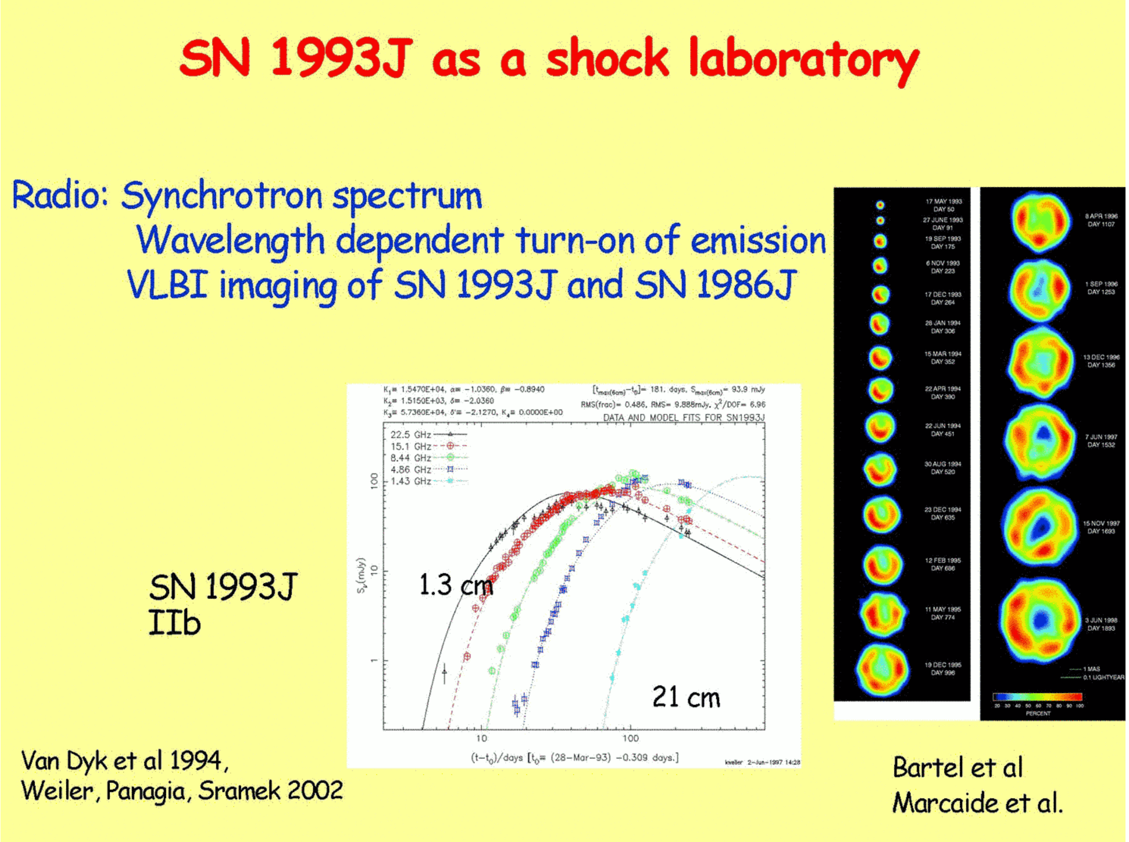
Shock physics in Type II SNe

1. Radio and X-rays in SN 1993J and implications for particle acceleration and B-field generation. Non-relativistic analogue of GRBs
2. The ring collision of SN 1987A



SN 1993J as a shock laboratory

Radio: Synchrotron spectrum
Wavelength dependent turn-on of emission
VLBI imaging of SN 1993J and SN 1986J

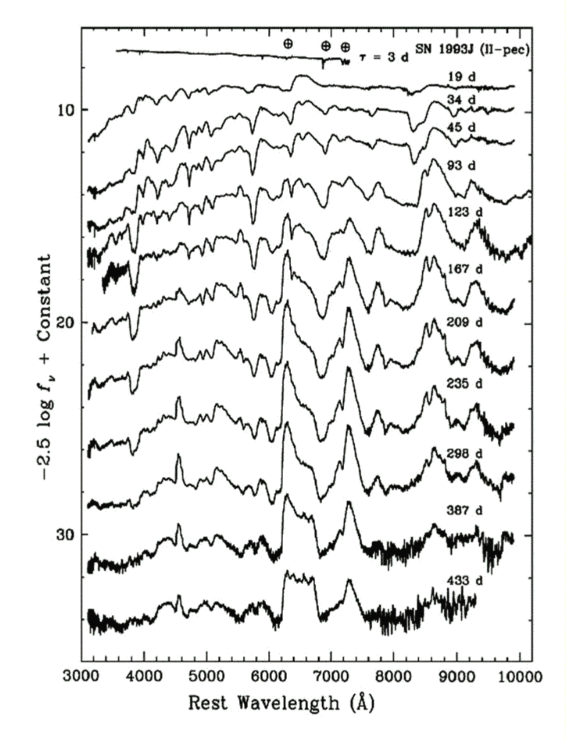
SN 1993J
IIb

Van Dyk et al 1994,
Weiler, Panagia, Sramek 2002

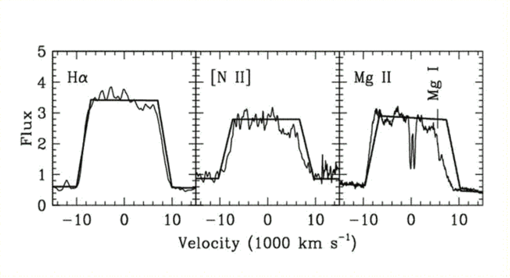
Bartel et al
Marcaide et al.

SN 1993J optical

Filippenko et al 1994
Fransson et al 2004

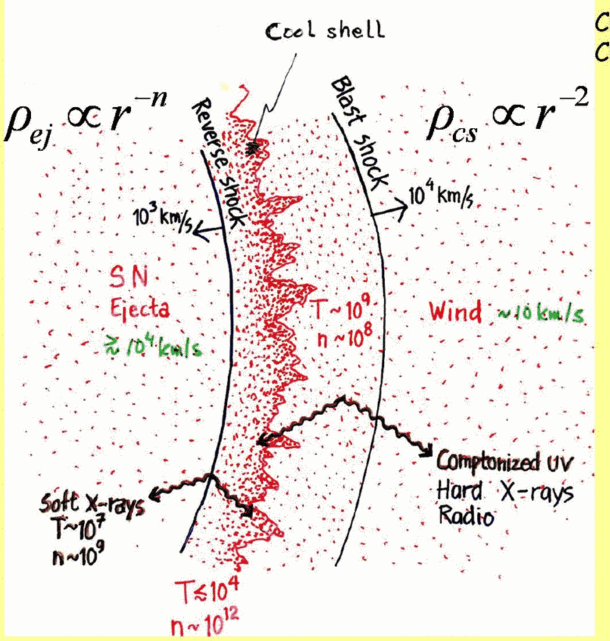


Transition from Type II to Type Ib



Box-like line profiles ⇒ narrow emitting shell

Chevalier (1982)
Chevalier & CF (1994)

