limit on mass loss rate for SN 1992A:  $< 1.3 \times 10^{-5} M_{\odot}/\text{yr}$  (for  $10 \text{ km/s}$ ) (Lundqvist et al. 2007)**

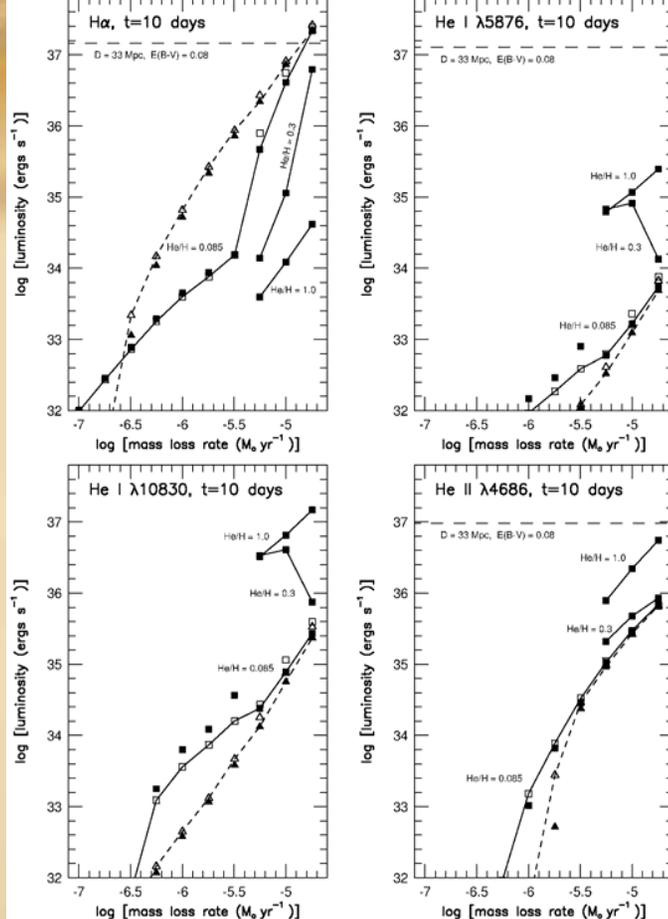
# Chandra X-ray observations of SN 2002bo

(Hughes et al., 2007)

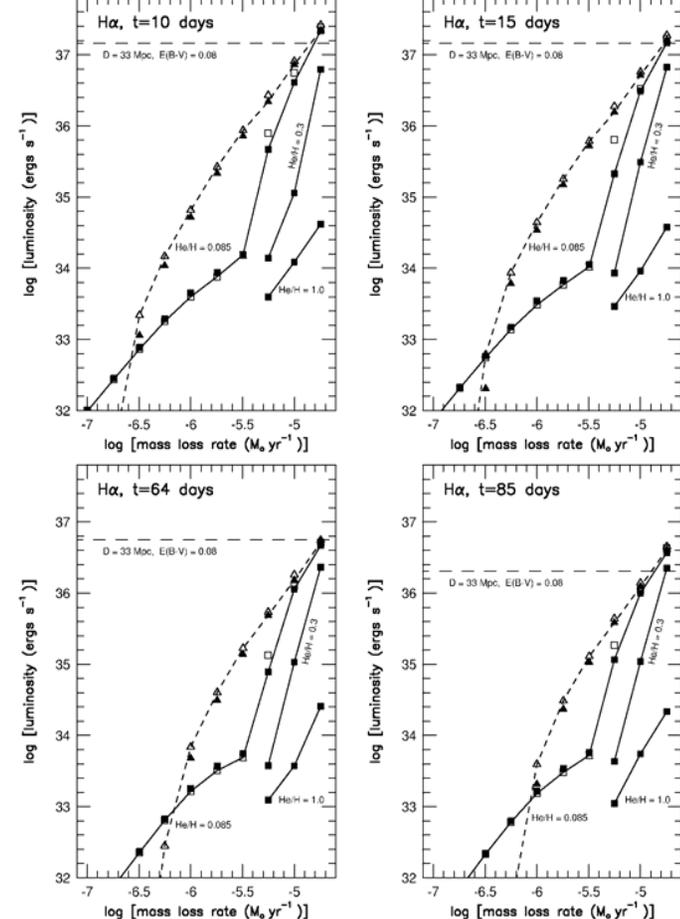


”Red” models are the same as in Lundqvist et al. (2007). Other models are described in Hughes et al. (2007). Mass loss rate limit is the same as the revised one for SN 1992A.

# Optical and near-IR lines (models compared to data.)



**Fig. 11.** Line luminosities at 10 days as a function of mass loss rate, assuming a wind speed of  $10 \text{ km s}^{-1}$ . Squares show models in which ionizing radiation is only produced by the reverse shock, while in models marked by triangles we have also included the photospheric emission from the model w7jz1155.ph of Blinnikov & Sorokina (2001). Filled symbols are for temperature equipartition between electrons and ions behind the reverse shock, whereas for open symbols  $T_e = T_{rev}/2$ . Models are shown for three values of the number density ratio He/H. The observed limit is for the first epoch in Table 2 for the case of a wind temperature of  $2.8 \times 10^4 \text{ K}$  and a wind speed of  $10 \text{ km s}^{-1}$ . For SN 2000cx we have assumed a distance of 33 Mpc and an extinction of  $E(B - V) = 0.08$ . For further details, see text.



**Fig. 12.** H $\alpha$  luminosity as a function of mass loss rate at four epochs corresponding to the epochs listed in Table 2 for SN 2000cx, assuming a wind speed of  $10 \text{ km s}^{-1}$ . The lines and symbols have the same meaning as in Fig. 11. The observed limits are for the four epochs in Table 2, assuming a wind temperature of  $2.8 \times 10^4 \text{ K}$  and a wind speed of  $10 \text{ km s}^{-1}$ .

Data are for SN 2000cx (Lundqvist et al. 2007). Limit on mass loss rate is  $1.2 \times 10^{-5} M_{\odot} / \text{yr}$  for  $10 \text{ km/s}$ .

Optical campaigns were launched in 2000 using echelle spectrographs at VLT\* and Subaru.

## Early Evolution of Nearby Type Ia Supernovae

(Probing the nature of the progenitors of thermonuclear supernovae)

### ESO runs

(**ESO Period 65 run**: April 1, 2000 - September 30, 2000)  
 (**ESO Period 66 run**: October 1, 2000 - March 31, 2001)  
 (**ESO Period 67 run**: April 1, 2001 - September 30, 2001)  
 (**ESO Period 68 run**: October 1, 2001 - March 31, 2002)  
 (**ESO Period 69 run**: April 1, 2002 - September 30, 2002)  
 (**ESO Period 70 run**: October 1, 2002 - March 31, 2003)  
 (**ESO Period 71 run**: April 1, 2003 - September 30, 2003)  
 (**ESO Period 72 run**: October 1, 2003 - March 31, 2004)  
 (**ESO Period 73 run**: April 1, 2004 - September 30, 2004)  
 (**ESO Period 75 run**: April 1, 2005 - September 30, 2005)

**Investigators:** P. Lundqvist (PI), S. Mattila, J. Sollerman,  
 E. Baron, P. Ehrenfreund, C. Fransson, B. Leibundgut, K. Nomoto  
 & **The SN Ia RTN team**

