CIRCUMSTELLAR GAS AROUND SN 1987A

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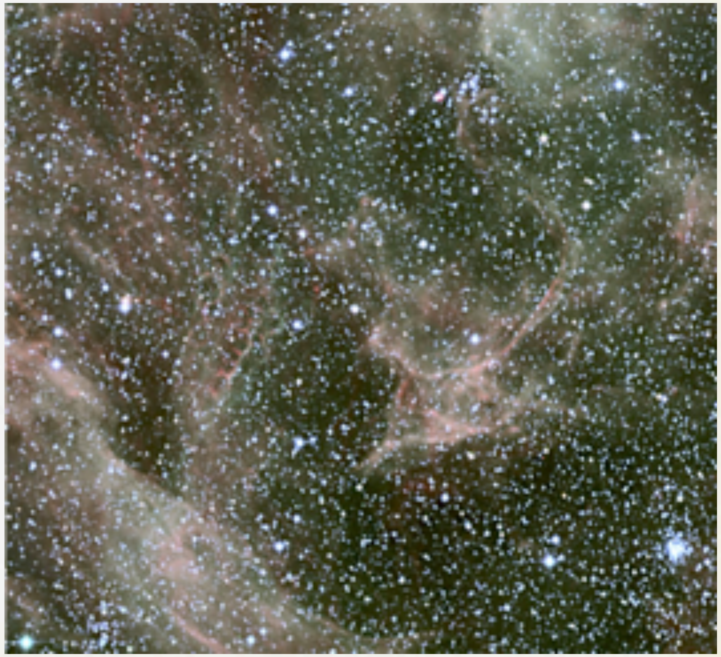
(Talk at AlbaNova, August 12, 2011)

THE SN 1987A ENVIRONMENT

After and before explosion (AAO)

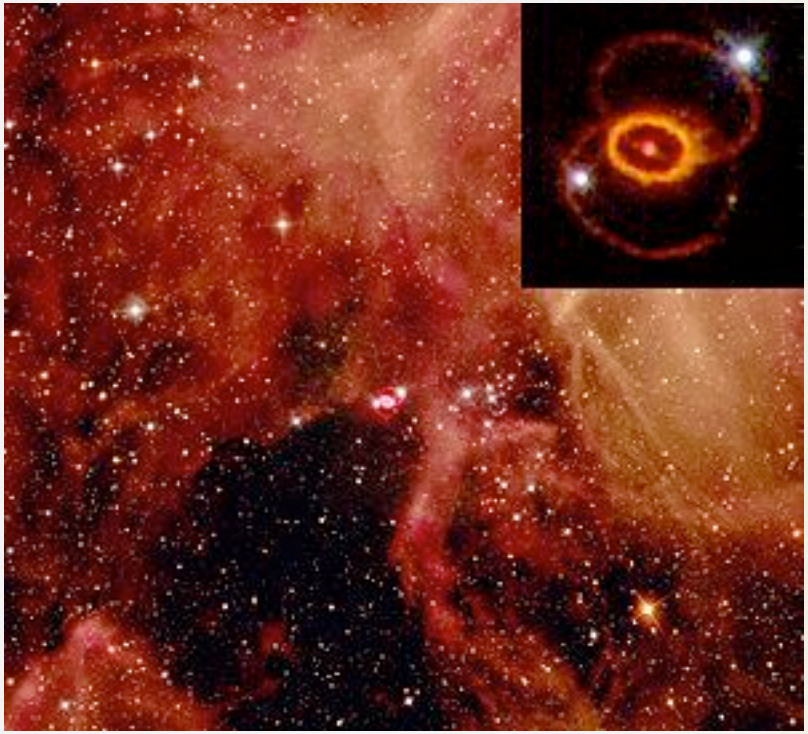
SN 1987A + Honeycomb Nebula (ESO)



Thursday, August 18, 2011

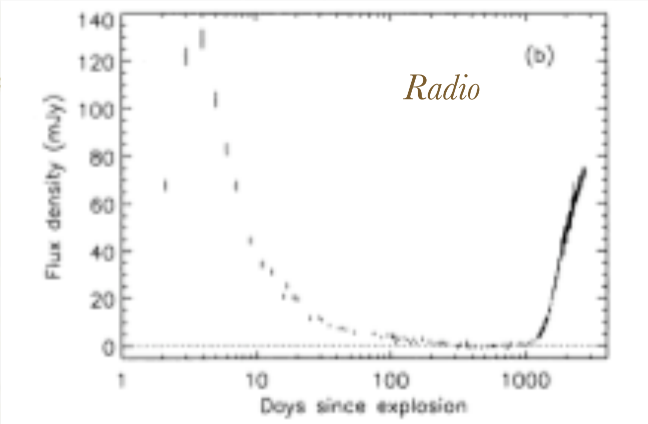
THE SN 1987A ENVIRONMENT

SN 1987A + Honeycomb Nebula (ESO)

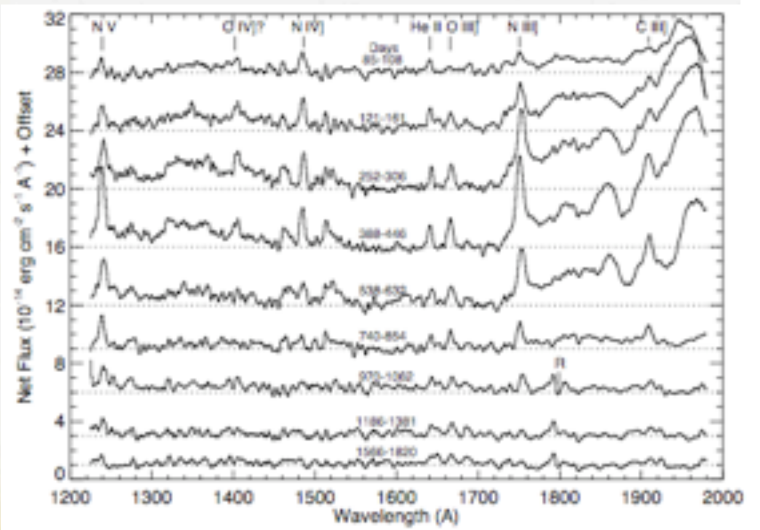


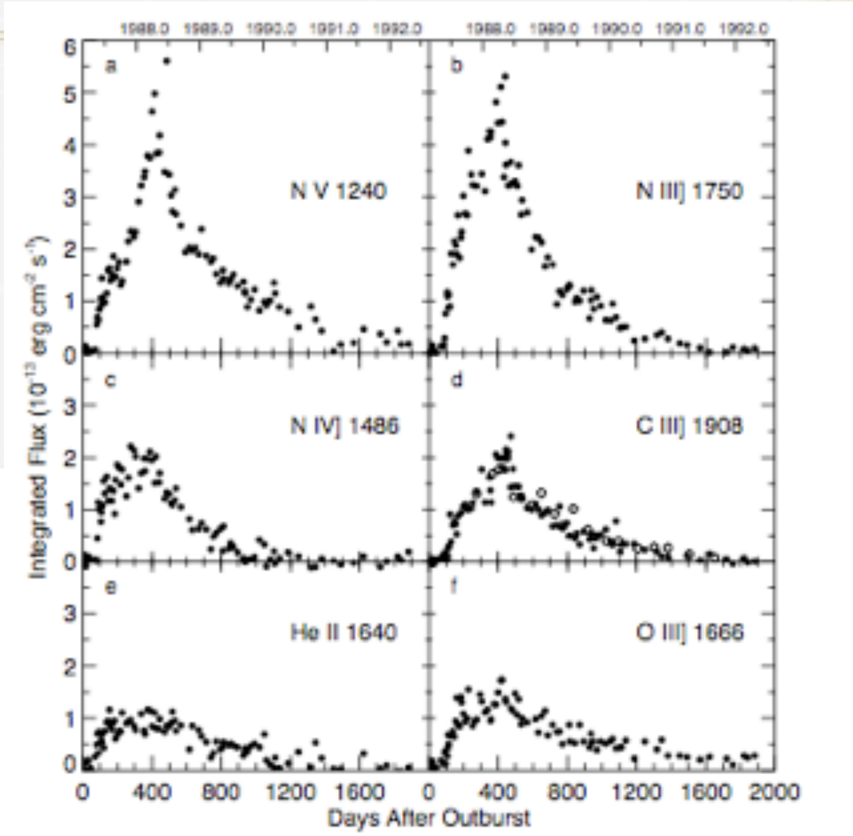
SN 1987A in 1999 (HST)

FIRST EVIDENCE OF CIRCUMSTELLAR GAS



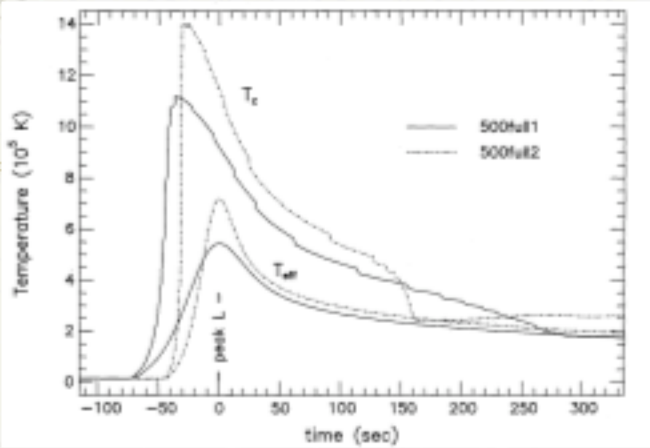
Early 843 MHz lightcurve (Ball et al. 1995)



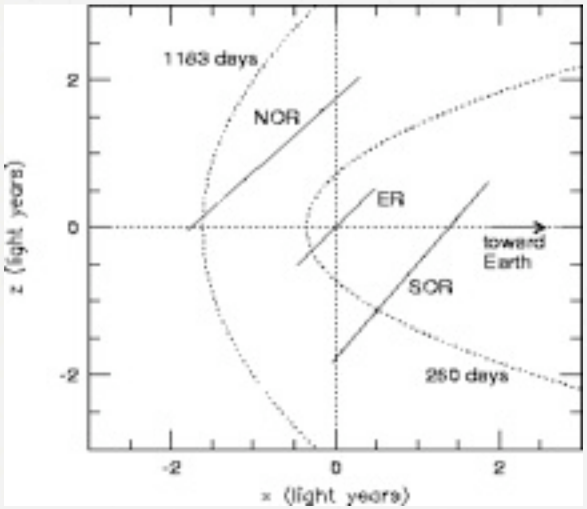


IUE Observations (Sonneborn et al. 1997)