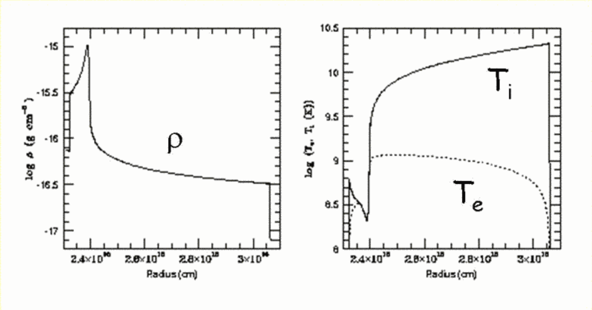


$$R_s \propto t^{(n-3)/(n-2)}$$

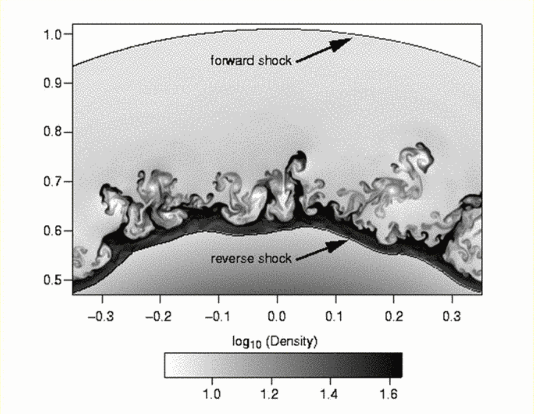
$$V_s \propto t^{-1/(n-2)}$$

$$\boxed{T_{\rm CS} = 1.4{\rm x}10^9 \left(\frac{V}{10^4 {\rm km/s}}\right)^2 \ {\rm K} \qquad T_{\rm reverse} = \frac{T_{\rm CS}}{(n-2)^2} = 10^6 - 10^7 \ {\rm K}}$$

Shock structure



Fransson et al 1996



Chevalier & Blondin 1995

CS shock adiabatic

Reverse shock radiative

SN 1993J X-rays

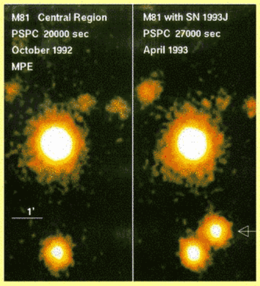
ROSAT 0.1 - 2.4 keV (Zimmermann et al 1994, Immler et al 2002)

ASCA 1 – 10 keV (Uno et al 2002)

COMPTON-GRO/OSSE 50 – 200 keV (Leising et al 1994)

Chandra (Swartz et al 2002)

XMM/Newton (Zimmermann & Aschenbach 2003))



t < 50 days kT ~ 100 keV

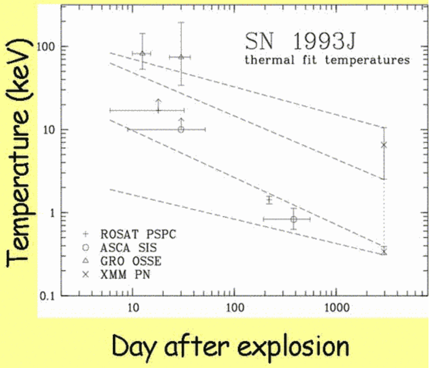
$L_x \approx 5\times10^{40}$ erg/s 50 - 200 keV

2×10^{39} erg/s 0.1 - 2.4 keV

t > 200 days kT ~ 1 keV

$L_x \approx 1\times10^{39}$ erg/s 0.1 - 2.4 keV

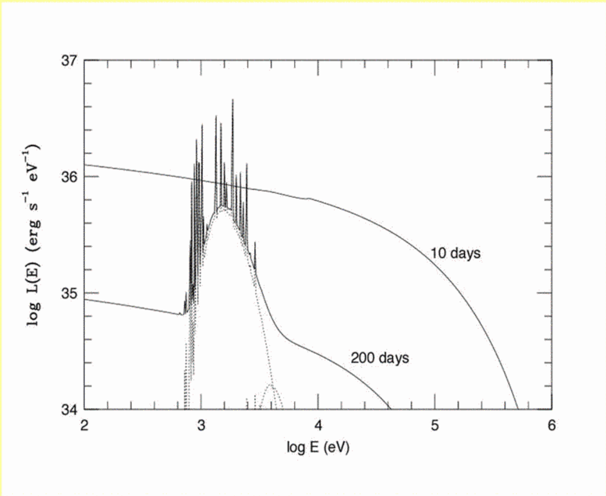
Transition from hard to soft spectrum!

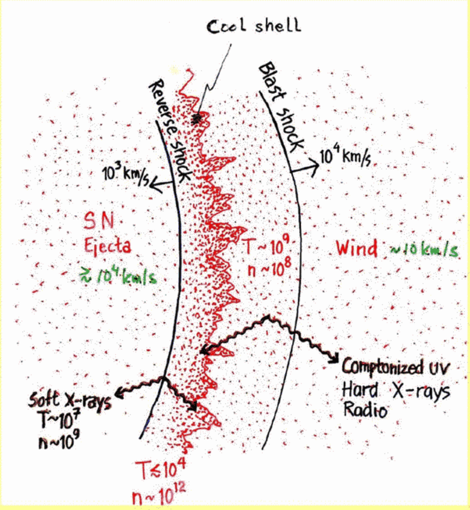


Zimmermann & Aschenbach 2003

X-ray evolution

CF, Lundqvist & Chevalier 1996



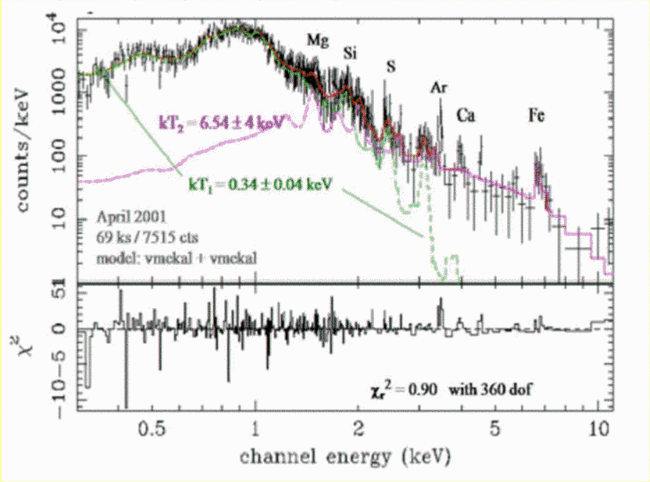


At 10 days: Only X-rays from outer, CS shock $T \sim 10^9$ K
At 200 days: X-rays from reverse shock dominates $T \sim 10^7$ K

Hard to soft evolution natural consequence of the cool shell

SN 1993J X-rays

XMM: Zimmermann & Aschenbach 2003
Chandra: Swartz et al 2003



Thermal
$kT \sim 0.34 + 6.5$ keV

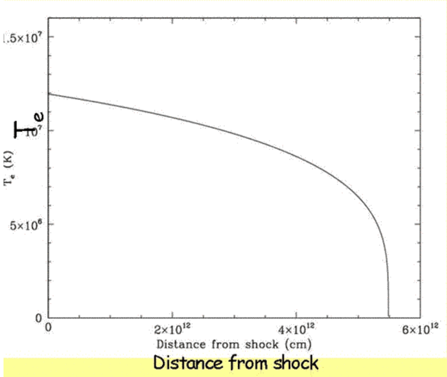
Enhanced Si (?) (Swartz et al)