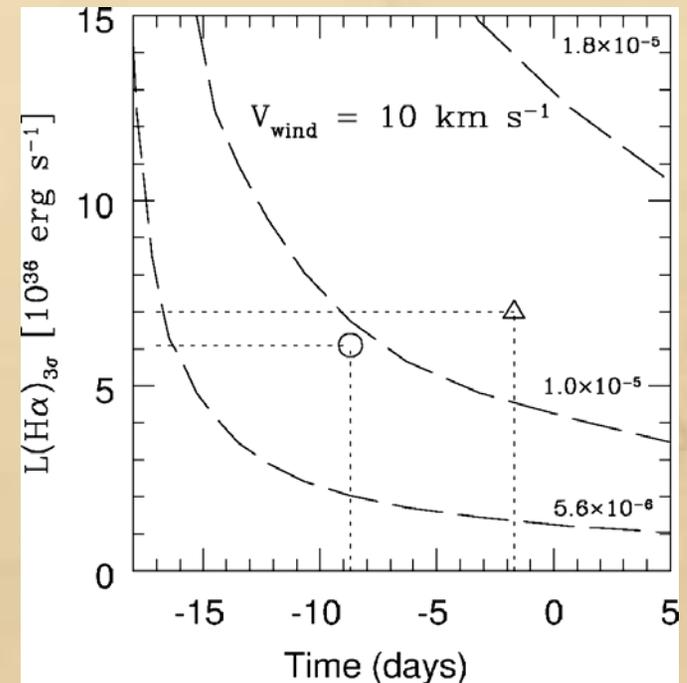
### Subaru runs

(**Subaru Semester S04A run**: April 1, 2004 - September 30, 2004)  
 (**Subaru Semester S04B run**: October 1, 2004 - March 31, 2005)  
 (**Subaru Semester S05A run**: April 1, 2004 - August 31, 2005)

**Investigators:** P. Lundqvist (PI), S. Mattila, K. Nomoto, J.  
 Sollerman,  
 H. Ando, J. Deng, P. Ehrenfreund, C. Fransson, R. Kotak, K.  
 Maeda, A. Tajitsu, H. Terada

Last updated - June 11, 2005  
 by [Peter Lundqvist, peter@astro.su.se](mailto:peter@astro.su.se)

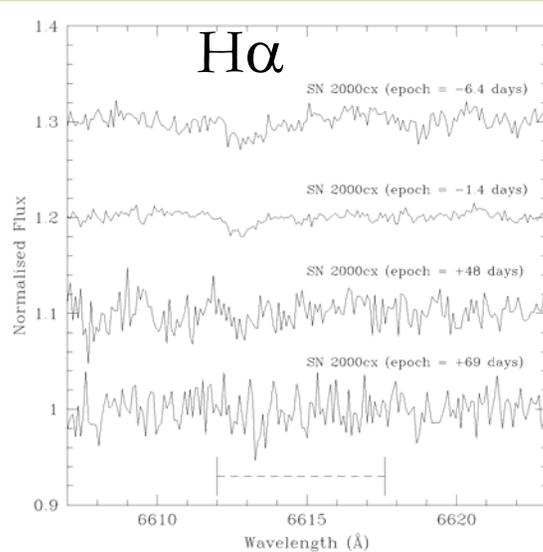
For a smooth  $r^{-2}$  wind it is important to do very early observations. One could then reach down to a few  $\times 10^{-6} M_{\odot}/\text{yr}$ .



(Mattila et al. 2005)

\* / Part of the EU-RTN

# Results from the optical observations (SN 2000cx)



**Fig. 1.** Normalized UVES spectra in the expected spectral region around H $\alpha$  for SN 2000cx on four epochs: July 20.3, July 25.3, September 3.2, and October 12.3 (UT) 2000. The expected wavelength range of H $\alpha$  is marked with a horizontal dashed line. No signs of CS H $\alpha$  lines are visible either in emission or absorption (note that the feature at 6613 Å visible in the SN 2000cx spectra has been identified to be due to instrumental/atmospheric effects).

**Table 2.**  $3\sigma$  upper limits on CS emission line fluxes of SN 2000cx. (Fluxes are not dereddened.)

Julian day (24500+)	epoch <sup>a</sup> (days)	line	FWHM (km s <sup>-1</sup> )	flux (ergs s <sup>-1</sup> cm <sup>-2</sup> )
1745.8	-6.4	H $\alpha$	37 <sup>b</sup>	8.4(-17) <sup>c</sup>
		H $\alpha$	62 <sup>d</sup>	1.3(-16)
		H $\alpha$	106 <sup>e</sup>	1.5(-16)
		H $\alpha$	203 <sup>f</sup>	2.3(-16)
		He I <sup>g</sup>	21 <sup>b</sup>	7.2(-17)
		He I <sup>g</sup>	53 <sup>d</sup>	1.1(-16)
1750.8	-1.4	He II <sup>h</sup>	21 <sup>b</sup>	4.7(-17)
		He II <sup>h</sup>	53 <sup>d</sup>	7.9(-17)
		H $\alpha$	37 <sup>b</sup>	8.7(-17)
		H $\alpha$	62 <sup>d</sup>	1.4(-16)
		He I <sup>g</sup>	21 <sup>b</sup>	7.2(-17)
		He I <sup>g</sup>	53 <sup>d</sup>	1.3(-16)
1799.7	+47.5	He II <sup>h</sup>	21 <sup>b</sup>	4.0(-17)
		He II <sup>h</sup>	53 <sup>d</sup>	7.7(-17)
		H $\alpha$	37 <sup>b</sup>	3.1(-17)
		H $\alpha$	62 <sup>d</sup>	4.8(-17)
1820.7	+68.5	H $\alpha$	37 <sup>b</sup>	1.3(-17)
		H $\alpha$	62 <sup>d</sup>	1.7(-17)
		H $\alpha$	106 <sup>e</sup>	2.0(-17)
		H $\alpha$	203 <sup>f</sup>	3.0(-17)

<sup>a</sup>Relative to *B*-band maximum (JD2451752.2, Li et al. 2001). To obtain the time since explosion used in, e.g., Figs. 11 and 12, a rise time of 16 days was assumed (as found for SN 1994D in Riess et al. 1999).

<sup>b</sup>Assuming  $T = 2.8 \times 10^4$  K and  $v = 10$  km s<sup>-1</sup> for the wind.

<sup>c</sup>9.2(-17) stands for  $9.2 \times 10^{-17}$ .

<sup>d</sup>Assuming  $T = 2.8 \times 10^4$  K and  $v = 50$  km s<sup>-1</sup> for the wind.

<sup>e</sup>Assuming  $T = 2.8 \times 10^4$  K and  $v = 100$  km s<sup>-1</sup> for the wind.

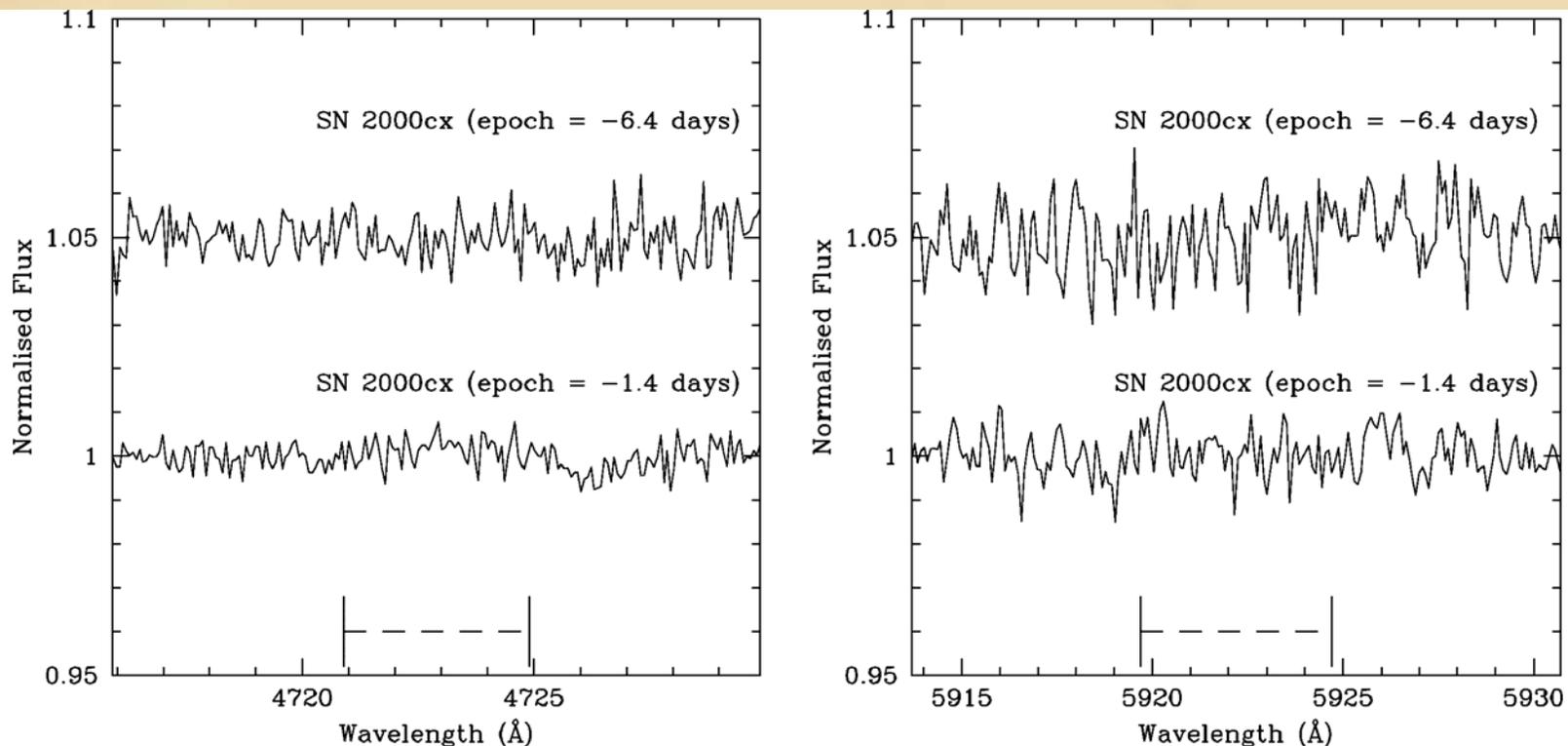
<sup>f</sup>Assuming  $T = 2.8 \times 10^4$  K and  $v = 200$  km s<sup>-1</sup> for the wind.