THE INNER RING

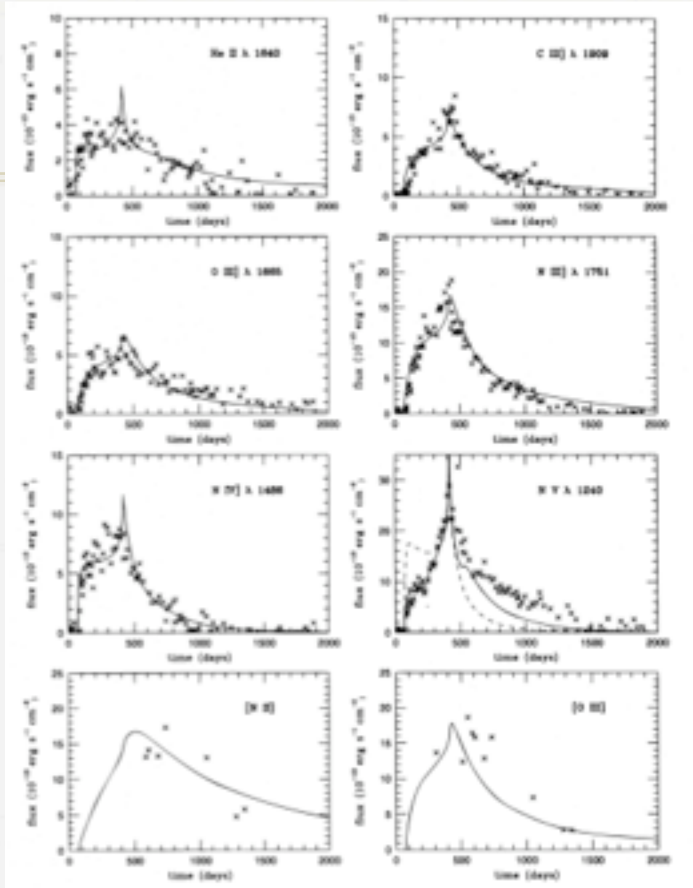


Shock breakout (Ensman & Burrows 1992)



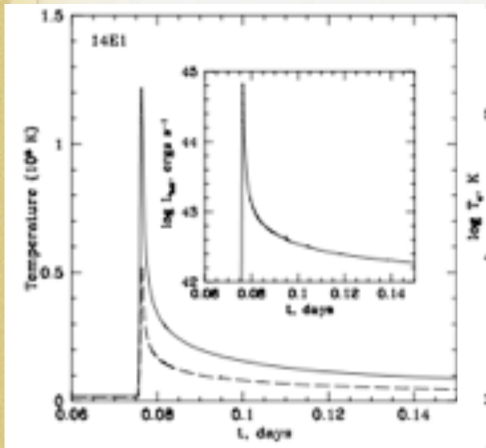
Sweeping of the light echo paraboloid acrossthe ring system.

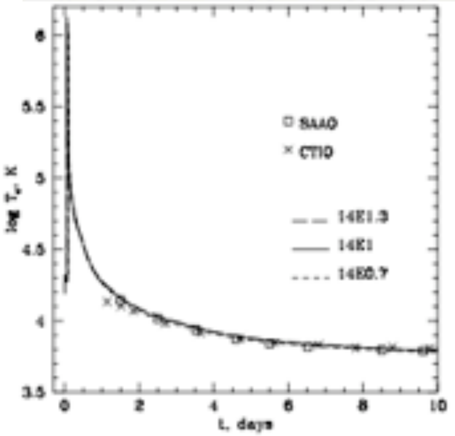
Geometry of the rings (Lundqvist 2007)



Line lightcurve models (Lundqvist & Fransson 1996)

- Densities range between (0.6 – 3.3)x10^4 cm^{-3}.
- Burst: 500full1 (Ensman & Burrows 1992)
- Abundances: He/H = 0.25, N/C = 5.0, N/O = 1.1, (C+N+O) = (He + H +Z) = 0.30 solar
- Radius: 6.3 x 10^{17} cm and Ionized mass: 0.045 M_o
- N V λ1240 is the only resonance line – requires further constraints to be successfully modeled.





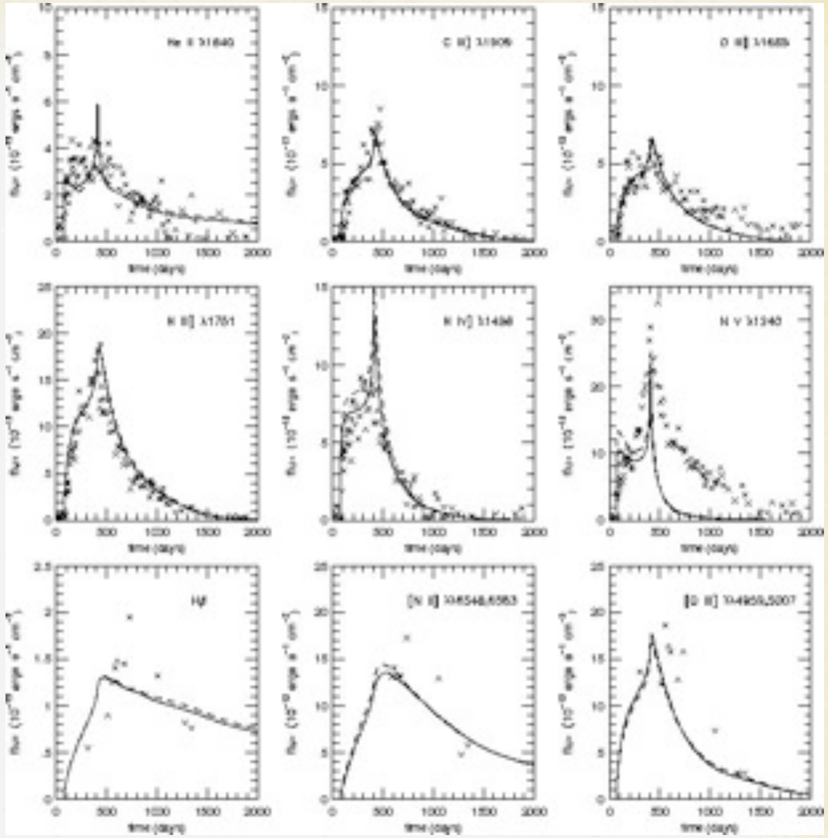


Table 1. Number of ionizing photons and ionizing energy for two models of the breakout of SN 1987A.

Energy range	500full1[a]	14E1[b]	500full1	14E1
(eV)	(Number of photons[c])		(Energy[d])	
13.6–54.4	9.02	8.51	3.33	3.16
54.4–100	0.71	0.65	0.81	0.76
100–500	0.83	0.91	2.71	3.03
> 500	0.03	0.05	0.27	0.56
> 13.6	10.6	10.1	7.12	7.50

[a]Ensman & Burrows (1992).

[b]Blinnikov et al. (2000).

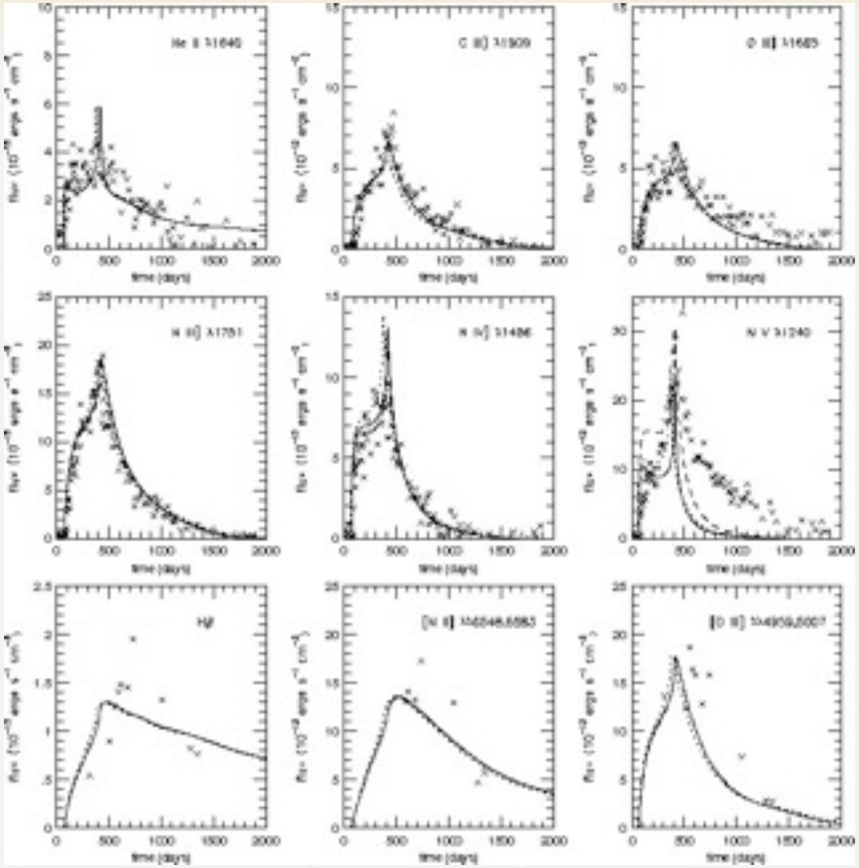
[c]In units of 10^{56}.

[d]In units of 10^{46} ergs.

No surprise that 500full1 and 14E1 by Blinnikov et al. (2000) give very similar results. Is the burst now fully constrained?

Same as in Lundqvist & Fransson (1996), but with updated atomic data and with new burst.

- Solid lines: Blinnikov et al. (2000) 14E1 burst.
- Dashed lines: Ensman & Burrows, 500full1 (1992).
- Densities range between (0.6 – 3.2)x10^4 cm^{-3}.
- Abundances: He/H = 0.25, N/C = 4.5, N/O = 1, (C+N+O) = (He + H +Z) = 0.29 solar
- Radius: 6.2 x 10^{17} cm.
- N V λ1240 not so well modeled

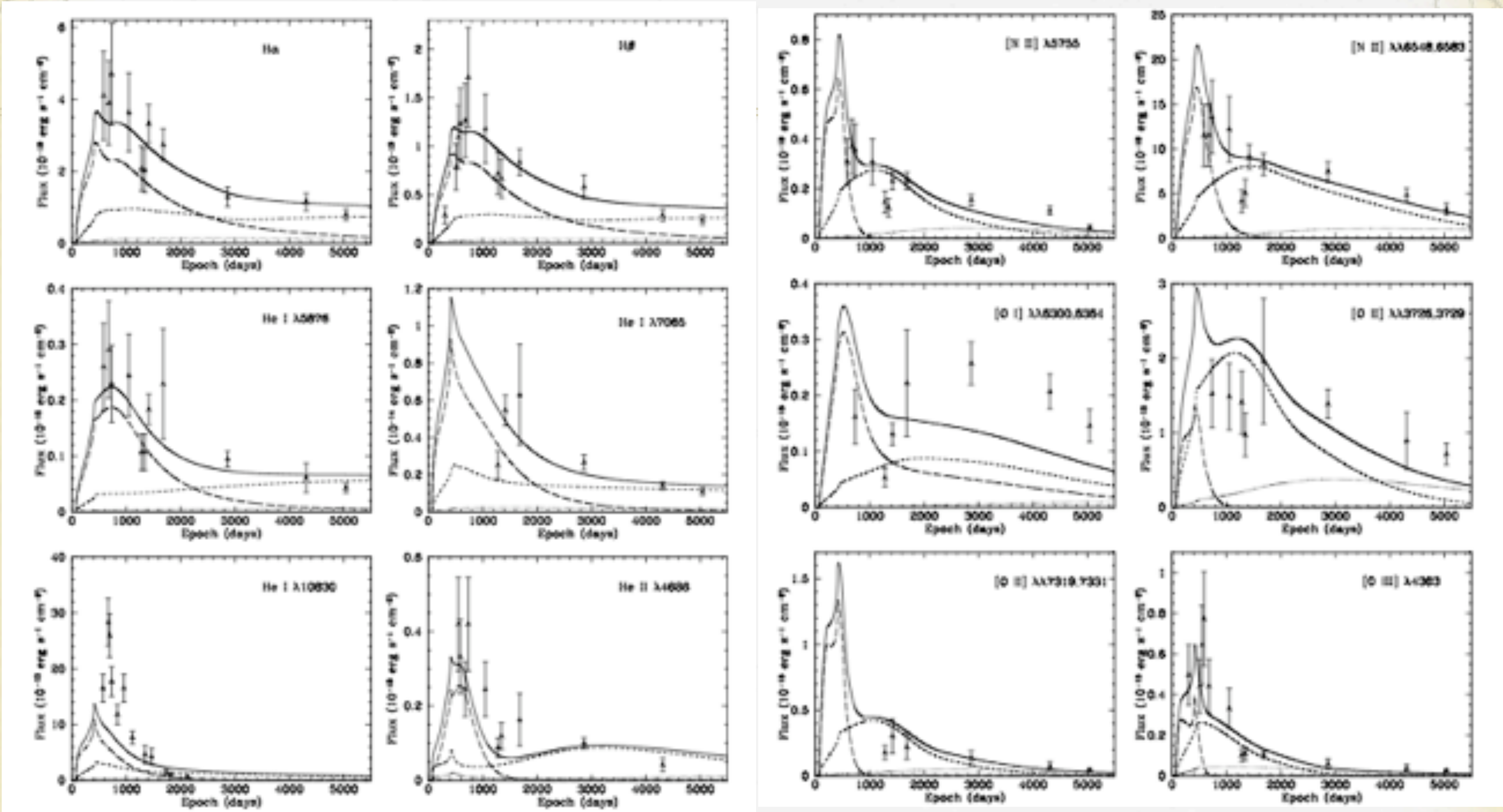


IF we believe the burst is fixed we can use the ring to test atomic data:

- Dashed: Old data for N VI → N V dielectronic recombination. (Used in LF96.)
- Solid: Data from Nahar & Pradhan (1997). 50% lower at 10^5 K.