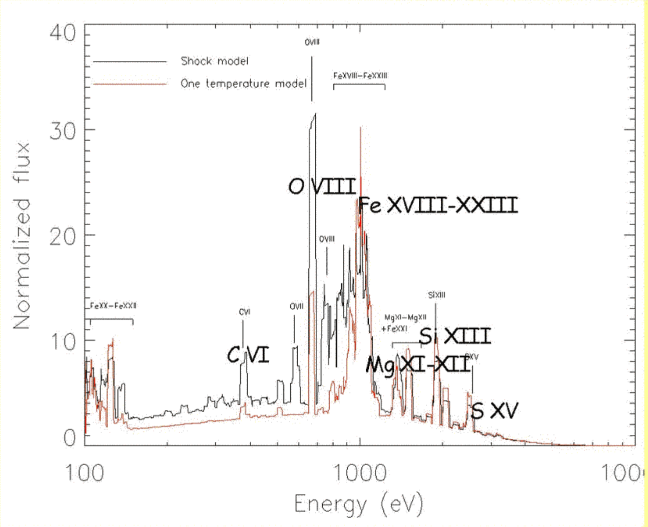
Can NOT use a one (or two) temperature components.

Cooling reverse shock +
shell absorption +
forward shock

Radiative reverse shock spectra

T. Nymark, CF, C. Kozma 2006





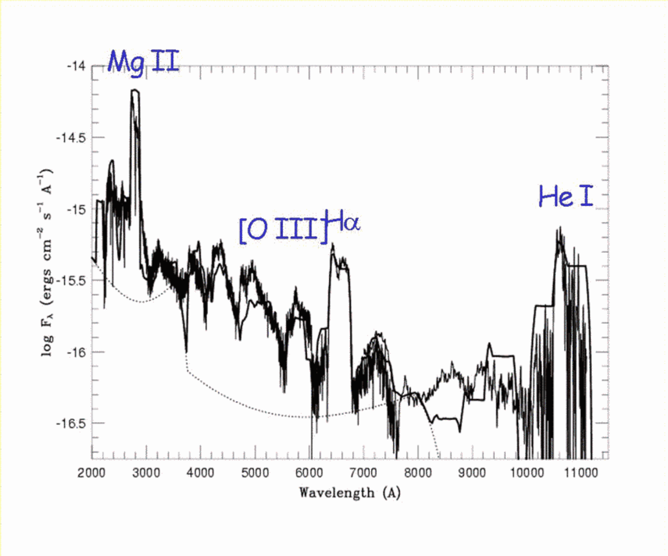
RS radiative for $\dot{M} > 5\times10^{-5}(u_w/10\,\mathrm{km\,s^{-1}})$ $M_\odot$/yr

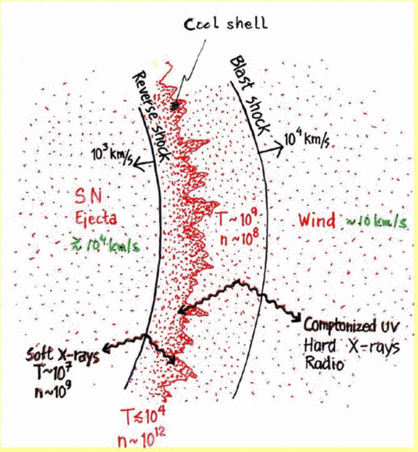
One-temperature spectrum bad approx. for cooling shock .

Affects abundance estimates by large factor!

SN 1993J optical/UV

HST (SINS) + Keck





Good fit with ionized ejecta (O III etc) +
cool, dense shell (Hα, Mg II, Fe II)
Consistency of X-ray flux and UV/optical flux

RADIO
I. Free-free absorption by the CSM

$$n_e(r) = \frac{\dot{M}}{4\pi r^2 u_w} \qquad r = V_{\rm exp} t$$

$$\tau(\nu) \propto \nu^{-2}\, T^{-3/2} \left(\frac{\dot{M}}{u_w}\right)^2 V_{\rm exp}{}^{-3} t^{-3}$$

$$\boxed{\tau(\nu) = 1 \quad \Rightarrow \quad \frac{\dot{M}}{u_w}}$$

$T_{\rm wind} \sim 10^5$ K (Lundqvist & CF 1989)

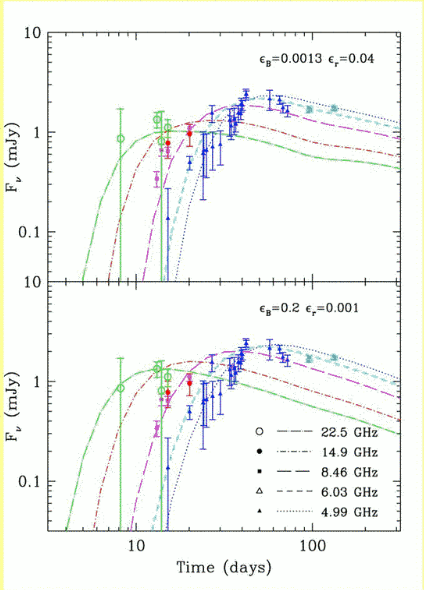
Good fit to Type IIL SNe (SN 1979C, 1980K.....)

dM/dt = 5×10^{-5} - 10^{-4} $M_\odot$/yr for u=10 km/s

Type IIP radio

SN 2004et
Obs: Stockdale (2004),
Beswick et al (2004), Argo et al (2005)

(Chevalier, CF, Nymark 2006)



Inverse Compton scattering by photospheric photons suppresses radio at optical max.

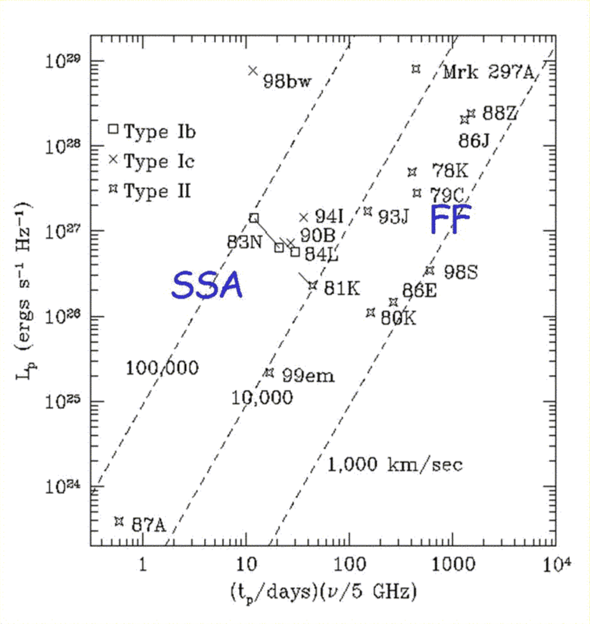
$\varepsilon_B \ll \varepsilon_e$ indicated by flat light curve (?)