<sup>g</sup>He I  $\lambda$ 5876

<sup>h</sup>He II  $\lambda$ 4686

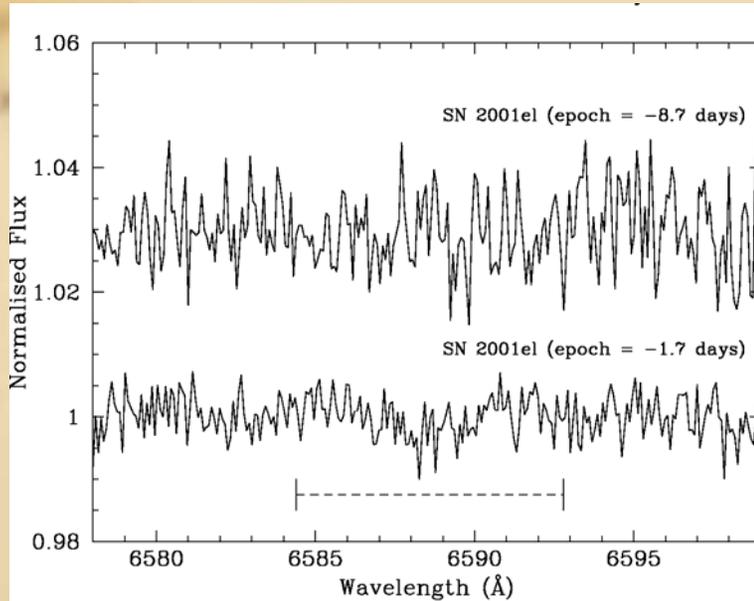
(Lundqvist et al. 2007)

## SN 2000cx: helium lines

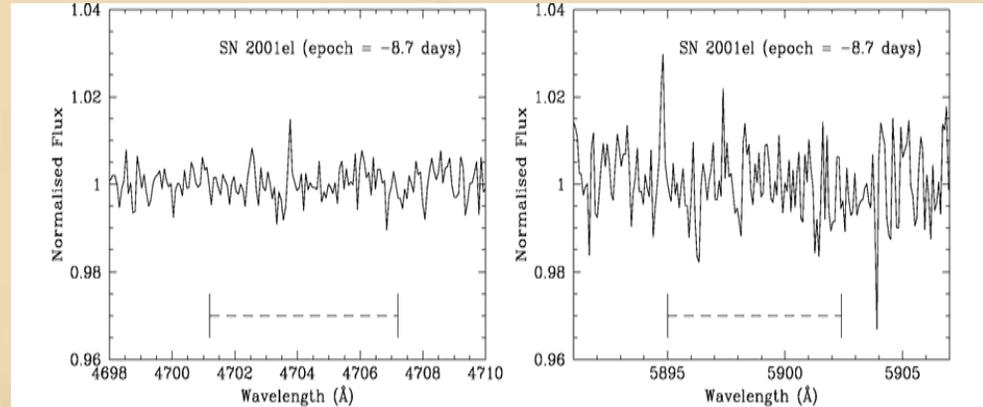


**Fig. 2.** Normalized UVES spectra in the expected spectral regions around He II  $\lambda 4686$  and He I  $\lambda 5876$ ) for SN 2000cx on two epochs July 20.3, July 25.3 (UT) 2000. The expected wavelength range of the CS line is marked with a horizontal dashed line. No signs of CS lines are visible either in emission or absorption.

# SN 2001el



**Fig. 3.** Normalised and rebinned ( $\sim 4 \text{ km s}^{-1} \text{ pixel}^{-1}$ ) UVES spectra in the expected spectral region around  $H\alpha$  for SN 2001el on two epochs, September 21.3 and 28.3 (UT) 2001, i.e., 8.7 and 1.7 days before the SN maximum light, respectively. The expected wavelength range of  $H\alpha$  is marked with a horizontal dashed line, and the upper spectrum has been shifted vertically for clarity. No significant emission or absorption lines are visible.



**Fig. 4.** Normalised and rebinned ( $\sim 4 \text{ km s}^{-1} \text{ pixel}^{-1}$ ) UVES spectra in the expected spectral regions around He II (4686 Å) and He I (5876 Å) for SN 2001el on September 21.3 (UT) 2001, i.e., 8.7 days before the maximum light. The expected wavelength range of the CSM lines is marked with a horizontal dashed line. No significant emission or absorption lines are visible.

Limit on mass loss rate:  $9 \times 10^{-6} M_{\odot}/\text{yr}$  (for a  $10 \text{ km/s}$  wind) (Mattila et al. 2005).

# Radio observations of SNe Ia

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## A SEARCH FOR RADIO EMISSION FROM TYPE Ia SUPERNOVAE

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 CHRISTOPHER J. STOCKDALE,<sup>6</sup> AND KIMBERLY P. MURATA<sup>7</sup>

Received 2006 February 21; accepted 2006 March 29

Using Chevalier's model  
 From 1983 and adopting  
 scaling of emission from SNe  
 Ib and Ic, Panagia et al. (2006)  
 obtain very low upper limits  
 on the wind density.