- Could also signal that we have left out a low-density component

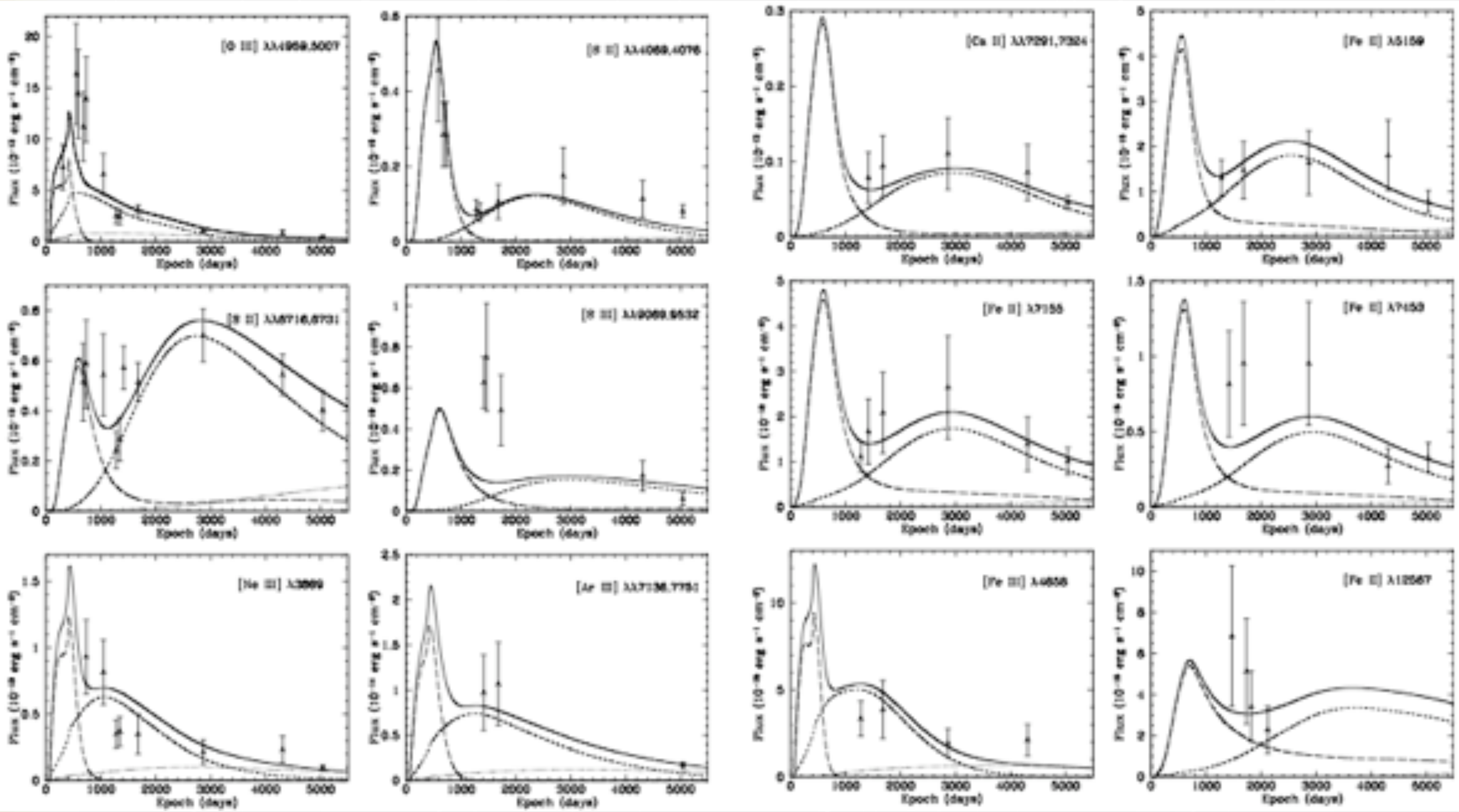
THE INNER RING AT LATER EPOCHS



Light curves for many more lines (Mattila et al. 2010)

- Densities: 3×10^4 cm^{-3}, 3×10^3 cm^{-3} and 1×10^3 cm^{-3}.
- Abundances: He/H = 0.25, N/C = 4.5, N/O = 1,
  (C+N+O) = (He + H +Z) = 0.29 solar
- Radius: 6.2×10^{17} cm.
- N V λ1240 not so well modeled

THE INNER RING AT LATER EPOCHS



Light curves for many more lines (Mattila et al. 2010)

THE INNER RING AT LATER EPOCHS

Elemental Abundances

Element	Solar(AG89)	Solar(GAS07)	LMC(+)	LMC(X-ray,H)	LMC(H07)	87A(X-ray,D)	87A(X-ray,Z)	87A(LF96)	This Work	Lines
He	10.93(0.01,*)	10.93(0.01,*)	10.94(0.03)	...	...	...	...	11.40	$11.23^{+0.13}_{-0.19}$	4
C	8.56(0.04)	8.39(0.05)	8.04(0.18)	...	7.75	...	...	7.51	...	...
N	8.05(0.04)	7.78(0.06)	7.14(0.15)	...	6.90	7.81(0.07)	7.81(0.06)	8.26	$8.44^{+0.15}_{-0.22}$	4
O	8.93(0.04)	8.66(0.05)	8.35(0.06)	8.21(0.07)	8.35	7.85(0.06)	7.85(0.05)	8.20	$8.27^{+0.08}_{-0.10}$	5
Ne	8.09(0.10)	7.84(0.06)	7.61(0.05)	7.55(0.08)	...	7.56(0.10)	7.55(0.03)	...	7.93	1
S	7.21(0.06)	7.14(0.05)	6.70(0.09)	6.77(0.13)	...	6.69(0.11)	6.68(0.09)	...	$7.12^{+0.19}_{-0.34}$	3
Ar	6.56(0.10)	6.18(0.08)	6.29(0.25)	...	...	...	6.29	...	6.23	1
Ca	6.36(0.02)	6.31(0.04)	5.89(0.16)	...	...	...	5.89	...	6.51	1
Fe	7.67(0.03)	7.45(0.05)	7.23(0.14)	7.01(0.11)	...	6.97(0.04)	6.97(0.02)	...	$6.98^{+0.19}_{-0.34}$	5

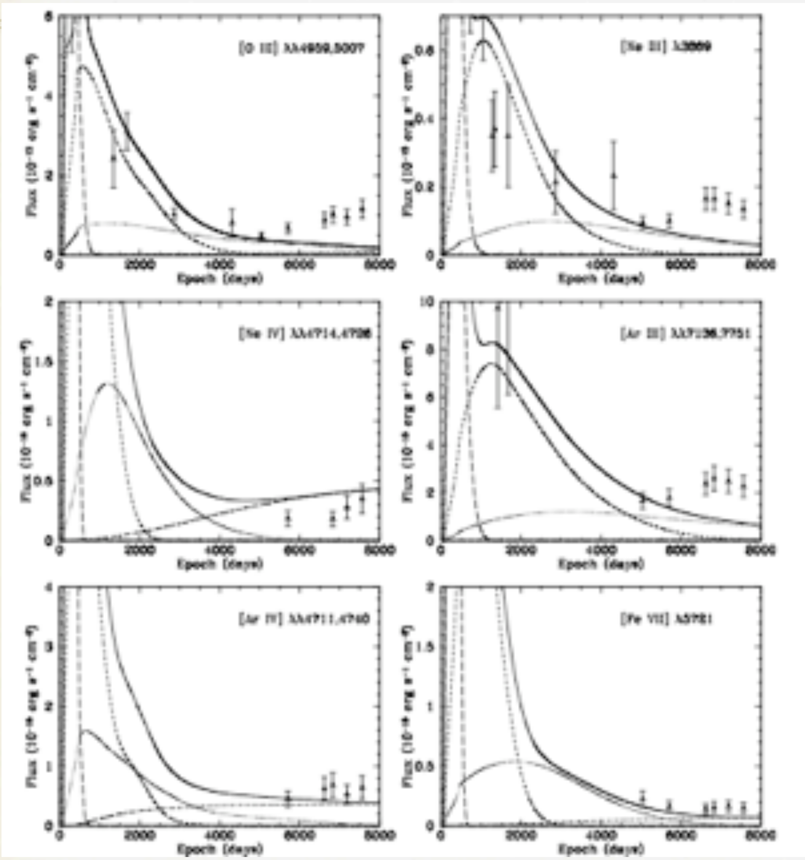
Notes. The elemental abundances are in units of $12 + \log[n(X)/n(H)]$ and the errors are given in parentheses. The abundance estimates from this work are the average of the estimates from different emission lines (see Table 6) and the quoted errors are the standard deviations. The number of emission lines used for each average abundance is given in Column 11. (*): GAS07, Grevesse et al. (2007) (values are for photospheric abundances). AG89: Anders & Grevesse (1989). (+): Russell & Dopita (1992). H: Hughes et al. (1998). D: Dewey et al. (2008). H07: Hunter et al. (2007). Z: Zhekov et al. (2009). LF96: Lundqvist & Fransson (1996).