degeneracy between ε_B and ε_e

$$\boxed{\dot{M} \approx (2-10)\times10^{-6} \left(\frac{T_e}{10^5\ {\rm K}}\right)^{3/4} \left(\frac{u_w}{10\ {\rm km\,s^{-1}}}\right) M_\oplus {\rm yr}^{-1}}$$

Typical for galactic RSG mass loss rates

Free-free vs synchrotron self-absorption



Chevalier 1998

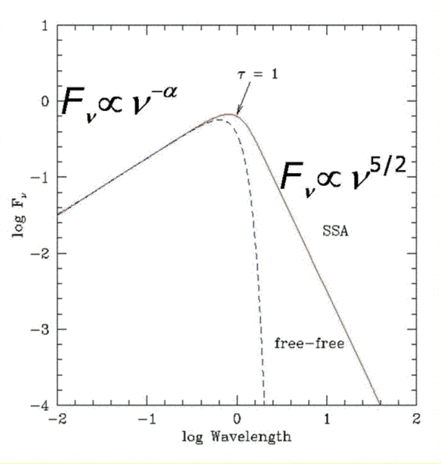
High $\dot{M}/u$ & low V $\Rightarrow$ F-F; Low $\dot{M}/u$ & high V$\Rightarrow$ SSA

II. Synchrotron self-absorption

Absorption by same rel. electrons as are emitting

$$F_\nu = R^2 B^{-1/2} \nu^{5/2} \left(1 - e^{-\tau(\nu)}\right)$$

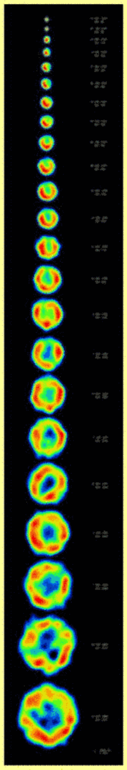
$$\tau(\nu) \propto \nu^{-5/2-\alpha} B^{\alpha+3/2} N_e$$

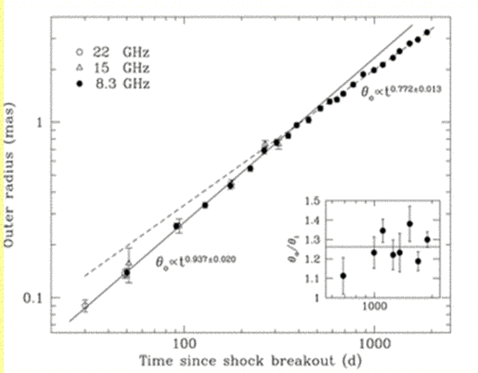


F_{peak}, & $\tau(\nu,t)=1$, $R = V_{\mathrm{exp}} t \Rightarrow$
$B(t)$, $N_e(t)$

Note: Expansion velocity, i.e. radius, from line profiles or VLBI, not a parameter, c.f. GRB's

Size of radio emitting region



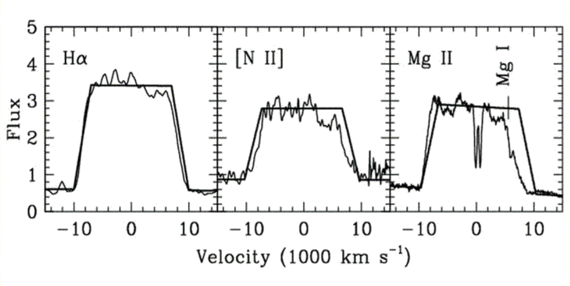


VLBI

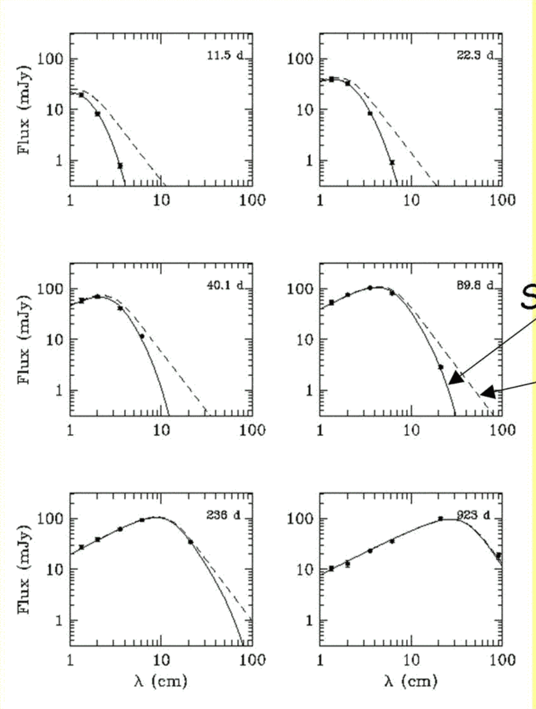
Bartel et al 2001

HST, SINS

Line widths
$(1.0\text{-}1.5)\times10^4$ km s^{-1}



SN 1993J



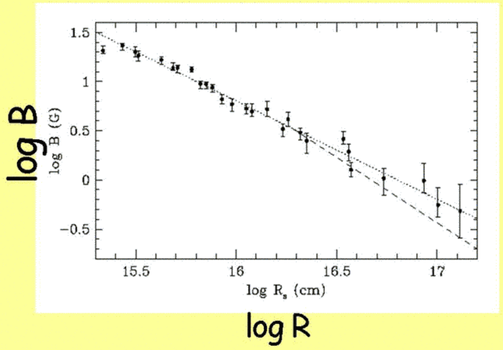
Fit to each epoch +
radius ⇒ B(t) & N(t)

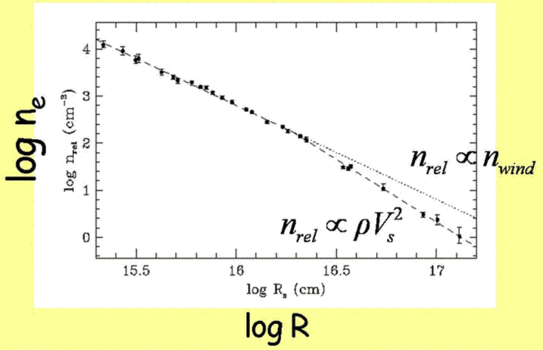
SSA + free-free

SSA only

dM/dt = 5×10^{-5} $M_\odot$/yr for
u=10 km/s

Magnetic field and rel. particle density





$$B = 64\left(\frac{R_s}{10^{15}\ cm}\right)^{-1}\quad G$$

$$U_e = \varepsilon_e\, U_{therm} = \varepsilon_e \frac{9}{8}\rho V_s^2 \propto t^{-2}$$

$$R_s \propto t^m \qquad m = (n-3)/(n-2)$$

1. Wind B-field 1-2 mG at 10^{16} cm (Cohen et al 1987)
   Amplification of B-field behind shock. Weibel instab.?
   (Medvedev & Loeb 1999)
2. $U_B \approx 0.15\ U_{therm}$
3. $U_e \approx 10^{-4}\ U_{therm}$