TABLE 3  
 LOWEST UPPER LIMITS TO SN Ia PROGENITOR MASS-LOSS RATES

SN (1)	Distance (Mpc) (2)	Epoch (days) (3)	Wavelength (cm) (4)	Radio Luminosity <sup>a</sup> (ergs <sup>-1</sup> Hz <sup>-1</sup> ) (5)	$\dot{M}^b$ ( $M_{\odot}$ yr <sup>-1</sup> ) (6)
1980N.....	23.3	71	6	$2.5 \times 10^{26}$	$1.1 \times 10^{-6}$
1981B.....	16.6	17	6	$6.5 \times 10^{25}$	$1.3 \times 10^{-7}$
1982E.....	23.1	1416	20	$2.3 \times 10^{26}$	$7.3 \times 10^{-6}$
1983G.....	17.8	71	6	$5.0 \times 10^{25}$	$4.1 \times 10^{-7}$
1984A.....	17.4	74	6	$7.1 \times 10^{25}$	$5.3 \times 10^{-7}$
1985A.....	26.8	55	20	$1.2 \times 10^{26}$	$2.5 \times 10^{-7}$
1985B.....	28.0	69	20	$3.1 \times 10^{26}$	$6.1 \times 10^{-7}$
1986A.....	46.1	57	6	$2.6 \times 10^{26}$	$9.2 \times 10^{-7}$
1986G.....	5.5	28	6	$5.0 \times 10^{25}$	$1.7 \times 10^{-7}$
1986O.....	28	71	6	$1.3 \times 10^{26}$	$7.4 \times 10^{-7}$
1987D.....	30	83	6	$1.3 \times 10^{26}$	$8.4 \times 10^{-7}$
1987N.....	37.0	67	20	$4.2 \times 10^{26}$	$7.4 \times 10^{-7}$
1989B.....	11.1	15	3.6	$8.1 \times 10^{24}$	$3.3 \times 10^{-8}$
1989M.....	17.4	50	6	$9.2 \times 10^{25}$	$4.4 \times 10^{-7}$
1990M.....	39.4	32	3.6	$1.5 \times 10^{26}$	$5.4 \times 10^{-7}$
1991T.....	14.1	28	3.6	$2.3 \times 10^{25}$	$1.5 \times 10^{-7}$
1991bg.....	17.4	29	3.6	$1.1 \times 10^{26}$	$2.0 \times 10^{-7}$
1992A.....	24.0	29	6	$4.1 \times 10^{25}$	$1.6 \times 10^{-7}$
1994D.....	14	61	6	$2.8 \times 10^{25}$	$2.5 \times 10^{-7}$
1995al.....	30	17	20	$1.7 \times 10^{26}$	$1.2 \times 10^{-7}$
1996X.....	30	66	3.6	$1.9 \times 10^{26}$	$1.2 \times 10^{-6}$
1998bu.....	11.8	28	3.6	$1.3 \times 10^{25}$	$1.1 \times 10^{-7}$
1999by.....	11.3	15	3.6	$2.1 \times 10^{25}$	$8.0 \times 10^{-8}$
2002bo.....	22	95	20	$6.8 \times 10^{25}$	$3.0 \times 10^{-7}$
2002cv.....	22	41	20	$6.8 \times 10^{25}$	$3.0 \times 10^{-7}$
2003hv.....	23	61	3.6	$6.2 \times 10^{25}$	$5.8 \times 10^{-7}$
2003if.....	26.4	68	3.6	$8.1 \times 10^{25}$	$7.6 \times 10^{-7}$

<sup>a</sup> The spectral luminosity upper limit ( $2\sigma$ ), as estimated at the wavelength given in col. (4), which, when combined with the age of the SN at the time of observation, yielded the lowest mass-loss rate limit.

<sup>b</sup> The upper limit ( $2\sigma$ ) to the mass-loss rate,  $\dot{M}$ , is calculated from the spectral luminosity lowest upper limit given in col. (5), as measured at the wavelength given in col. (4) at an epoch after explosion given in col. (3). The mass-loss limits are calculated with the assumption that the SN Ia progenitor systems can be modeled by the known properties of SN Ib/c progenitor systems, and that the pre-SN wind velocity establishing the CSM is  $v_{\text{wind}} = 10 \text{ km s}^{-1}$ .

# Ongoing radio program

Australia Telescope Compact Array

2006OCTS / C1303

## Probing the radio emission from a young Type Ia supernova

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Stuart Ryder	sdr@aao.gov.au	Anglo-Australian Observatory	Australia	No	No

As radio observations do appear to be the most sensitive to detect smooth mass loss, we are since 2004 running a program at ATCA as well as doing modeling.

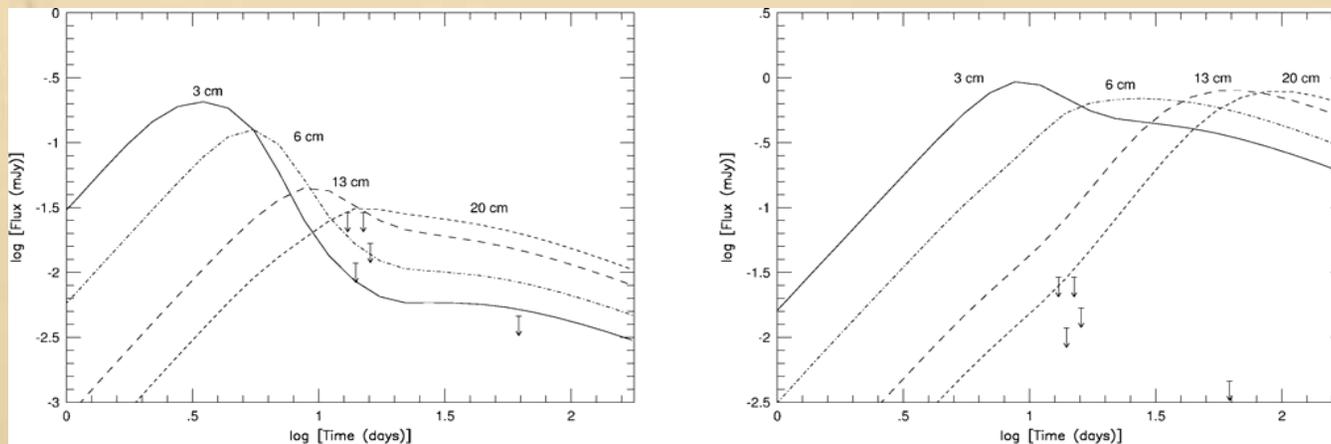
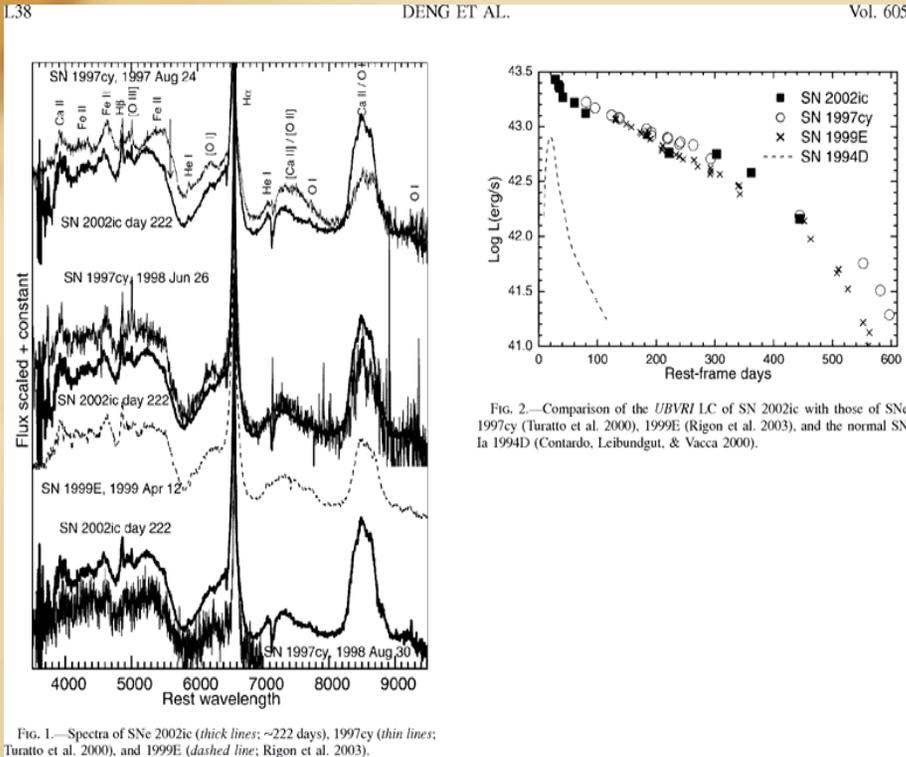


