20,079 Years of SN1987A

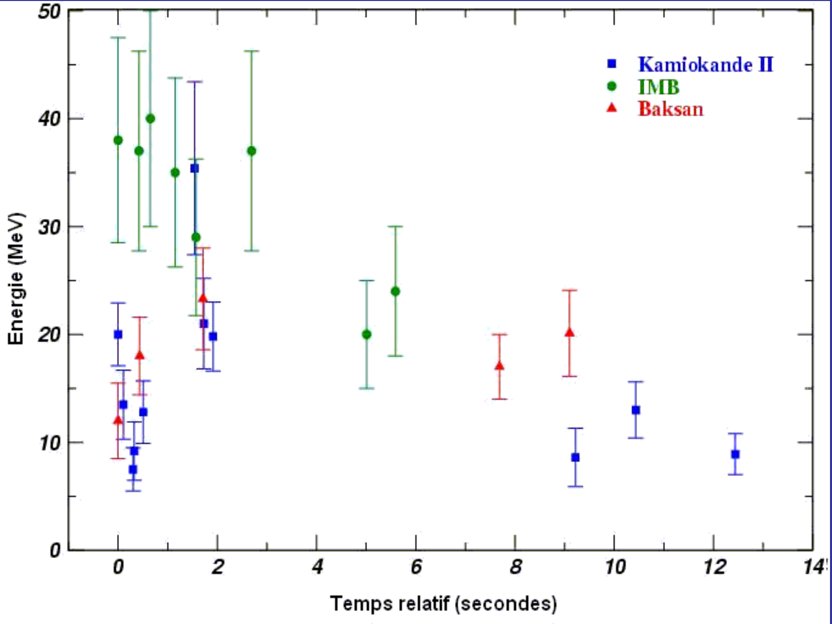
(in 45 minutes???)

- Most intensively studied SN of all time:
- Radio: initial detection, turned on again in ~1990
- X-ray: no initial detection, turned on in ~1990
- Soft Gamma-ray decay lines from 56Co detected Aug-Oct 1987
- Dust in the ejecta (1989) & in the CSM (2004)

➔ ADS: ~2824 (~2.7/week) refereed papers (since 1987)

Patrice Bouchet
ANPE
Guest at GEPI
Observatoire de Paris

Neutrinos



- Temperature: ~ 4±1 MeV
- Decay time: ~ 4 s

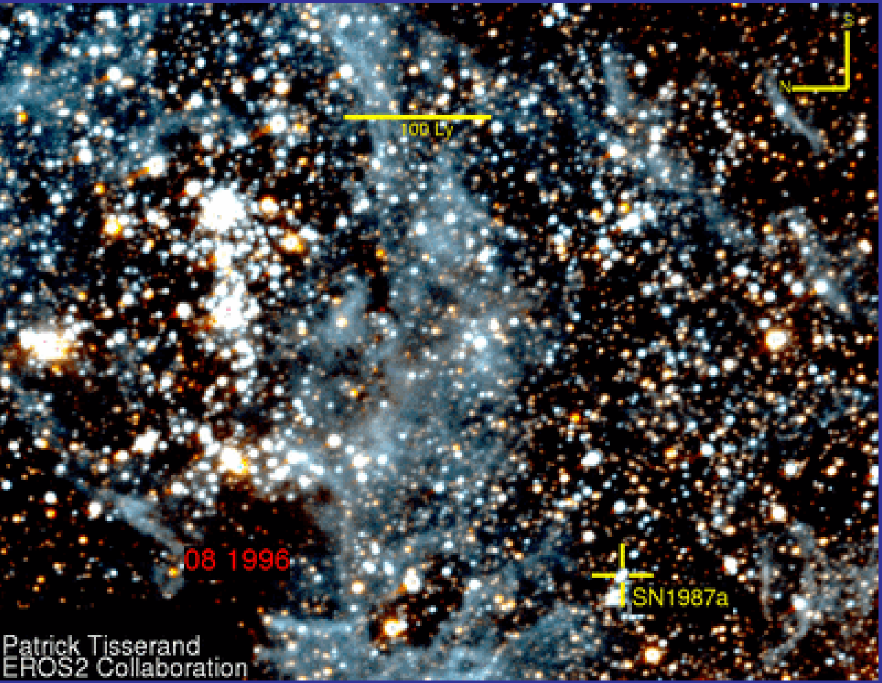
➔Just about right for neutron star formation; results close to modern theory