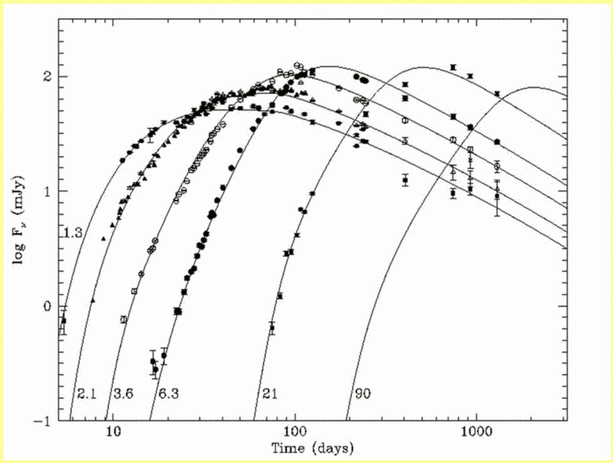
i.e. $\varepsilon_B \approx 0.15 \quad \varepsilon_e \approx 10^{-4}$

Model and VLA light curves

Assume ε_B and ε_e constant
Self-consistent calculation of rel. electron spectrum,
including all cooling processes, as well as radiative transfer

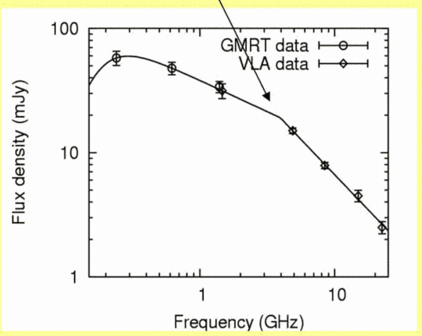
CF & Björnsson 1998

Obs: VLA: van Dyk et al 1994,
Weiler, Panagia, Sramek 2002



Synchrotron cooling gives $\alpha \sim 1.0$

Cooling break observed with GMRT and VLA at ~3400 days close to predicted (Chandra et al 2004)



Results from radio modeling

1. $\rho_{csm} \propto r^{-2}$ OK!! No evidence for mass loss variations or $s \neq 2$.

2. $dM/dt = 5\text{x}10^{-5}\ M_O/yr$ for u=10 km/s, same as from X-rays

3. Injection spectrum $n_e \propto \gamma^{-2.1}$. Synchrotron cooling steepens this!

4. $\varepsilon_B \approx 0.15 \quad \varepsilon_e \approx 10^{-4}$. (Note : *If* $n_e(\gamma) \sim n_p(\gamma)$, then

   $\varepsilon_p \sim m_p/m_e\, \varepsilon_e \sim 0.2$??)

5. Compton cooling by photospheric photons important for first ~ 100 days. Synchrotron for years

6. Need independent velocity information from line profiles or VLBI to break degeneracy of ε_B and ε_e

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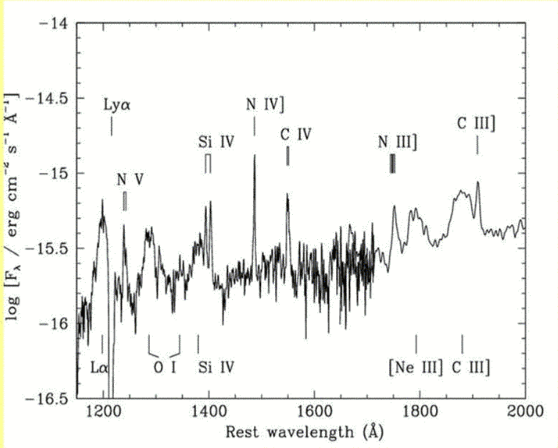
CNO diagnostics

SN 1979C (IIL), 1987A (IIP), 1993J (IIb), 1995N (IIn), 1998S (IIn
all have N/C » 1

(Fransson et al 1989, 2001, 2004)

SN 1998S HST (SINS)

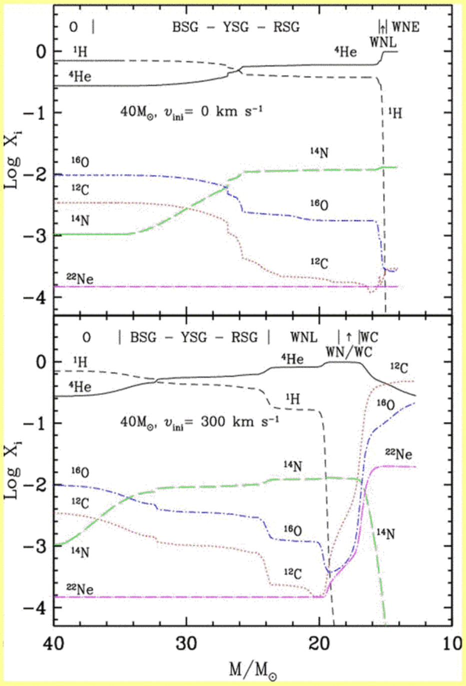


SN 1998S	IIn	N/C ~ 6
SN 1995N	IIn	N/C ~ 4
SN 1993J	IIb	N/C ~ 12
SN 1987A	IIP	N/C ~ 5
SN 1979C	IIL	N/C ~ 8
Solar		N/C ~ 0.25

All indicate CNO processing and mass loss and/or mixing

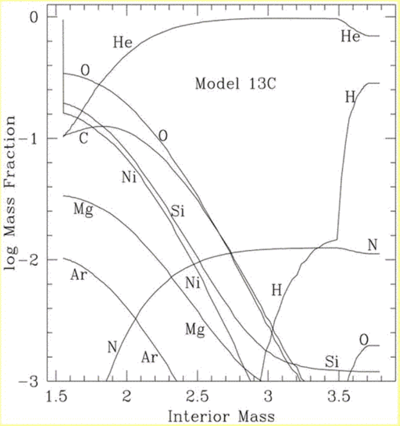
N/C strong fcn of mass loss

40 M at ZAMS
Meynet & Maeder 2003



N/C >> 1 ⇒ CNO burning ⇒
heavy mass loss + mixing
Rotation helps!
Roche lobe overflow

SN 1993J binary model
Woosley et al 1994



Mass loss rates

Type IIP's dM/dt ~10^{-6} $M_\odot$ yr^{-1} (for u = 10 km s^{-1}). RSG wind OK

Type IIL's dM/dt ~ 2×10^{-5} – few x 10^{-4} $M_\odot$ yr^{-1} (for u = 10 km s^{-1}).
'super wind' (Heger et al)
$t = V_s/u\, t_{obs} \approx 5\times10^2\ t_{obs} > 10^4 / (u/10 \text{ km s}^{-1})$ yrs
i.e., several $M_\odot$ lost