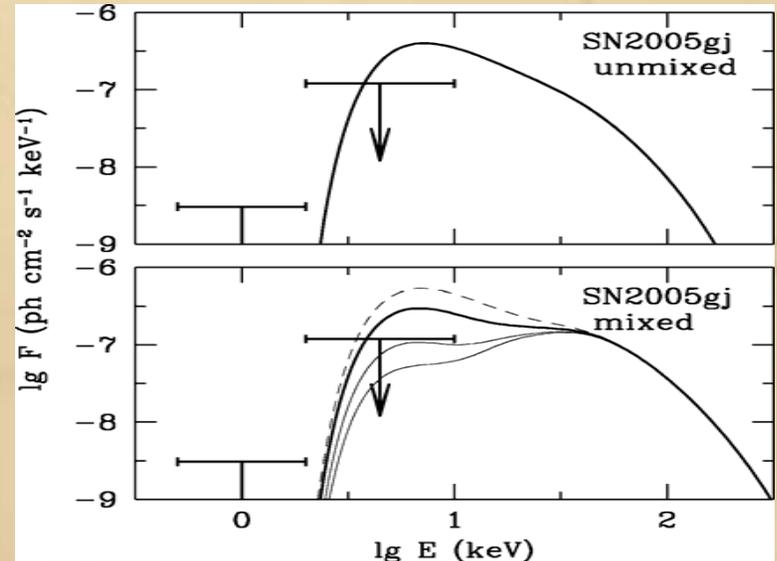
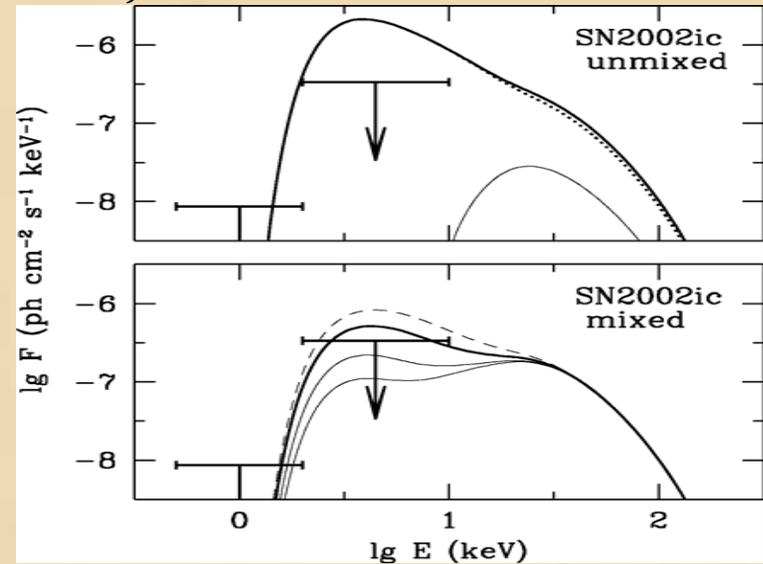
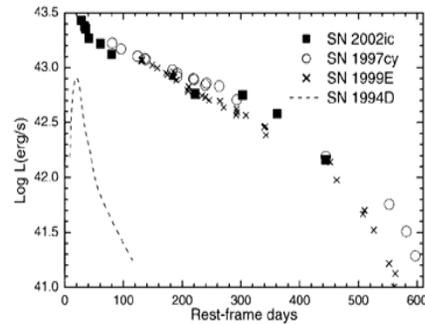
Figure 1: Radio light curves for a mass loss rate of  $10^{-7} M_{\odot} \text{ yr}^{-1}$  (for  $V_{\text{wind}} = 10 \text{ km s}^{-1}$ ) and two assumptions about the ratio of the energy densities of the magnetic field and relativistic electron density: 1% (left) and 10% (right). The expansion velocity on day 1 after explosion is  $50,000 \text{ km s}^{-1}$ , and the ejecta density decreases as  $r^{-7}$  (e.g., Chevalier 1982). All cooling processes, like synchrotron and Compton cooling, are included. Note the earlier turn on of the flux for the lower efficiency case. The depression of the emission around 20 days at mainly high frequencies is due to Compton cooling. The distance to the modeled event is 20 Mpc.  $3\sigma$  upper limits of observed events have also been included, after scaling for their actual distances: 1986G ( $t = 13$  days,  $\lambda = 2$  cm), 1998bu ( $t = 14$  days,  $\lambda = 3.6$  cm), 1989B ( $t = 15$  days,  $\lambda = 3.6$  cm), 1999by ( $t = 16$  days,  $\lambda = 3.6$  cm), and 1994D ( $t = 62$  days,  $\lambda = 6$  cm).

For the only SNe Ia displaying circumstellar emission, radio and X-rays have, however, failed to detect the SNe.

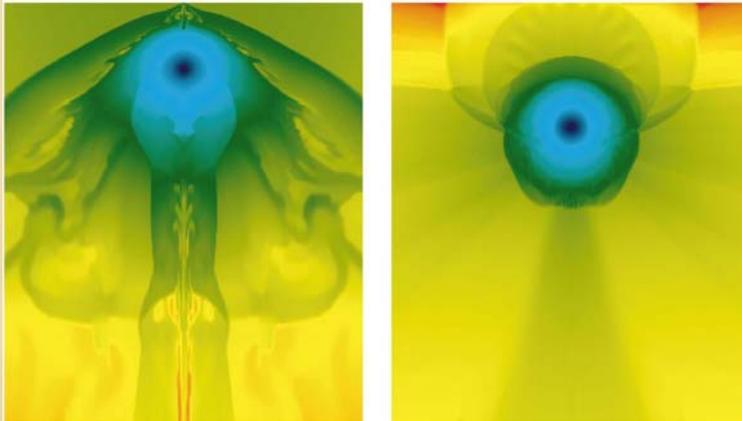


SN 2002ic (Deng et al. 2004)

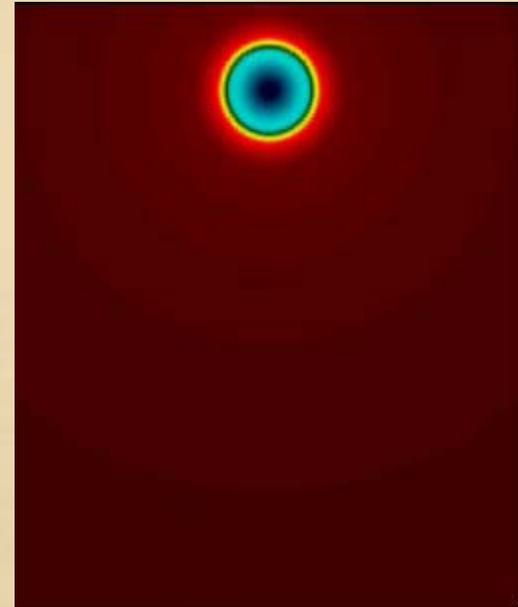
Chandra X-ray observations  
(Hughes et al. 2007)



# Looking for hydrogen at late stages



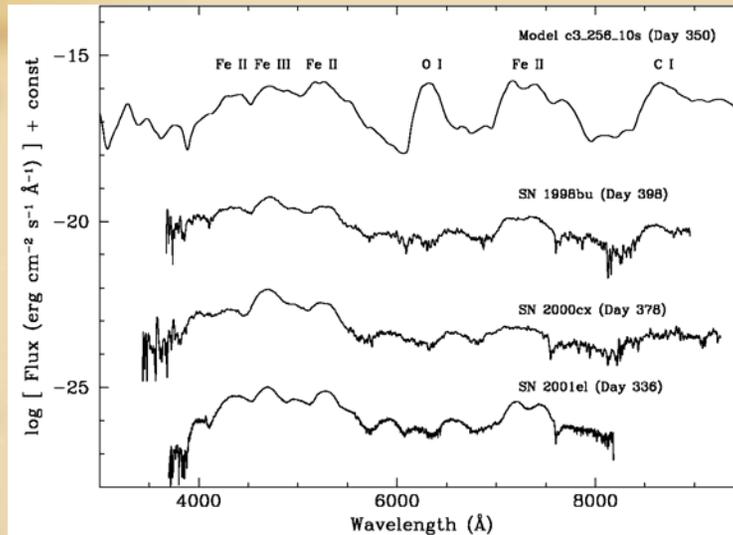
Simulations of a main sequence star being overtaken by the supernova ejecta (Marietta et al. 2000)