- Most of them $\bar{\nu}_e$ (energies, number, angles)
- Fluence at Earth 5.0±2.5 x 10^9 cm^{-2}
- During the early phase (t<1s), L_ν= 4 x 10^{52} ergs
- Core radius = 30±20 km
- Total $\bar{\nu}_e$ Energy: ~ 4±1 x 10^{52} ergs (D=51.2 Kpc)
- Total ν Energy: ~ 3±1 x 10^{53} ergs
- M_{Baryon} = 1.45±0.15 $M_{o;}$ $M_{Gravit.}$= 1.35±0.15 M_o

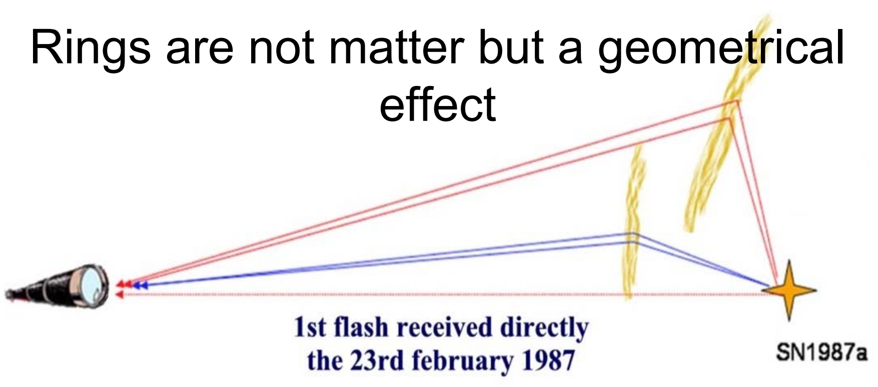
Mont Blanc (LSD) ~4.7 hours earlier??
2-stage explosion in a rapidly rotating collapsar could explain the difference between LSD/IMB-KII υ detections
(Imshennik & Ryazhskaya, 2003)

~1 nanogram of ν through IMB and KII and only 1 in 10^{15} were captured
➔ ~500 grams through the entire Earth ≡ 15MegaT of TNT (1 million people experienced 1 SN1987A ν_e event in their body and ~300 experienced 2 events)