(Mattila et al. 2010)

- Abundances: He/H = 0.17±0.06 and N/O = 1.5±0.7.
- With N/C = 5 from Lundqvist & Fransson (1996)
  - (C+N+O) = (He + H +Z) = 0.33 solar (Anders & Grevesse 1989)
  - (C+N+O) = (He + H +Z) = 0.60 solar (Grevesse et al. 2007)
  - (C+N+O) = (He + H +Z) = 1.6 LMC (Russell & Dopita 1992)
- Fe abundance is ~0.2 solar (Anders & Grevesse 1989) or ~0.3 solar (Grevesse et al. 2007).
- In general we obtain higher metal abundances than X-ray findings (e.g. Zhekov et al. 2009)
- Total ionized mass is ~0.058 $M_{\odot}$

THE INNER RING AT PRESENT EPOCHS

Narrow-line light curves (Mattila et al. 2010)

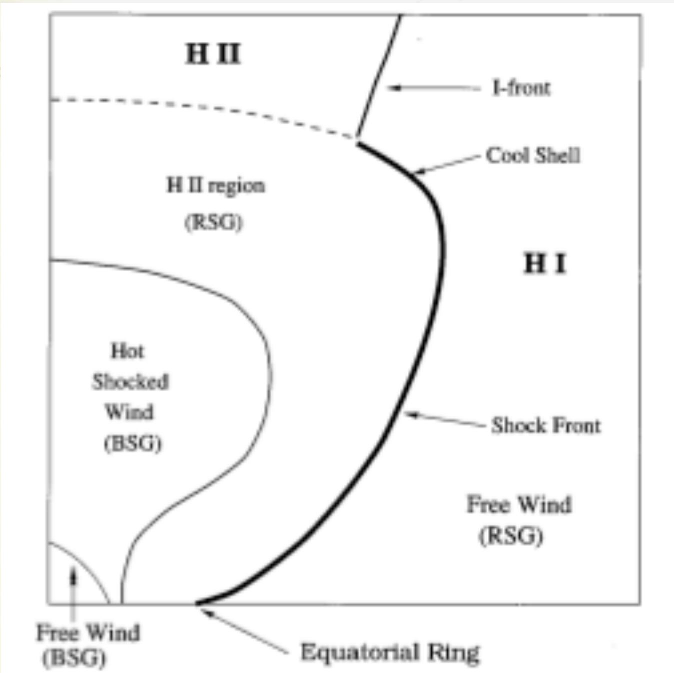


(Mattila et al. 2010)

- A 4th density 0.018 $M_\odot$ component (10^2 cm^{-3}) added to explain late emission.

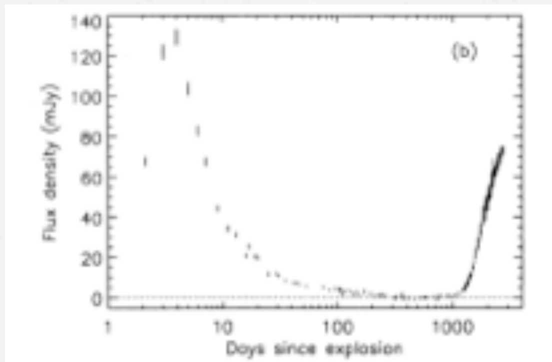
Why a 10^2 cm^{-3} component?

INSIDE THE INNER RING



Chevaliwr & Dwarkadas (1995) & Talk by Dwarkadas

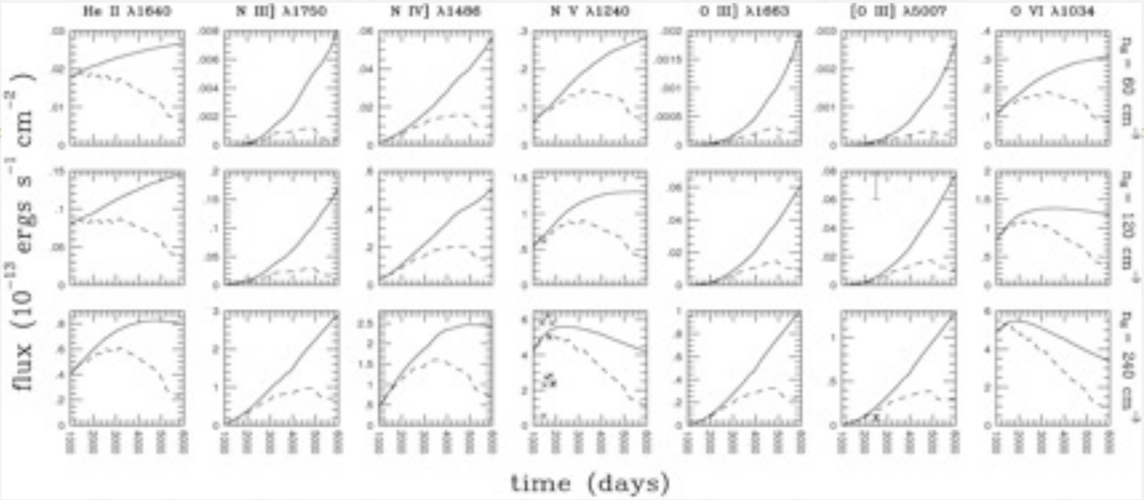
- Photoevaporation of the cool shell
- H II-region has a density of around 10^2 cm^{-3}. Helium neutral *(Lundqvist 1999).*
- BSG wind: $< 10^{-8}$ M_o yr^{-1}
- Broad region of H II-region (roughly half of ring radius)



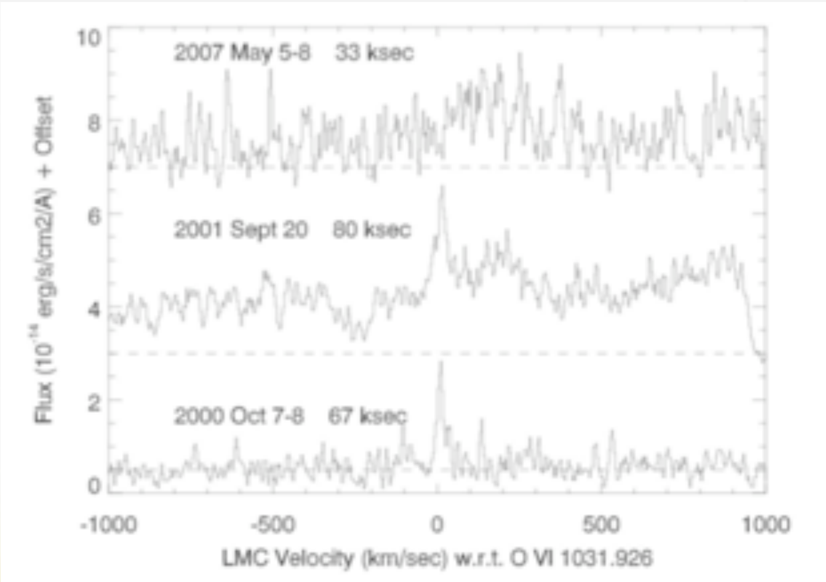
Radio upturn after ~1000 days

(Talk on radio by Ng!)

INSIDE THE INNER RING



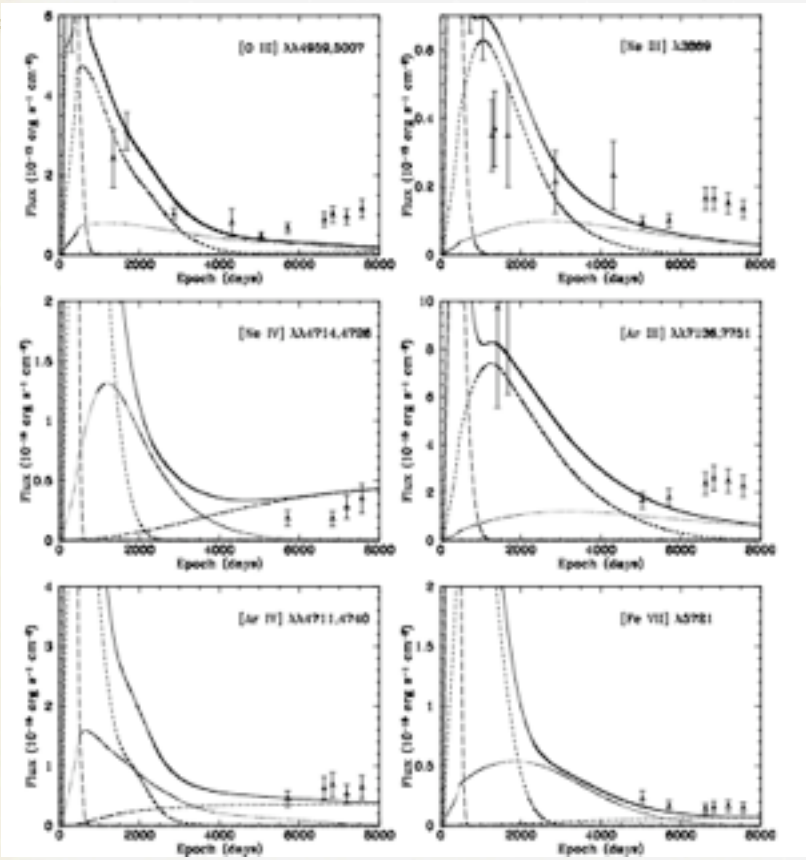
Lundqvist (1999)



FUSE observations around O VI λ1032 (Sonneborn et al. in prep.)

THE INNER RING AT PRESENT EPOCHS

Narrow-line light curves (Mattila et al. 2010)

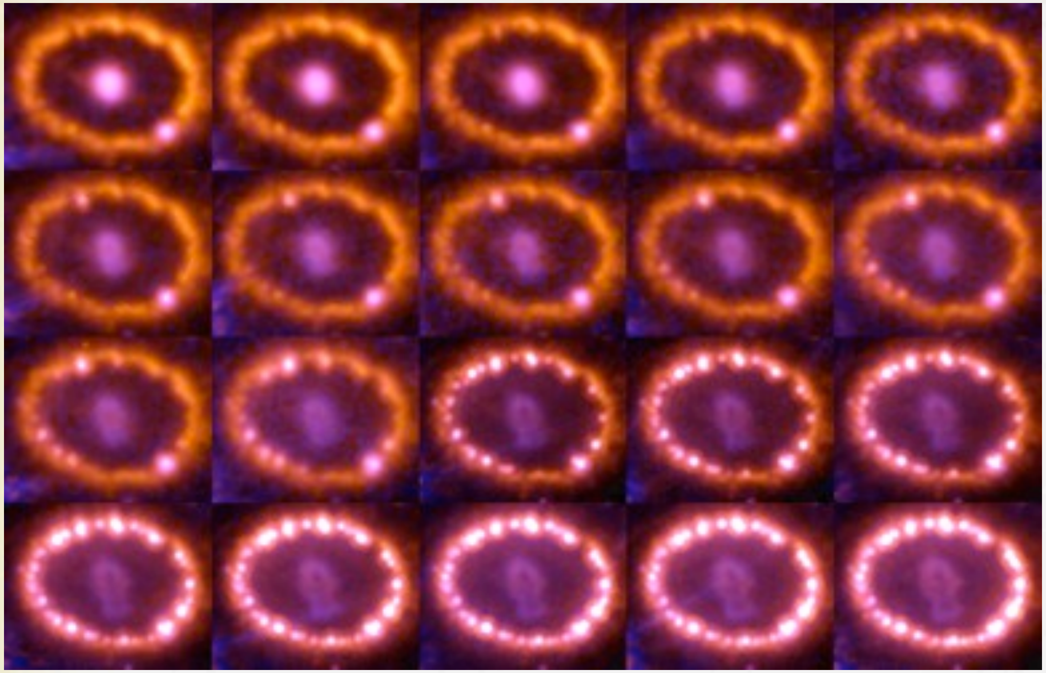


(Mattila et al. 2010)

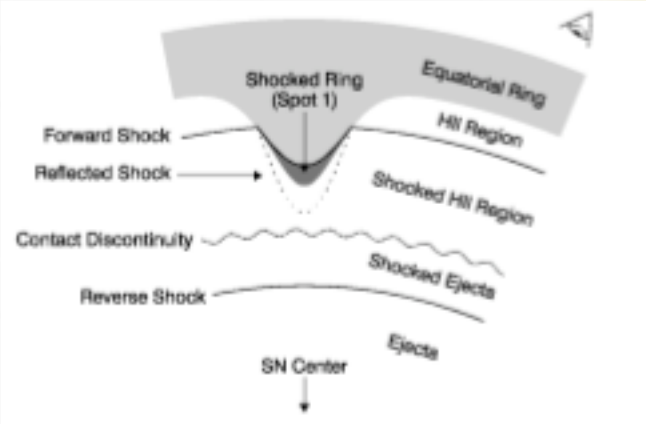
- One more source needed at late times..