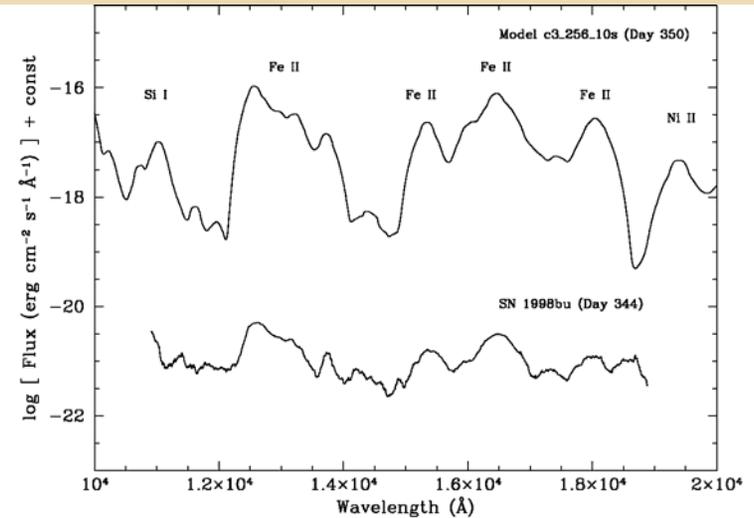
In no case, a faster than  $10^3$  km/s evaporation occurs. The material is deeply embedded in the SN ejecta and will not be seen until in the nebular phase.

# Late emission modeling

We have used the same code as in Kozma et al. (2005)....



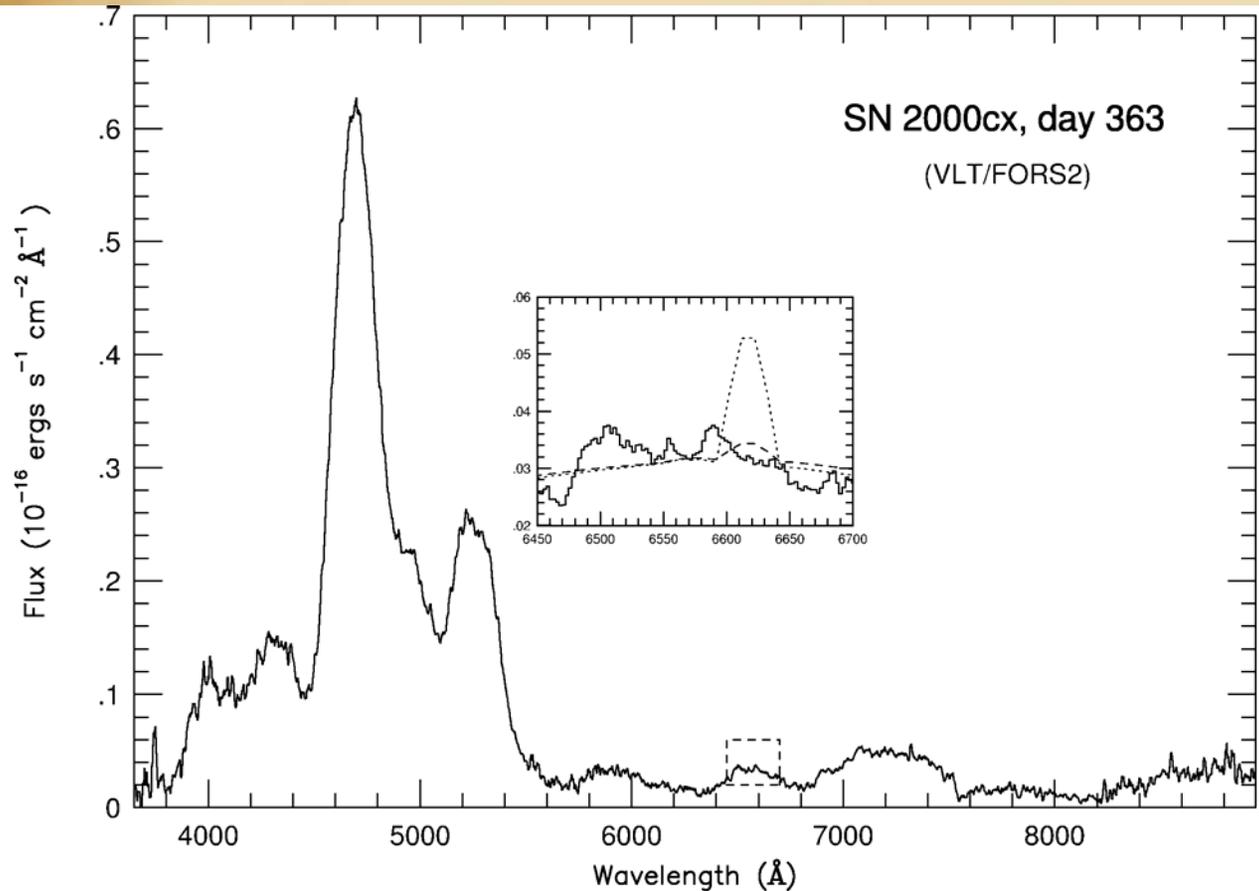
**Fig. 5.** Model spectrum at 350 days, for the c3\_3d\_256\_10s model compared to observations of SN 1998bu from day 398, SN 2000cx from day 378, and of SN 2001el from 336 days after explosion. For clarity the observed spectra have been shifted relative to each other, the SN 1998bu spectrum by  $-4$  dex, the SN 2000cx spectrum by  $-7$  dex, and the SN 2001el spectrum by  $-10$  dex. The observed spectra have been smoothed, dereddened, normalized to 350 days, and rescaled to a common distance of 10 Mpc as discussed in Sect. 3.1.



**Fig. 6.** Model IR spectrum at 350 days, for the c3\_3d\_256\_10s model compared to observations of SN 1998bu from day 344 (Spyromilio et al. 2004). For clarity the observed spectrum has been shifted by  $-4$  dex. The observations have been cleaned and heavily smoothed, using a Savitzky-Golay polynomial smoothing filter with a width of 50 wavelengthbins, corresponding to  $\sim 4500$  km s<sup>-1</sup>.