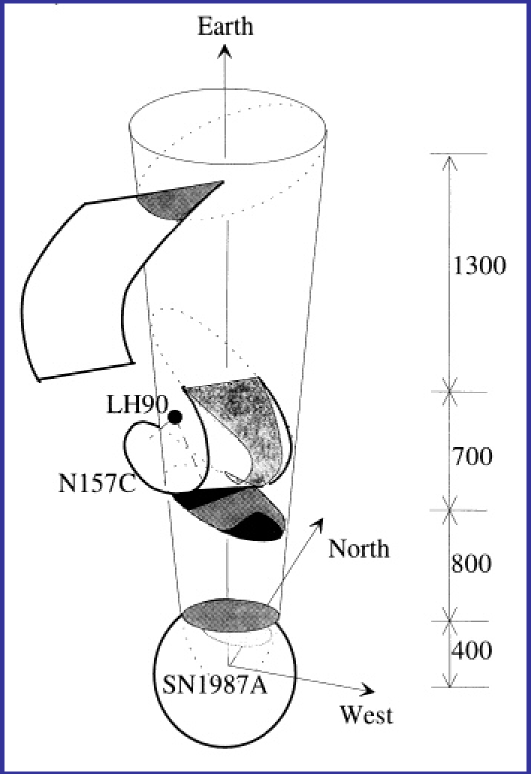
Light Echoes

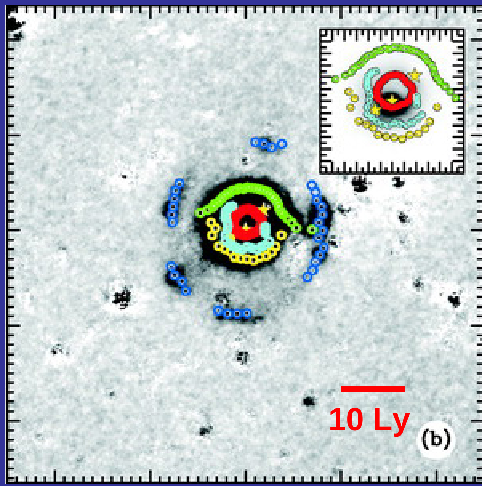


Distant echoes: interstellar clouds (P. Tisserand: ~1200 real EROS2 images from july 1996 to feb. 2002)



- R310, R430; W700, S730, N980; R1170 complex (5 echoes); SE3140, N3240
- 3-dimensional structure (Xu et al., 1995)





Nearby echoes: Napoleon's Hat etc.

➔ few solar masses ejected by progenitor

Progenitor Star

Sk -69°202: B3 Ia; Teff = 16300 K; R = 46.8R_o

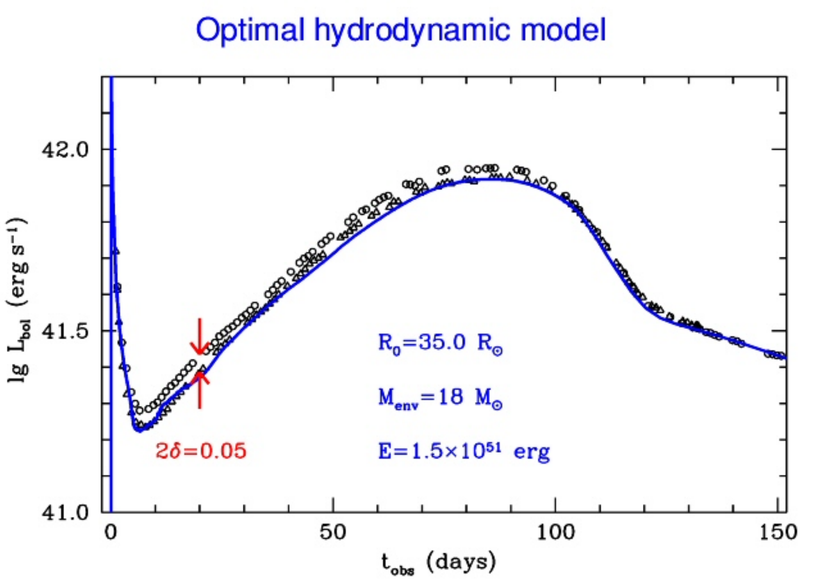
- Why blue giant, not red giant?

1. Low metallicity (Shkloskii, 1984; Arnett, 1987; Hillebrandt et al., 1987): Ni rich shell?
2. Mass loss (Maeder & Lequeux, 1982; Maeder, 1987): light curve and slow V ejecta?
3. Blue Loops (Summa & Chiosi, 1970): must have been RSG (Woosley, 1988)

- Mixing: 56Ni up to ~3000 kms-1, H down to ~500 kms-1?