The ejecta/ring interaction!

WHEN THE SN EJECTA REACHED THE INNER RING



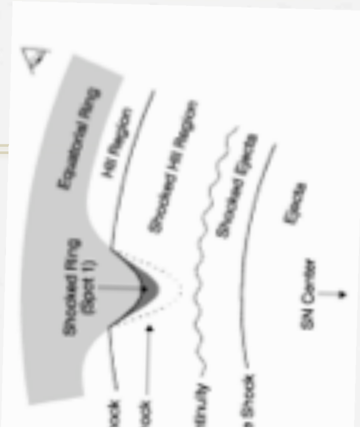
Evolution of ring spots until 2007 (SAINTS collaboration)
(First spot seen in 1997.)



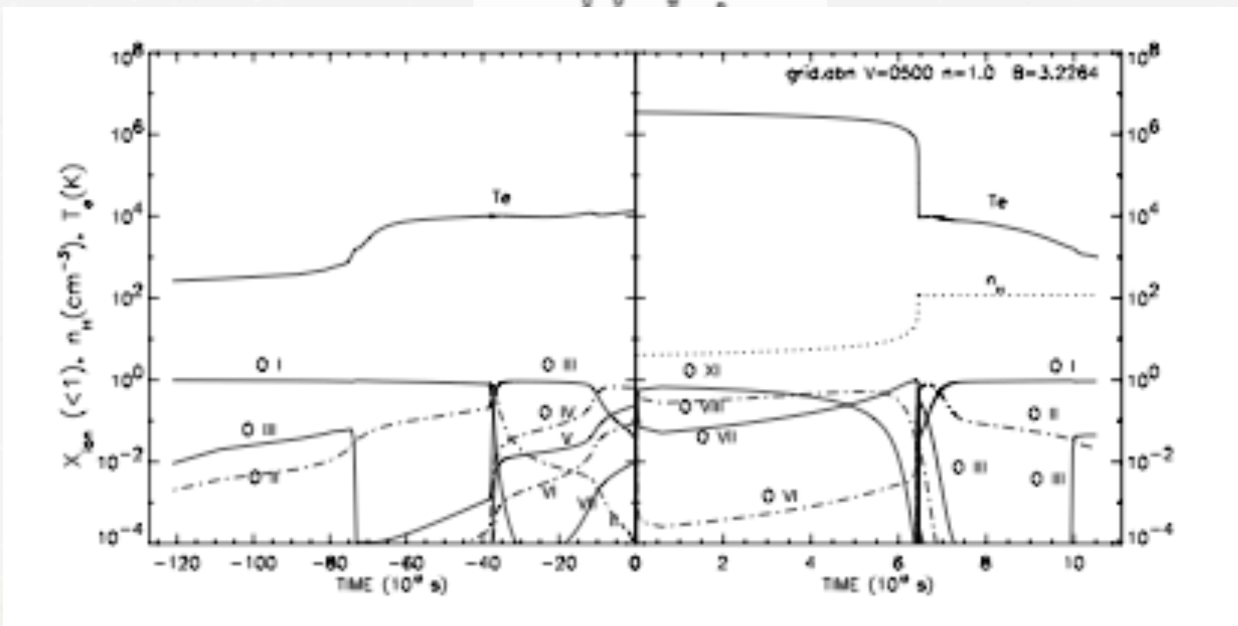
Michael et al. (2000)

(Talk on reverse shock by France!)

WHEN THE SN EJECTA REACHED THE INNER RING

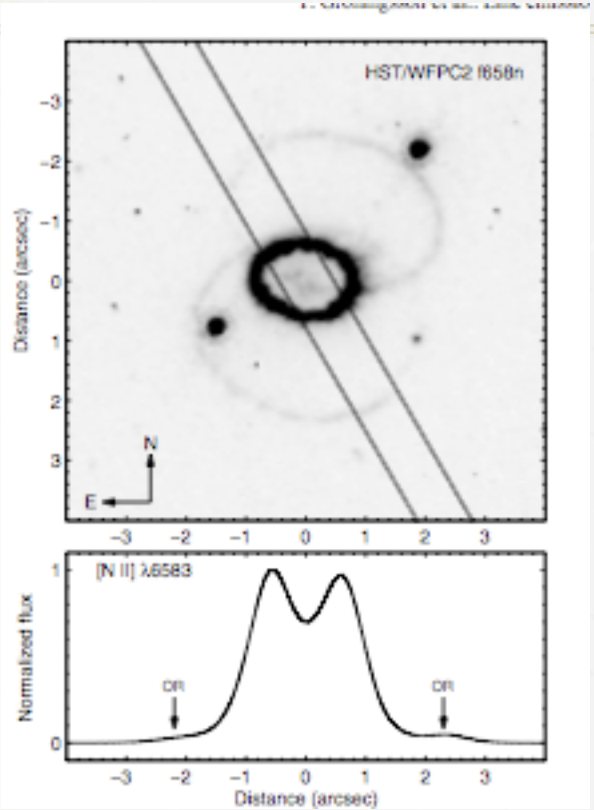


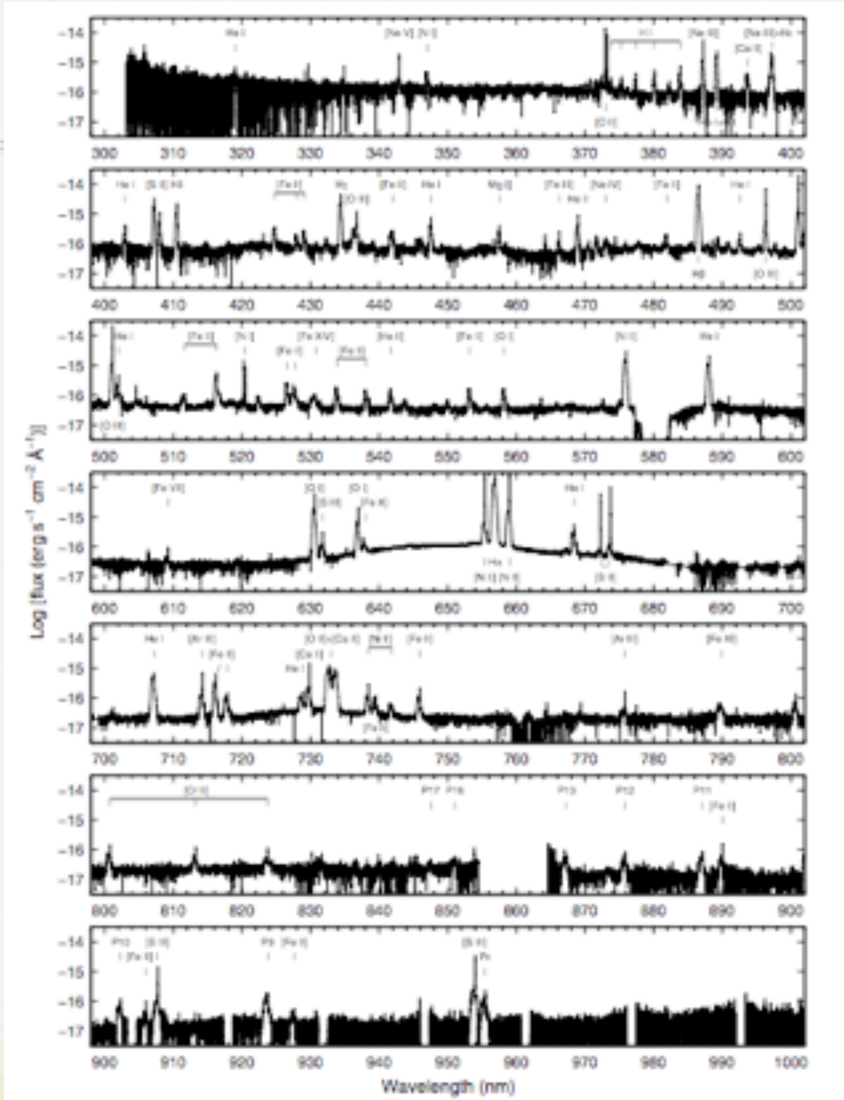
(Talks on X-rays by Park & Larsson)



Allen et al. (2008)

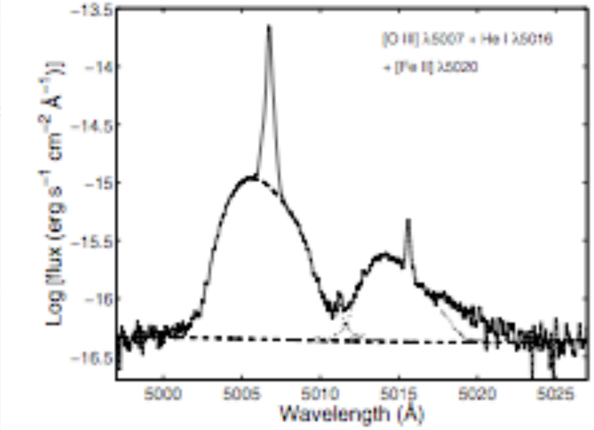
EJECTA/RING INTERACTION



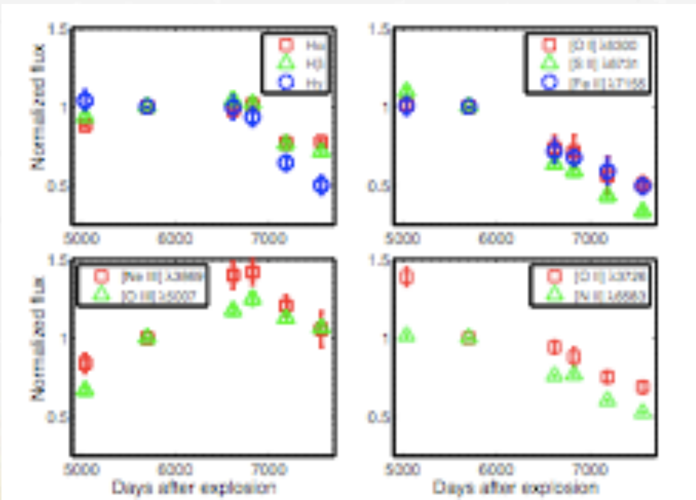


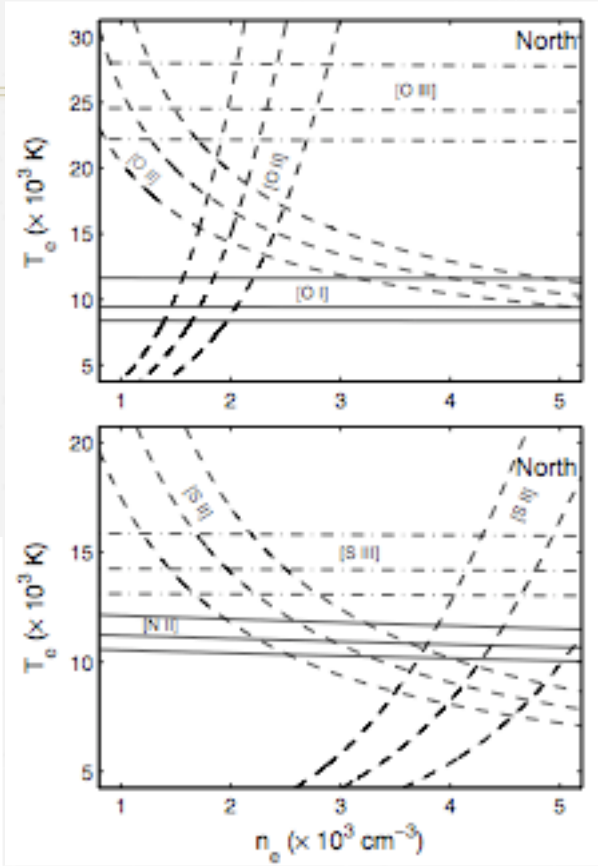
Gröningsson et al. (2008a)