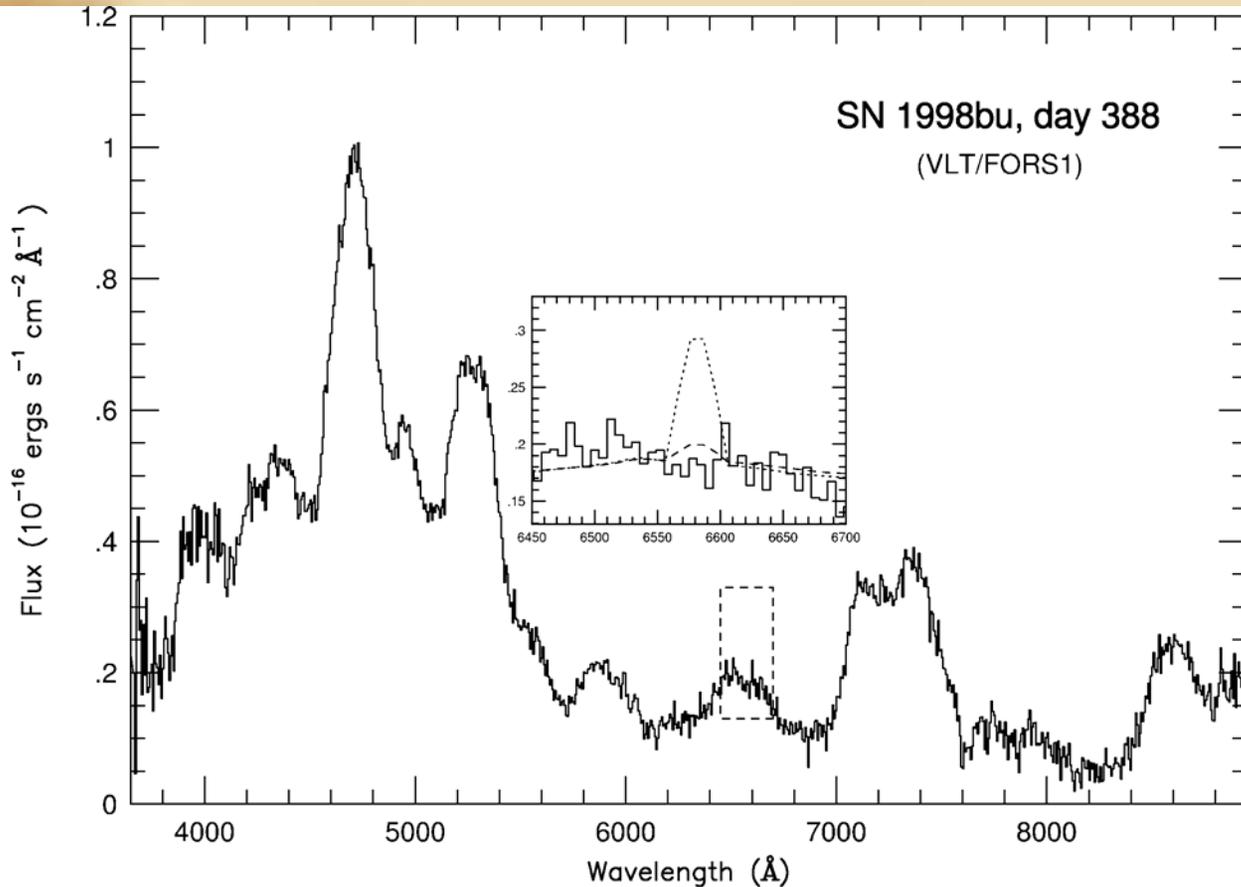
...although in our modeling we have used W7.  
We have inserted solar abundance material within  
the innermost 10<sup>3</sup> km/s ejecta and compared with data.

# SN 2000cx



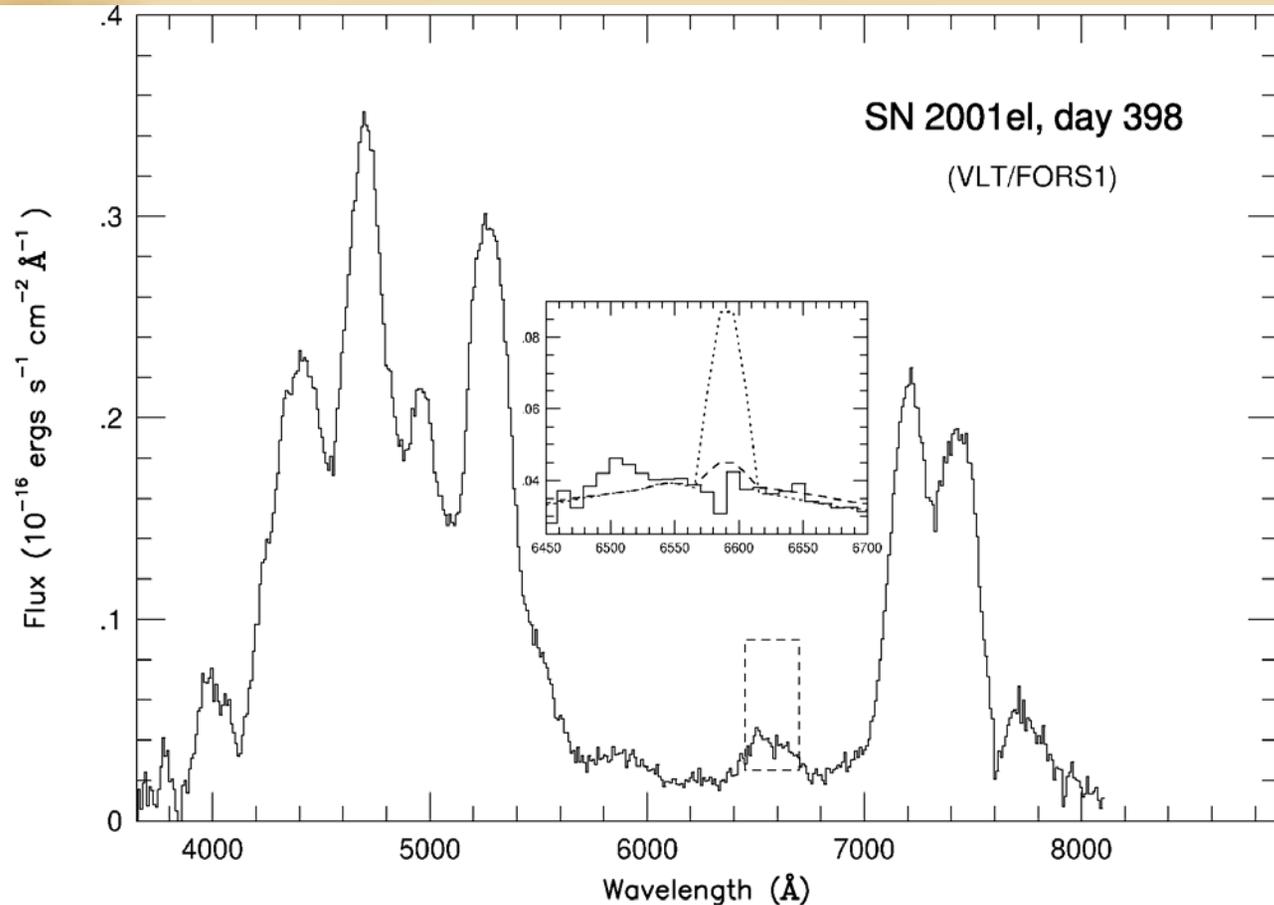
**Fig. 6.** VLT/FORS2 spectrum of SN 2000cx at 363 days after  $B$  maximum. The overall spectrum is described in Sollerman et al. (2004). The inset is a blow-up of the region marked by dashed lines, concentrating on wavelengths around  $H\alpha$ , i.e.,  $\sim 6615$   $\text{\AA}$  for the redshift of the supernova. The dashed and dotted spectra in the inset are models for the supernova, assuming  $0.01$  and  $0.05 M_{\odot}$  of solar abundance material, respectively, concentrated to  $\pm 10^3$   $\text{km s}^{-1}$  around the rest velocity of the supernova. This is to simulate  $H\alpha$  emission from gas removed from a possible companion star according to the models of Marietta et al. (2000). Our models for the  $H\alpha$  emission are described in the text. There is no sign of  $H\alpha$  emission in SN 2000cx at these wavelengths, which places a limit on low-velocity ( $< 10^3$   $\text{km s}^{-1}$ ) hydrogen-rich material of  $\sim 0.03 M_{\odot}$ .