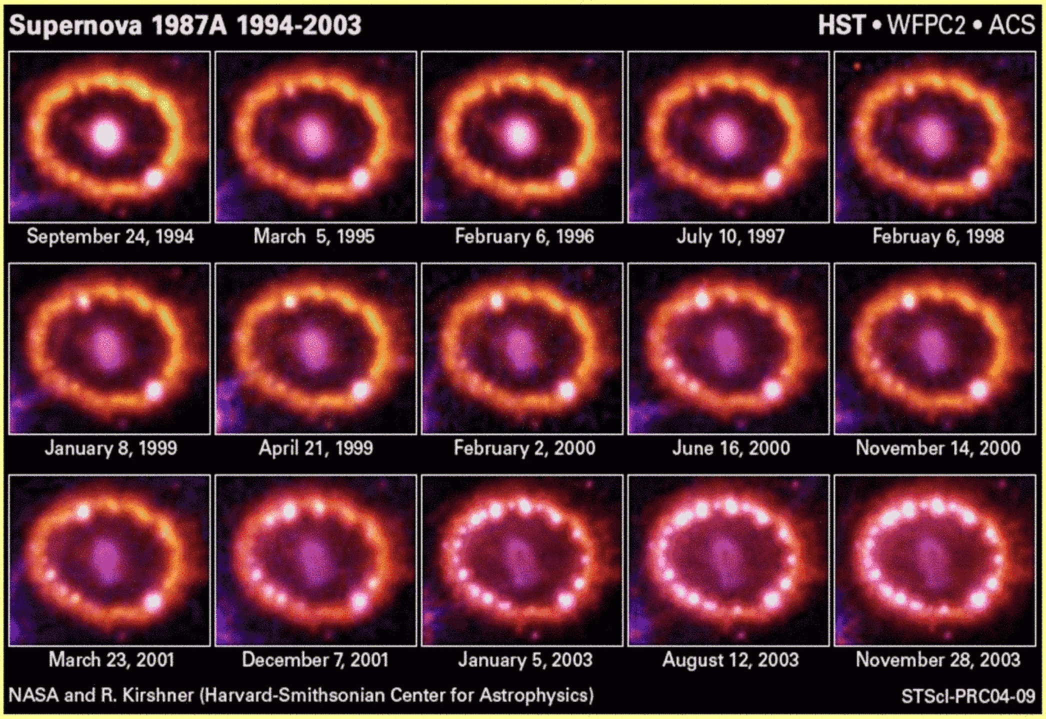
Type IIn's dM/dt ~ 10^{-4} -10^{-3} $M_\odot$ yr^{-1} (for u = 10 km s^{-1}). super wind

Clumping (Chugai)?
Asymmetric wind (Blondin, Chevalier, Lundqvist)?

Type Ib/c's dM/dt ~10^{-7} - 10^{-5} $M_\odot$ yr^{-1} (for u = 1000 km s^{-1}).
Mass loss rate uncertain

SN 1987A ring collision

SAINTS collab.



Origin of the rings

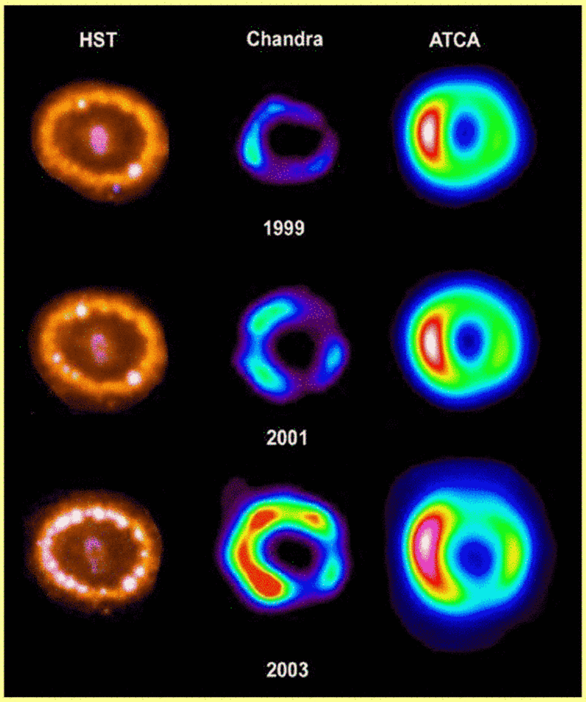
R ~ 10^{18} cm, V_{exp} ~10 km s^{-1} t_{dyn} ~$2x10^4$ years

Origin (?): Merger inducing the equatorial mass loss and outer rings (Podziadlowski 1992, Morris & Podziadlowski 2005)

Explains geometry as well as large N/C

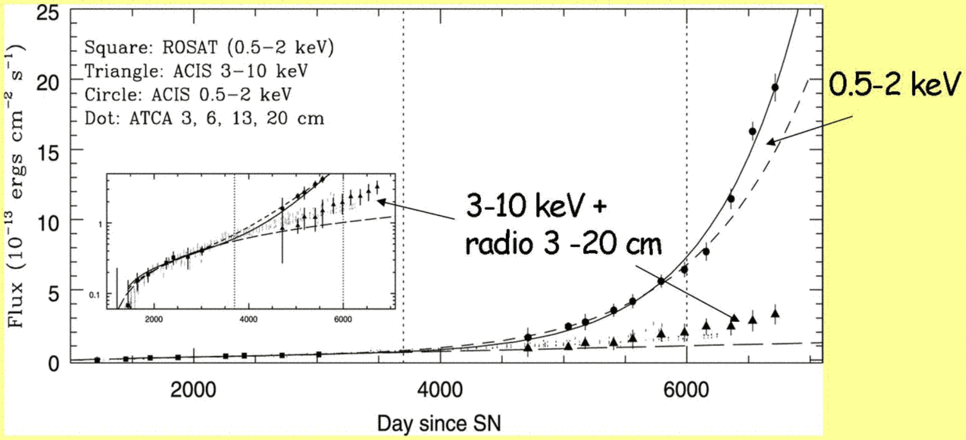
Can this happen in a Ic progenitor?

Chandra & ATCA



Park et al
Manchester et al

Radio and X-ray brightening



Park et al 2005
Manchester et al

Correlation of hard X-rays and radio
probably close to reverse shock

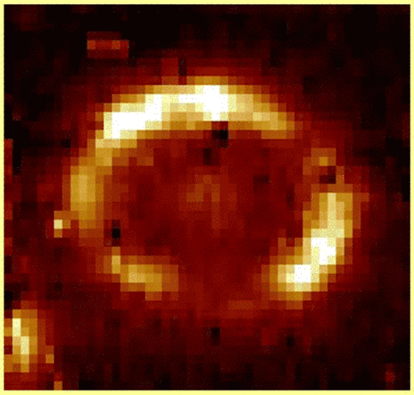
VLT/SINFONI

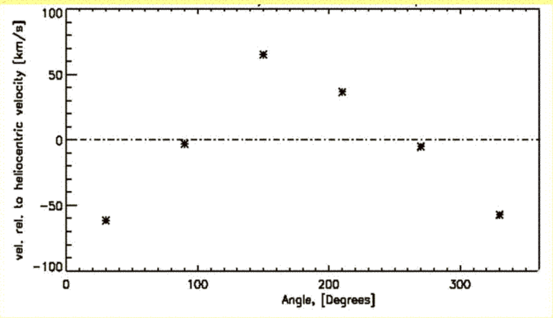
Adaptive optics integral field unit for J, H, K