EJECTA/RING INTERACTION



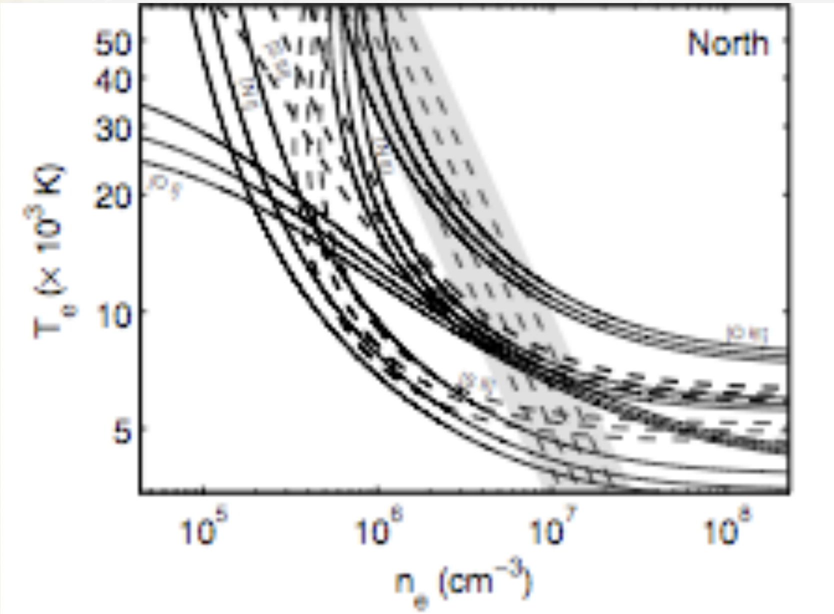
[O III] from the northern part of the ring (Gröningsson et al. 2008a)

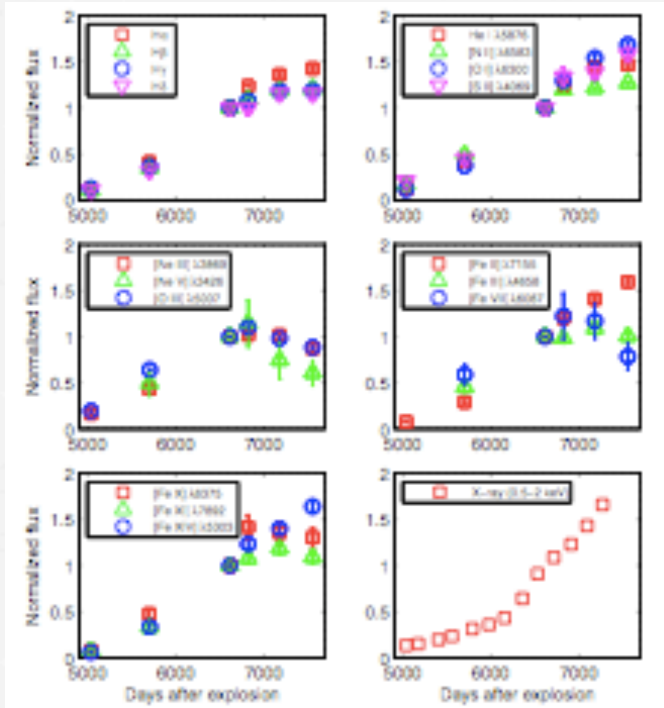




Evolution and diagnostic (day 5704) of the narrow velocity component from the northern part of the ring (Gröningsson et al. 2008ab)

EJECTA/RING INTERACTION





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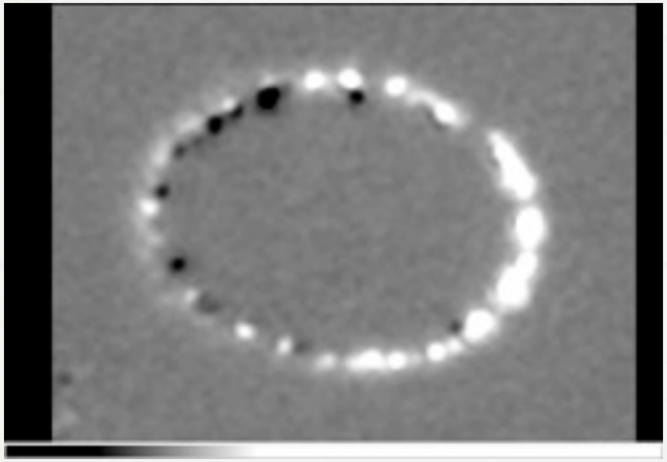
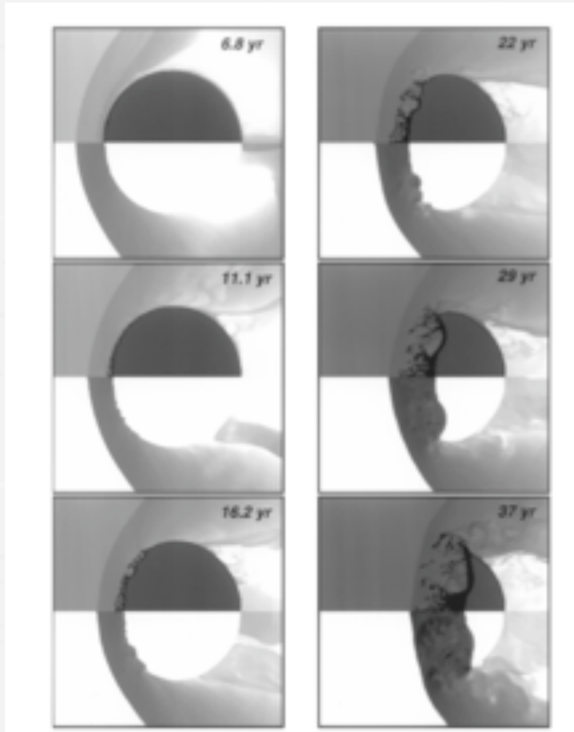
EJECTA/RING INTERACTION

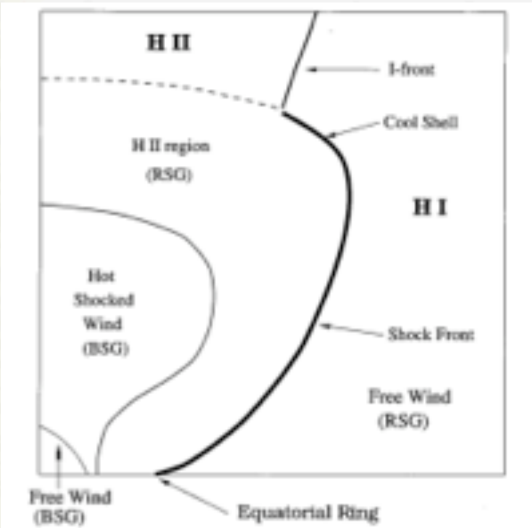


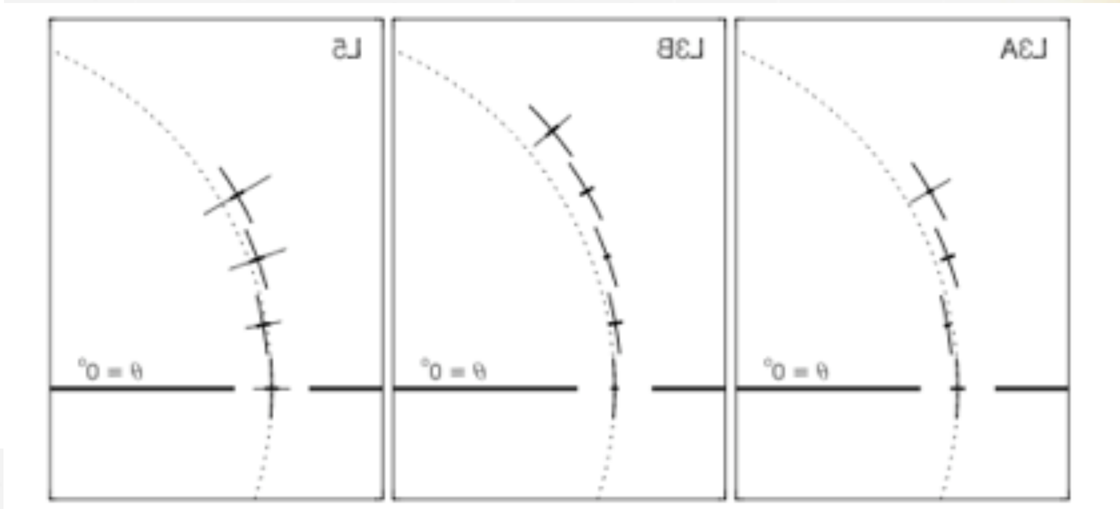
Ratio map [O III] (2006) / [O III] (2003) (SAINTS)



Borkowski et al. (1997)