# SN 1998bu



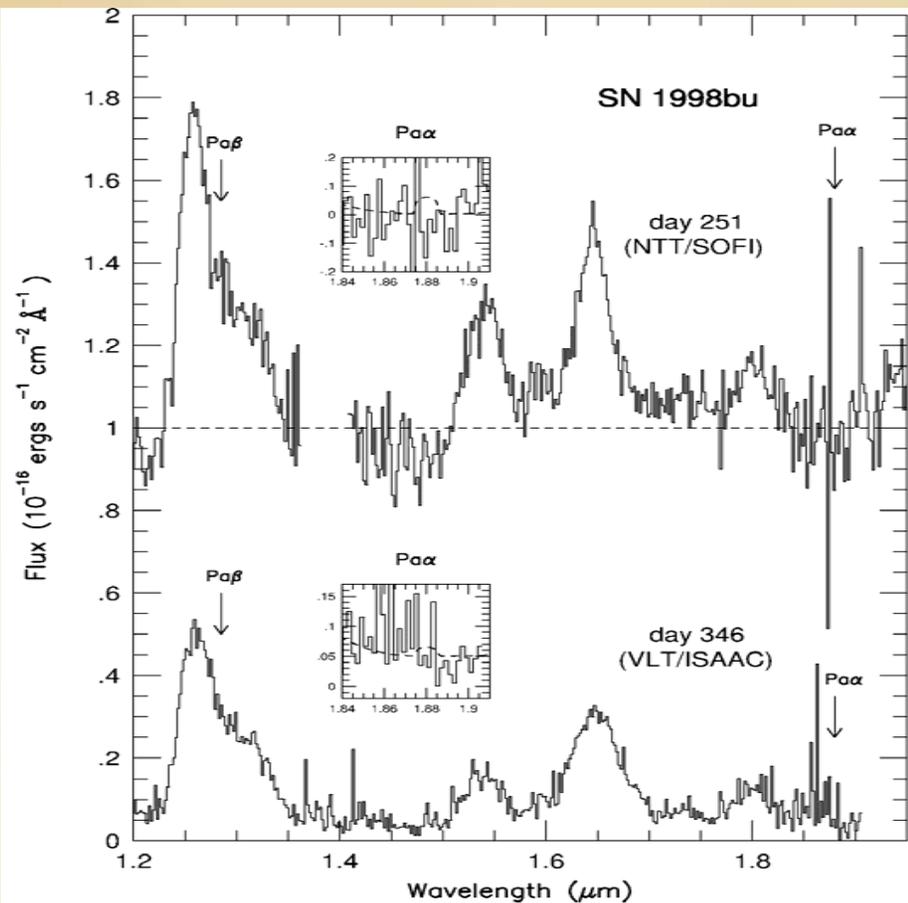
**Fig. 7.** VLT/FORS1 spectrum of SN 1998bu at 388 days after  $B$  maximum. The overall spectrum is very similar to the day 330 spectrum shown in Fig. 2 of Cappellaro et al. (2001), except for the stronger emission around 4000  $\text{\AA}$ , which is a result of a light echo from early emission. The inset is a blow-up of the region marked by dashed lines, concentrating on wavelengths around  $H\alpha$ . As in Fig. 6 we have plotted our model for  $H\alpha$  emission from a possible ablated companion star, and the mass within the core (i.e.,  $\pm 10^3$   $km\ s^{-1}$ ) is the same as in Fig. 6. We have assumed a distance to SN 1998bu of 11.2 Mpc, an extinction of  $A_V = 1.0$  and a redshift of  $750\ km\ s^{-1}$  (Munari et al. 1998; Centurion et al. 1998). There is no sign of  $H\alpha$  emission in SN 1998bu at the expected wavelength. The day 388 VLT/FORS1 spectrum, and its implications for the light echo, is further discussed in Patat et al. (in preparation).

# SN 2001el



**Fig. 6.** FORS1 spectrum of SN 2001el obtained on November 2.2 (UT) 2002, i.e., 398 days past the  $B$ -band maximum light. The inset shows an enlargement of the region marked by dashed lines, focusing on wavelengths around  $H\alpha$  for the redshift of the SN. The SN emission at these wavelengths is dominated by a blend of Fe II emission lines (e.g., 6561  $\text{\AA}$ ). The dashed and dotted spectra in the inset are models calculated at 380 days for the SN, assuming 0.01  $M_{\odot}$  and 0.05  $M_{\odot}$  of solar abundance material, respectively, concentrated to  $\pm 1000$   $km\ s^{-1}$  from the rest velocity of the supernova. This is to simulate  $H\alpha$  emission from gas removed from a possible companion star according to the models of Marietta et al. (2000). There is no sign of such  $H\alpha$  emission in SN 2001el at these wavelengths, which places a limit on hydrogen rich material of  $\sim 0.03 M_{\odot}$ . The model used to calculate the late emission is described in Sect. 4.3.

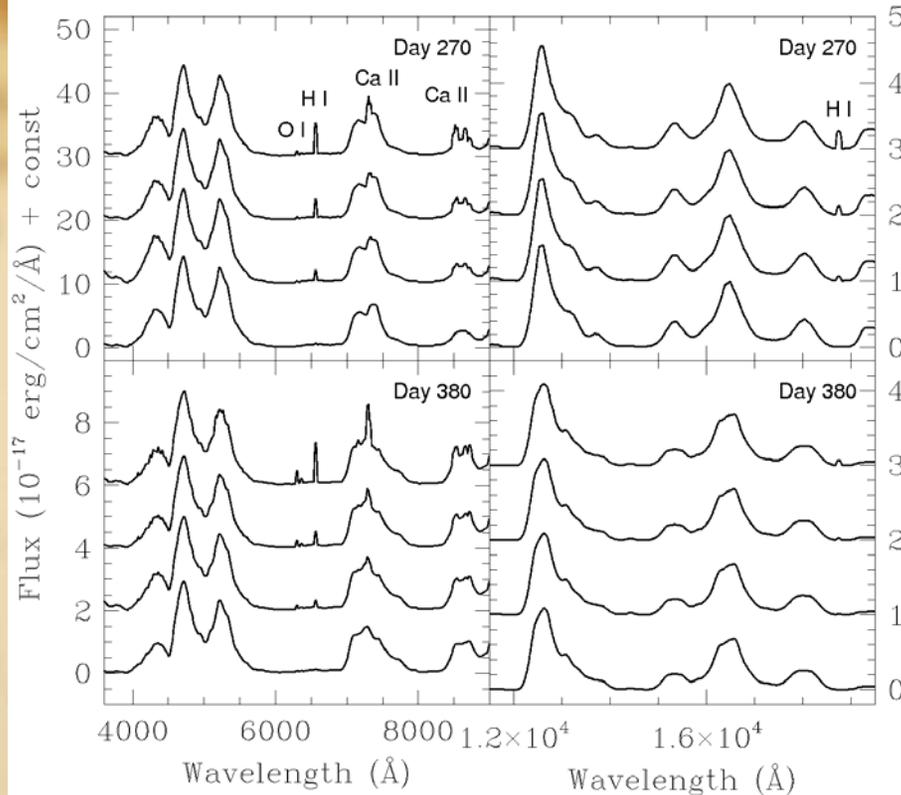
# SN 1998bu in the near-IR



**Fig. 8.** Infrared spectra of SN 1998bu in the nebular phase taken at 251 days (ESO/NTT/SOFI) and 346 days (ESO/VLT/ISAAC) after  $B$  maximum.

The arrows mark the rest wavelengths of  $\text{Pa}\alpha$  and  $\text{Pa}\beta$  for SN 1998bu. The insets show blow-ups of the spectral region around  $\text{Pa}\alpha$ . The dashed spectrum is for a model discussed in Sect. 3.2 and displayed in Fig. 3.3 assuming  $0.5 M_{\odot}$  of hydrogen-rich material within the innermost  $\pm 10^3 \text{ km s}^{-1}$  of the ejecta. This is to simulate the emission from the companion star in the models of Marietta et al. (2000). However, there is no sign of such  $\text{Pa}\alpha$  emission in SN 1998bu.

# An overview of which lines to expect



**Fig. 13.** Modeled spectra at two epochs, 270 and 380 days, for four models, with varying mass of the central, hydrogen rich region. The hydrogen mass increases from bottom to top in each frame, i.e., the lowest spectrum in each frame shows the model containing  $0.01 M_{\odot}$  of solar abundance matter, while the following spectra contain  $0.05$ ,  $0.10$ , and  $0.50 M_{\odot}$ , respectively. In these spectra we have also labeled the features originating in the hydrogen rich matter.

(Lundqvist et al. 2007)

# Conclusions

- No circumstellar emission from a "normal" Type Ia SN has never been seen in any wavelength region. Best limits are obtained in the radio and indicate  $<10^{-7} M_{\odot} \text{ yr}^{-1}$ .
- Optical evidence for episodic mass loss exist for at least two suspected Type Ia SNe (SN 2002ic and SN 2005gj). Radio and X-ray emission was not detected (due to absorption by the circumstellar shell). The shells could be asymmetric.
- Late emission from three normal Type Ia SNe indicate that at most  $0.03 M_{\odot}$  of solar abundance material exists in the center of any of these supernovae. This is much less than in any of the models calculated by Marietta et al. (2000) and put constraints on single degenerate models.