March 2005

He I 2.06 μ

Kjaer et al 2006





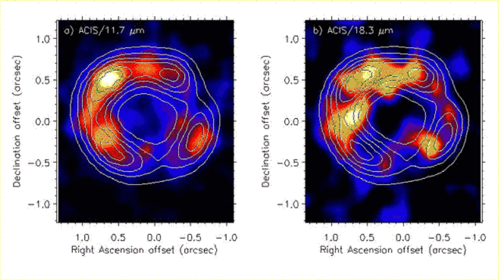
Expansion velocities along ring

He I correlates with soft X-rays

Dust emission

Gemini S + Chandra

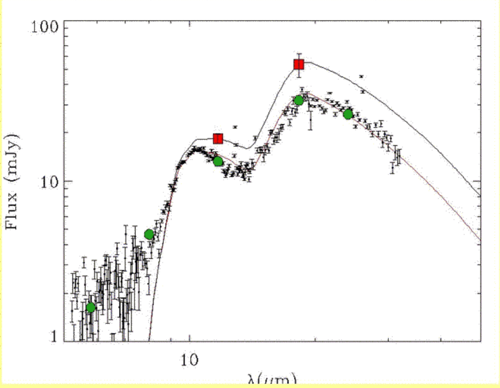
Bouchet et al 2006



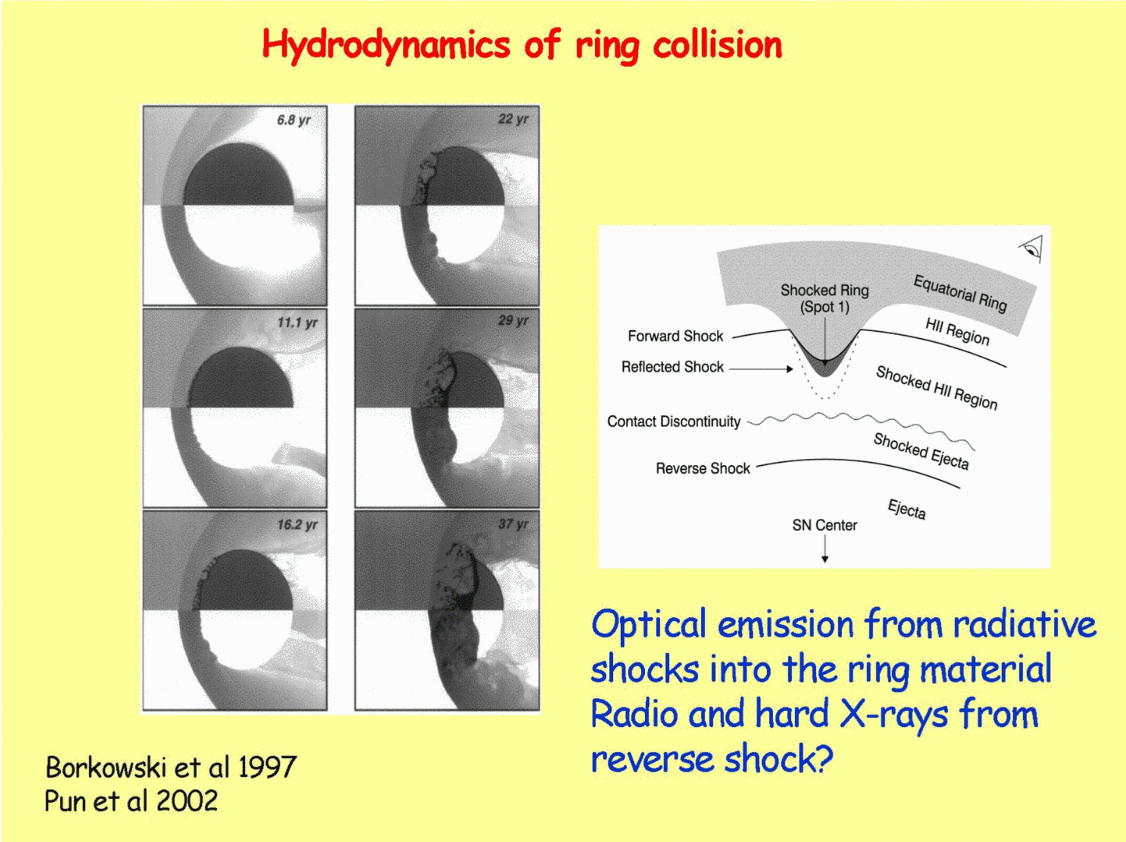
11.7 μ

18.3 μ

Spitzer



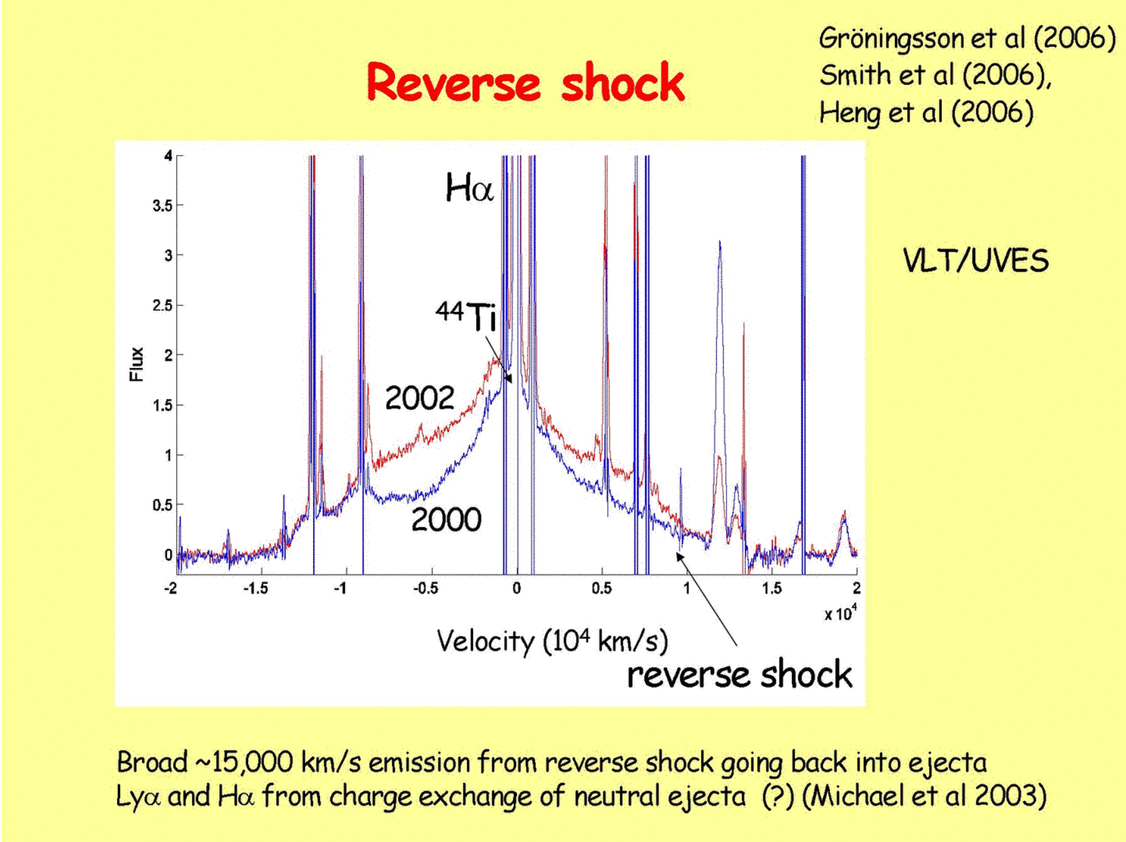
T ~ 166 K
Si feature
collisionally heated?