AWAY FROM THE INNER RING

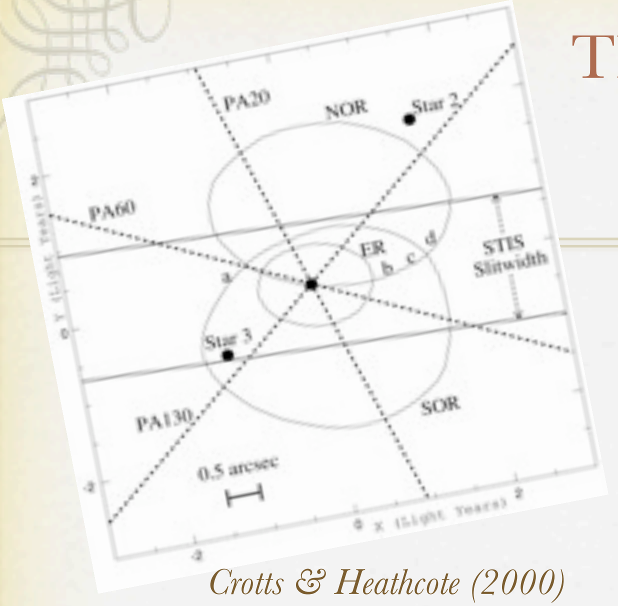




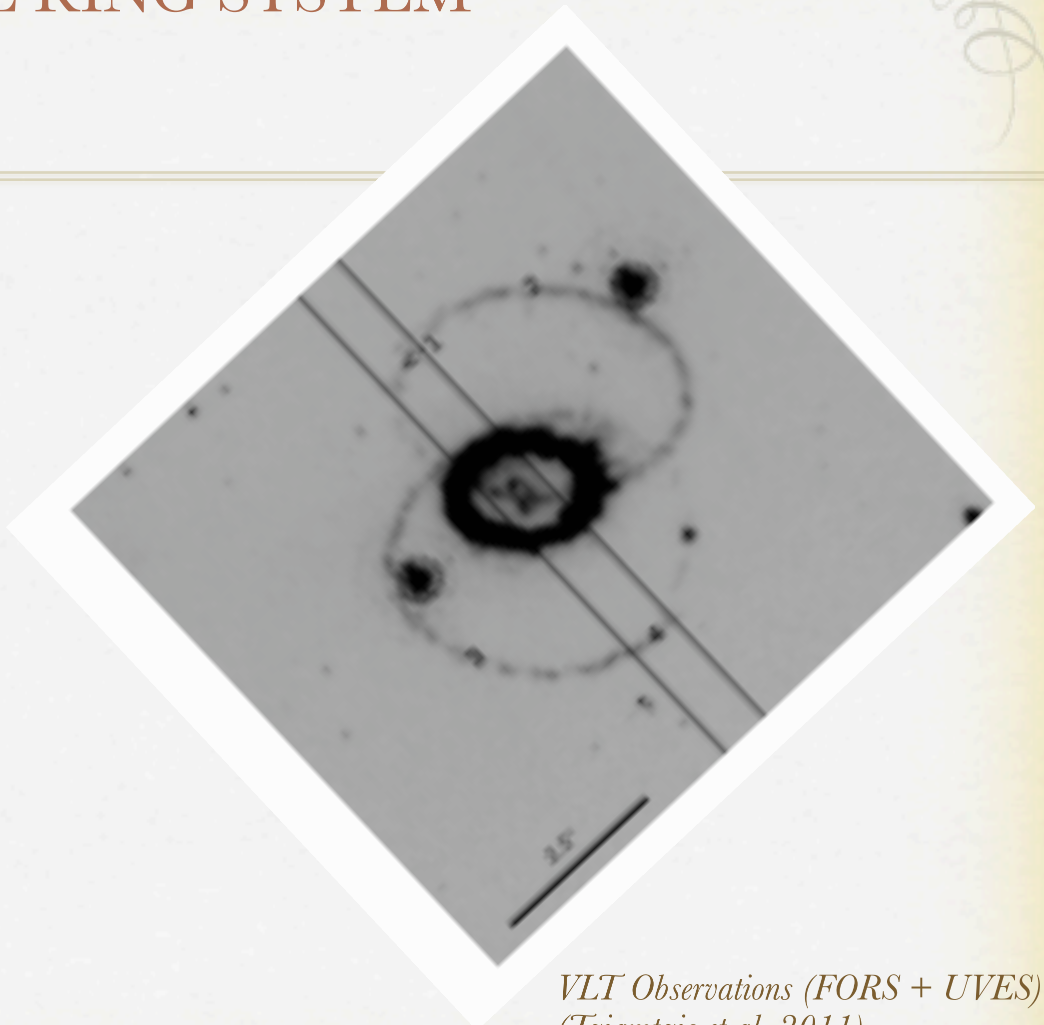
Structure of the reverse shock
(Michael et al. 2003)

(Talk by France!)

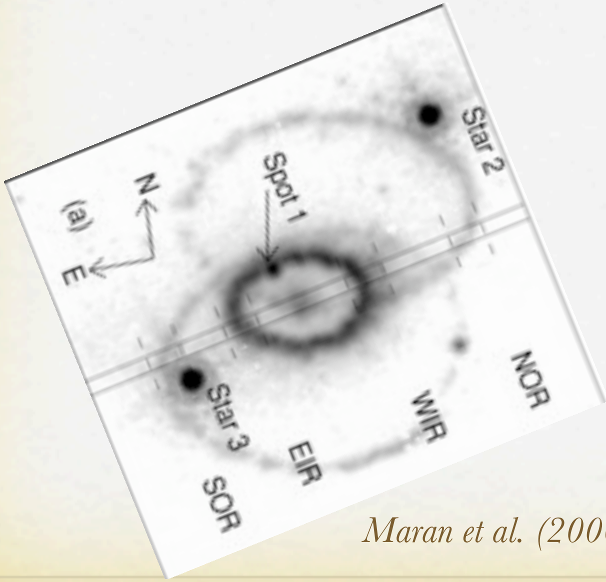
THE RING SYSTEM



Crotts & Heathcote (2000)

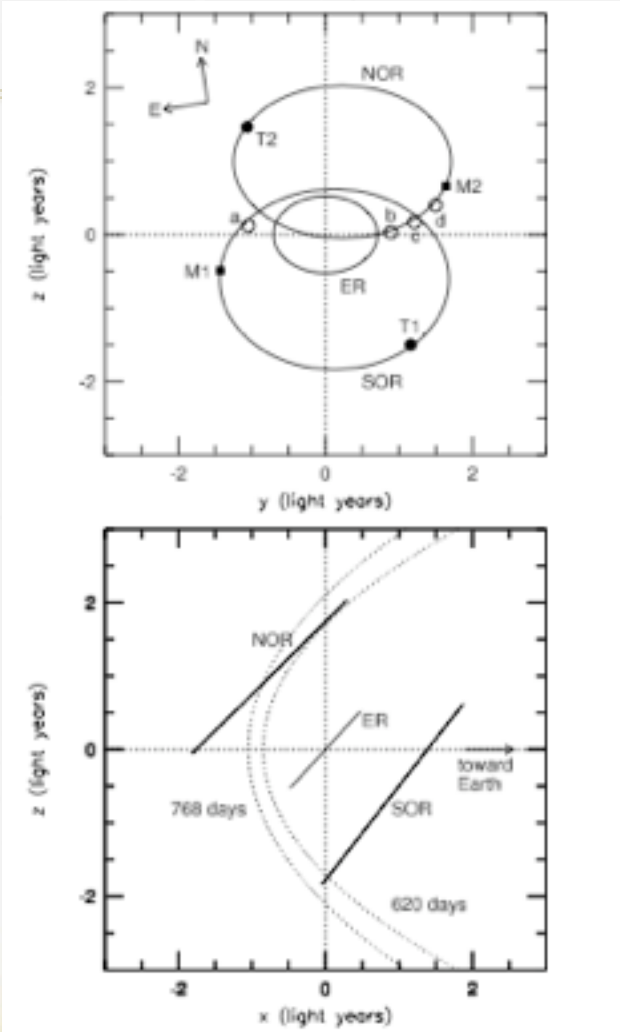


VLT Observations (FORS + UVES)
(Tziamtzis et al. 2011)



Maran et al. (2000)

THE OUTER RINGS



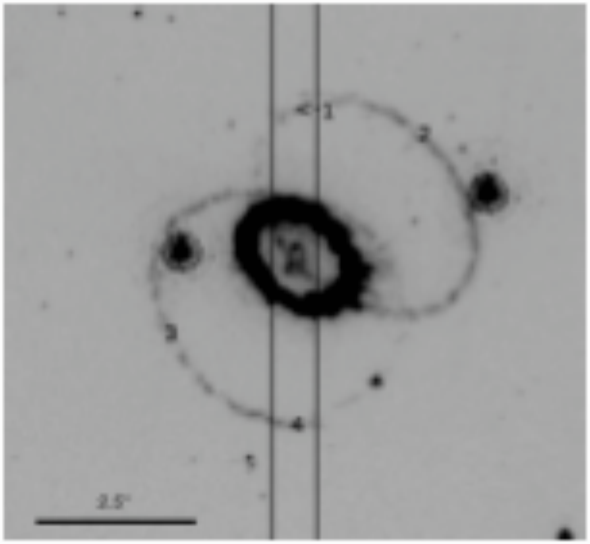
Simple model for the geometry of the ring system:

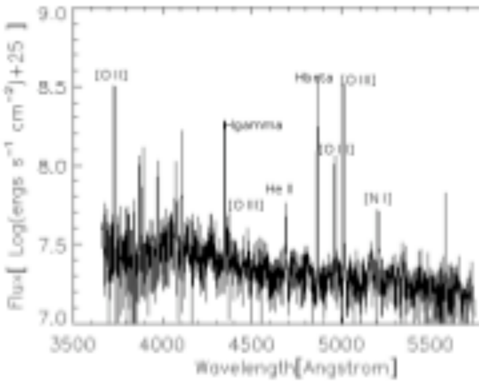
- Rings intrinsically circular
- Motion close to ballistic (a = -21.5 km/s, b = 22.3 km/s, c = 24.3 km/s, d = 21.1 km/s).
- Rings have their normal vector in x-z plane.
- Should intersect M1 and M2 (from Maran et al. 2000).
- Assume a distance of 50 kpc.

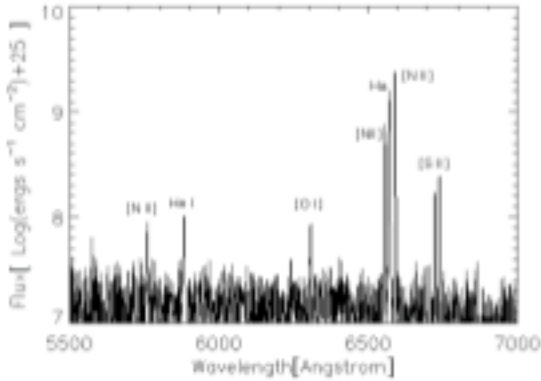
Result:

- Inclination angles of NOR, ER and SOR are: 45°, 43° and 38°, respectively.
- Both NOR and SOR are shifted westward with respect to the SN.
- Distances to M1 and M2 are 1.65×10^{18} cm and 2.05×10^{18} cm. (Not both 2.0×10^{18} cm as in Maran et al. 2000).

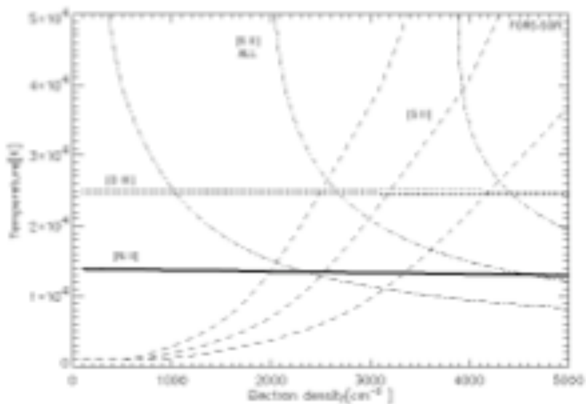
THE OUTER RINGS







Southern outer ring spectra in 2002
(Tziamtzis et al. 2011)