1. Convective mixing induced by rotation (Weiss et al., 1988)
2. semi-convection at low abundance of heavy elements (Woosley et al., 1988)
3. evolutionary effect in a close binary system (Podsiadlowski & Joss, 1989)

NTT / Wampler et al., 1990 → new constraints!
(at least rotational effects & convective mixing)

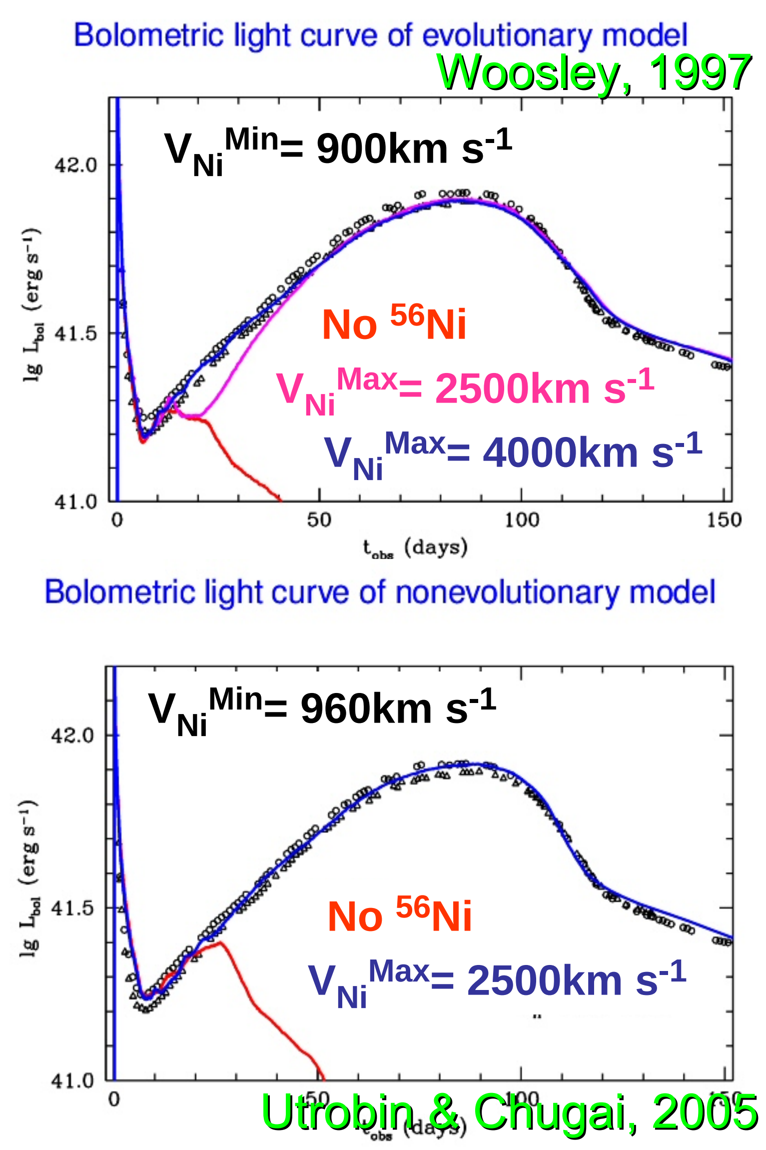


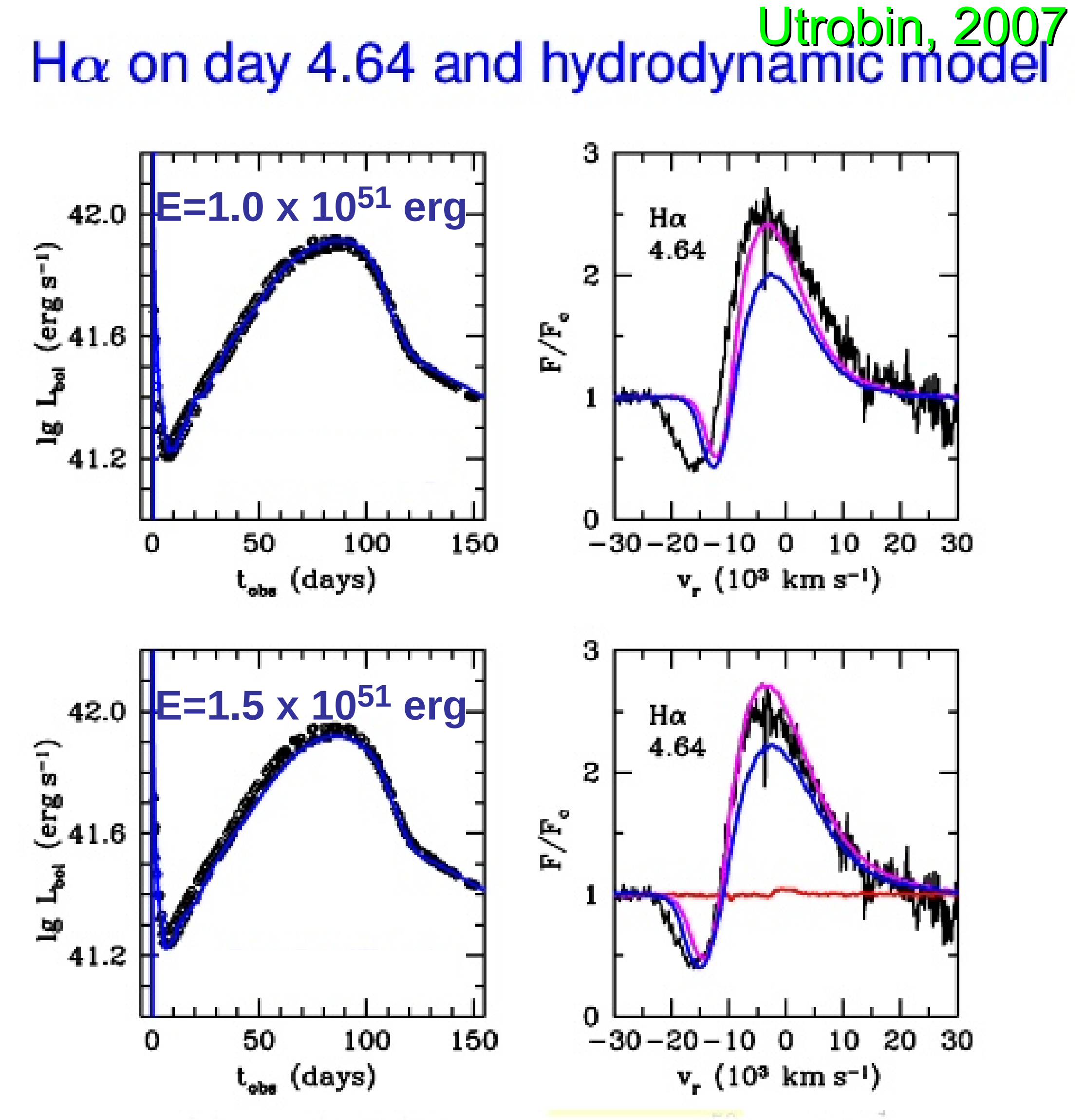
- $M_{envelope}$ = 18±1.5 M_o
- M_{He} = 6 ± 1 M_o, $M_{H,Envelope}$ = 5-10 M_o
- M_{Fe} = 1.45 ± 0.15 M_o
- M_{NS} = 1.40 ± 0.15 M_o (2-3 10^{53} ergs)
- Heavy Elements ejected = 1.5 ± 0.5 M_o (≤1500kms^{-1})