Hydrodynamics of ring collision

Optical emission from radiative shocks into the ring material
Radio and hard X-rays from reverse shock?

Borkowski et al 1997
Pun et al 2002



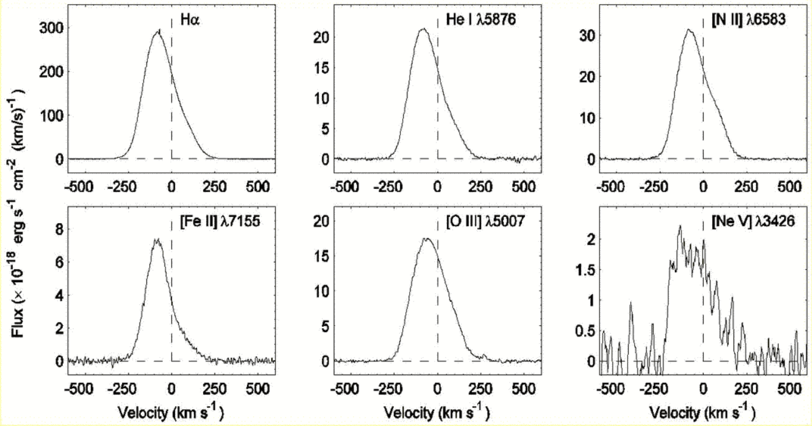
Reverse shock

Gröningsson et al (2006)
Smith et al (2006),
Heng et al (2006)

VLT/UVES

Broad ~15,000 km/s emission from reverse shock going back into ejecta
Lyα and Hα from charge exchange of neutral ejecta (?) (Michael et al 2003)

Intermediate velocity lines from shocked ring protrusions



Oct 2002

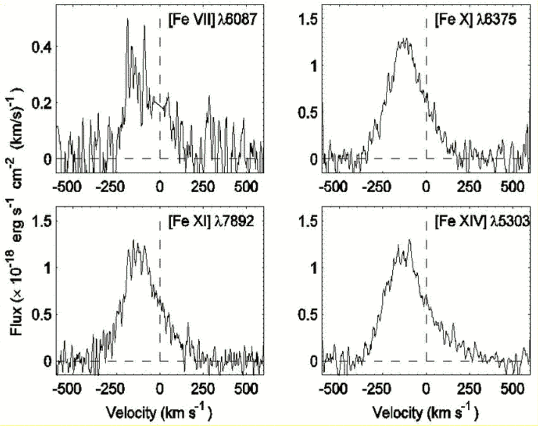
V ~ 200-300 km/s

Gröningsson et al 2006

H I, He I, N II, O I-III, Fe II, Ne III-V.....
Cooling, photoionized gas behind radiative shock into ring protrusions (e.g. Pun et al 2000)

Coronal lines

Gröningsson et al 2006



VLT/UVES spectrum

res. ~ 10 km/s

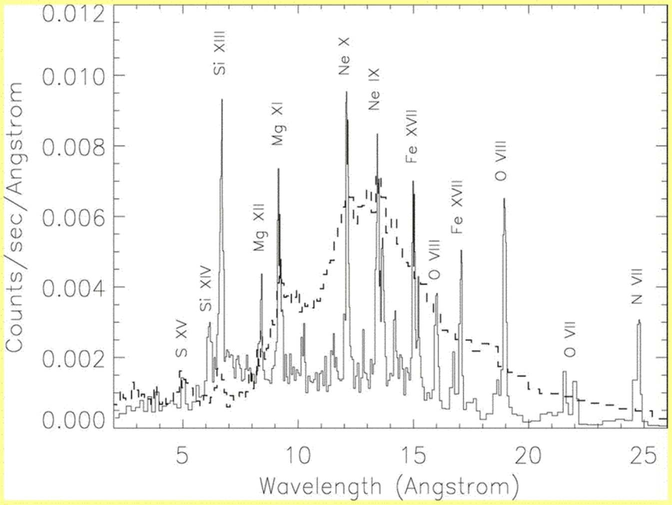
O III, Ne III-V,
Fe VII, Fe X-XI, Fe XIV.....

Max. velocity ~ shock velocity
~ 300-500 km/s

Fe XIV λ 5303 $\Rightarrow T_s \sim 2\times10^6$ K

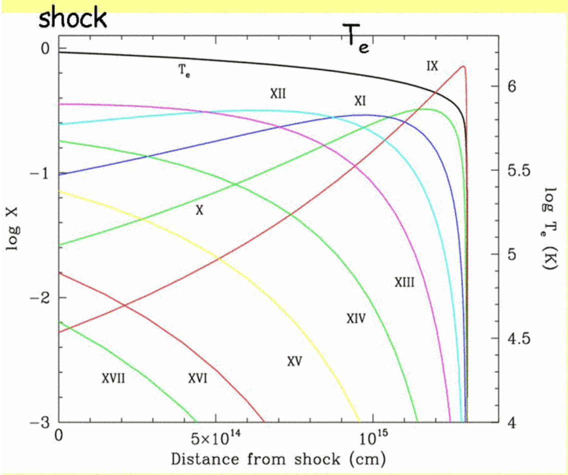
X-rays with Chandra

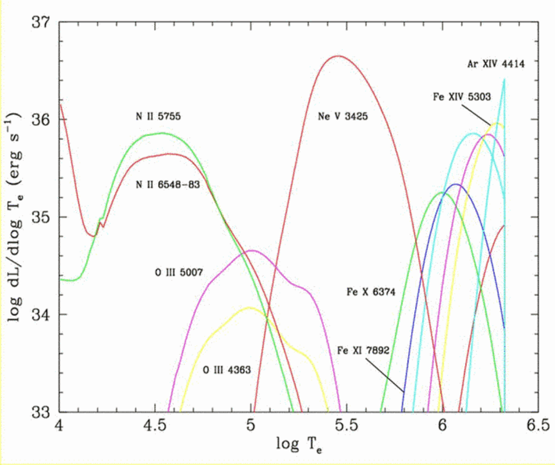
Zhekov et al (2005)



O VII-VIII, Ne IX-X, Mg XI-XII, Si XIII, Fe XVII.....

V ~ 300-1700 km/s





Shock velocity into hot-spots 300 – 500 km s^{-1}

Coronal lines complement the X-rays to probe whole temp. range

Conclusions

- ☐ Mass loss dominant factor for radio, X-rays and late optical
- ☐ Increasingly important for IIP → IIL → IIn,p → Ib/c. N/C important diagnostic
- ☐ Strong evidence for magnetic field amplification (and particle acceleration). In SN 1993J B-field close to equipartition. Electrons far below. Effects of cosmic rays?
- ☐ SN 1987A excellent shock lab. to study both thermal and non-thermal processes. Expect collision with main ring to start soon.