Thursday, August 18, 2011

THE OUTER RINGS

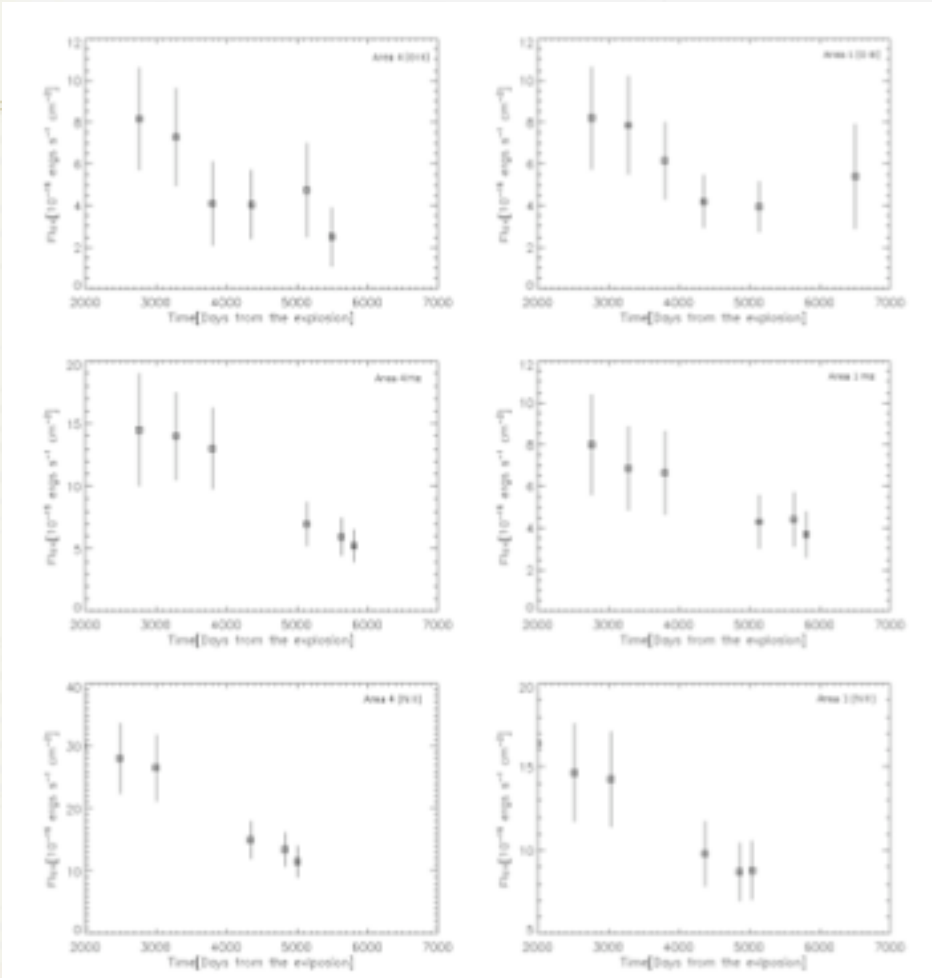
Table 8. Compilation of plasma diagnostics for the outer rings of SN1987A.

Epoch	Corrected epoch[a]	Ring	N_e (cm^{-3})	T (K)	Diagnostic	Reference
2877	2192	SOR	$<1.3\times10^{3,b}$		[O II]	Panagia et al. (1996)
2877	2217	NOR	$<1.3\times10^{3}$		[O II]	Panagia et al. (1996)
4282	3099	NOR	$<2.2\times10^{3}$		[S II]	Maran et al. (2000)
4282	4022	SOR	$<1.6\times10^{3}$		[S II]	Maran et al. (2000)
5702–5705	4902–4905	SOR	$<1.0\times10^{3}$		[O II]	This paper
5702–5705	4902–4905	SOR		$(1.00-1.10)\times10^{4}$	[N II]	This paper
5702–5705	4902–4905	SOR		$(1.95-2.00)\times10^{4}$	[O III]	This paper
5702–5705	4934–4937	NOR		$\sim1.2\times10^{4}$	[N II]	This paper
5702–5705	4934–4937	NOR		$\sim2.7\times10^{4}$	[O III]	This paper
5791	4991	SOR	$<3.3\times10^{3}$		[S II]	This paper
5791	4991	SOR		$(1.3-1.4)\times10^{4}$	[N II]	This paper
5791	4991	SOR		$\sim2.5\times10^{4}$	[O III]	This paper
7944–8021	7144–7221	SOR	$<2.3\times10^{3}$		[O II]	This paper
7944–8021	7144–7221	SOR	$<3.0\times10^{3}$		[S II]	This paper
7944–8021	7144–7221	SOR		$(1.15-1.25)\times10^{4}$	[N II]	This paper
7944–8021	7176–7253	NOR		$\sim1.2\times10^{4}$	[N II]	This paper

Notes. [a] In days. Corrected for light-travel time. [b] Allowing for a higher temperature than Panagia et al. (1996).

(Tziamtzis et al. 2011)

THE OUTER RINGS



Southern outer ring; Area 4 Northern outer ring; Area 1

Some findings:

- From H-alpha decay; density as high as 5×10^3 cm^{-3}. From forbidden lines < 3×10^3 cm^{-3}.
- Area 4 (T1) is redshifted by 6 km/s compared to the model.
- Density and temperatures are similar for the two outer rings.
- When the SN shock reaches the outer rings, the cloud shock may not be radiative as for the inner ring.
- The densities are somewhat higher than that of the inner ring, assuming simple "ballistic" expansion.

For a current radius of the blast wave in the direction of the ORs of $\sim 10^{18}$ cm, the collision with the ORs in areas 1 and 4 would occur in $\sim 95\,(3\times10^3/V_{\rm blast})$ years. There is, however, considerable uncertainty in the mass distribution of the circumstellar matter in the direction towards the ORs, so a collision with the ORs may occur much earlier than in ~ 100 years, and may only be $\lesssim 20$ years away, especially in those parts of the ORs which are closest to the supernova. According to Sect. 4.1 this is likely to be the southeastern part of the NOR. Furthermore, the supernova

HST photometry (Tziamtzis et al. 2011)

THE OVERALL STRUCTURE

N V λ1240 scattering.
Could be an important probe of the geometry.

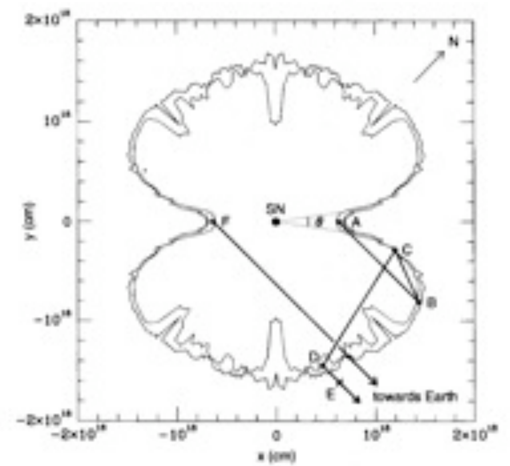
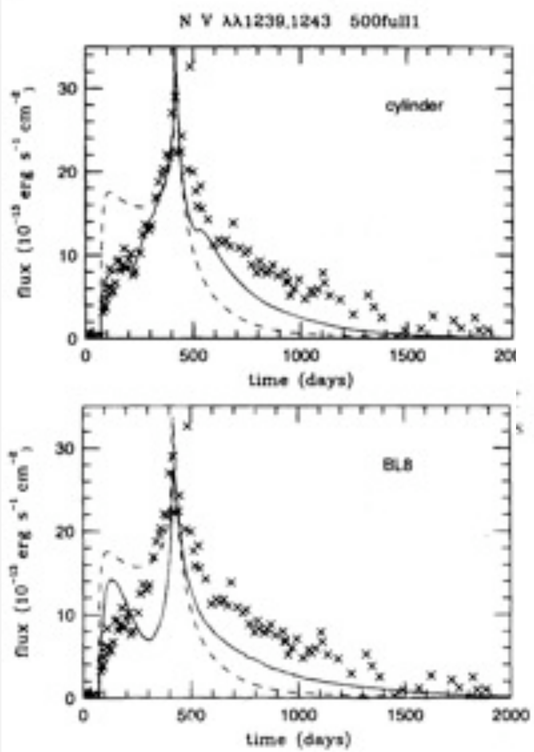
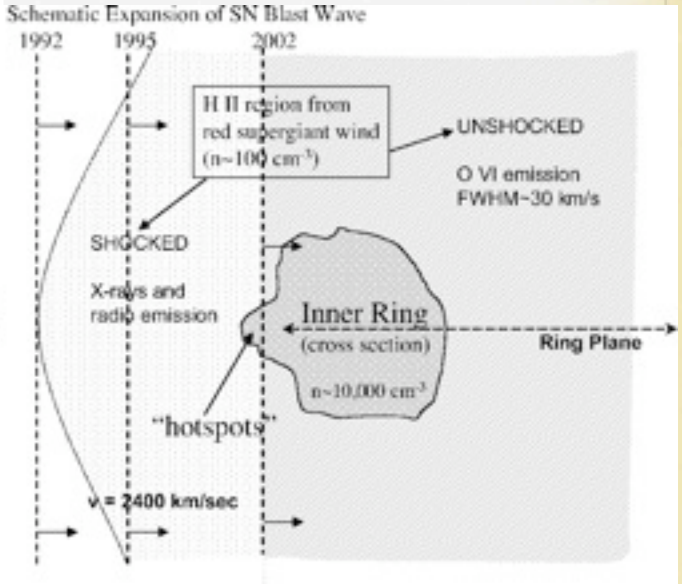


FIG. 6.—Structure of the radial optical depth in N v λ1240 for the BL8 model (Blondin & Lundqvist 1993; their model h) shortly after ionization. The 500full1 model by Ensman & Burrows (1992) was used for the supernova outburst. The N v λ1240 emission mainly comes from the equatorial plane of the nebula, which subtends an angle θ at the supernova. A photon emitted toward Earth from point *A* has a high probability to scatter at point *B*. Further scatterings are required to deflect it back toward Earth (path *BCDE*; path length Δ*l*). The extra time spent in the nebula due to scattering is Δ*l*/*c*. A photon emitted at *F* toward Earth does not scatter because of the large velocity difference between the emitting gas and the gas at the near side of the nebula. The calculations discussed in the text allow for scattering in all three dimensions. The nebula is assumed to be tilted 45° to the line of sight.





FORMATION

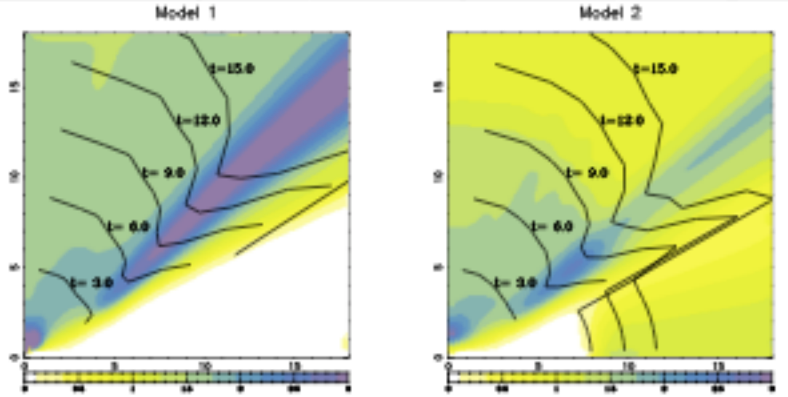
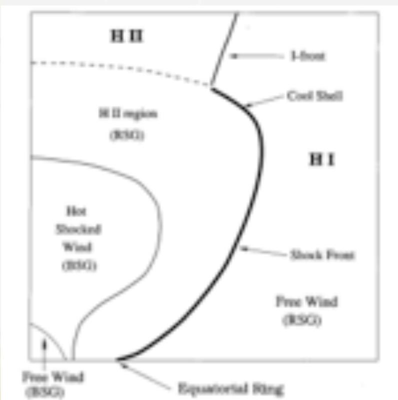


Figure 10. Mass enhancements in the ejecta flow, corresponding to merger models for SN 1987A (left-hand panel, Model 1 from section 3.1 with $\alpha = 0.33$ and $\beta = 0.817$) and Sheridan 25 (right-hand panel; Model 2 from section 3.2 with $\alpha = 0.35$ and $\beta = 0.665$). The solid curves give the locations that contain 50 % of the mass ejected at a particular solid angle at the time as indicated (in code

$(M_1+M_2 = 20\,M_\odot,\ P \sim 10\,\mathrm{yr})$,

Morris & Podsiadlowski (2005)



Further simulations needed!

CONGRATULATIONS!