M_{Prog} = (20.9 ± 2.2) M_o

$M_{Rotating\ pre\text{-}SN}$ = (19.4 ± 1.7) M_o

HYDRODYNAMIC MODEL





Hydrodynamic models of SN 1987A

Utrobin, 2007

Model	PSN	R_0 $(R_\odot)$	M_{env} $(M_\odot)$	E $(10^{51}$ erg)	$M_{\rm Ni}$ $(M_\odot)$	$v_{\rm Ni}^{max}$ (km s^{-1})	E/M_{env} $(10^{50}$ erg $M_\odot^{-1})$
Woosley (1988)	evol.	43.1±14.4	9.4–14.4	0.8–1.5	0.07	—	~ 0.73
Shigeyama & Nomoto (1990)	evol.	35.9–50.3	11.4–14.6	1.0±0.4	0.075	4000	~ 0.76
Blinnikov et al. (2000)	evol.	48.5	14.67	1.1±0.3	0.078	4200	~ 0.75
Utrobin (1993)	nonev.	47	15–19	1.25–1.65	0.075	2500	~ 0.85
Utrobin (2005)	nonev.	35±5	18.0±1.5	1.50±0.12	0.0765	3000	≈ 0.83

- Single star models:

1. How massive? (Utrobin 2005)
2. Rotation tends to suppress the blue solution by increasing the He core mass, but seems necessary to break spherical symmetry prior to the explosion (Woosley et al., 1997)

- Binary star models? (Podsiadlowski, 1992, Morris & Podsiadlowski, 2006)

ABUNDANCES

Thielemann et al., 1990; Woosley et al., 1997; Prantzos et al., 1990 (p-process → 3 x solar for 50% of the p-nuclei)

- Ca: $M_{Ca} \sim 1.7 \times 10^{-4} M_o$ (Li & McCray, 1993) ≡ LMC abundance of Ca in ~ 5 M_o of H → ~10 times less than nucleosynthesis models → pure clumps which cannot capture enough energy from the γ-rays to radiate the observed lines ([CaII]λλ7300, CaII λλ8600)
- O: very uncertain; $M_O \approx 3M_o$ (Danziger et al., 1989); $\sim 1.3M_o$ if clumps shielded from the γ-rays or radiate in CO (McCray, 1993); $0.1M_o$ of O in the central part ($V \leq 1500$ kms^{-1}) of the envelope lies close to H (Oliva, 1993)
- Fe, Co, Ni: $^{57}Co/^{56}Co \approx 1.2$-2 times solar (Danziger et al., 1991; Kurfess et al., 1992); newly formed Ni in ~300 clumps (within the 2500 kms-1 comoving radius) expand; ^{56}Ni & ^{56}Co decays create holes of Fe/Co/Ni surrounded by H, He, C, O, etc.. (Li et al., 1993) (~ yeast in dough)

r-Process

- Ba & Sr detected early (Williams, 1987)
- Profile: no Ba at the very surface (Mazzali, Lucy & Butler, 1992) ➔ must have been synthesized inside the star and did not exist in the ISM from which the Sk-69°202 was formed
- Ba & Sr overabundant vs. LMC (Mazzali & Chugai, 1995): ➔ s-process in the He burning core of the progenitor (Prantzos, Arnoult, & Cassé, 1988)
- <u>HOWEVER:</u> $(Ba/Sr)_{87A} \sim 2.5\ (Ba/Sr)_{Solar}$ ➔ inconsistent with s-process (Prantzos et al., 1988): $(Ba/Sr) \in [0.1, 0.6] \times (Ba/Sr)_{Solar}$
- Other Type-II SN (85P, 90E, 90H) didn't show overabundances (Chalabaev & Cristiani, 1987) although Prantzos et al. (1988) predict it irrespective of He core mass: Ba & Sr not s-process?
- In CS22892-052 & CS31082-001: r-process (McWilliam, 1998)

➔ Ba & Sr synthesized during explosion in the deepest layers of the ejecta where the matter is exposed to intense flux of neutrons (radioactive ^{56}Ni syntesized at the same place); brought to surface by RT; mixing finishes soon after blast wave hits the stellar surface.

- $M_{Ba} = 6 \times 10^{-6}\ M_o$ (Tsujimoto & Shigeyama, 2002) : very high!

➔ If stars are formed from the ISM comprising the ejecta of a single SN (Audouze & Silk, 1995) extremely metal-poor stars are descendant of SNe similar to SN 1987A, and 20 M_o SNe are predominant sites for r-process

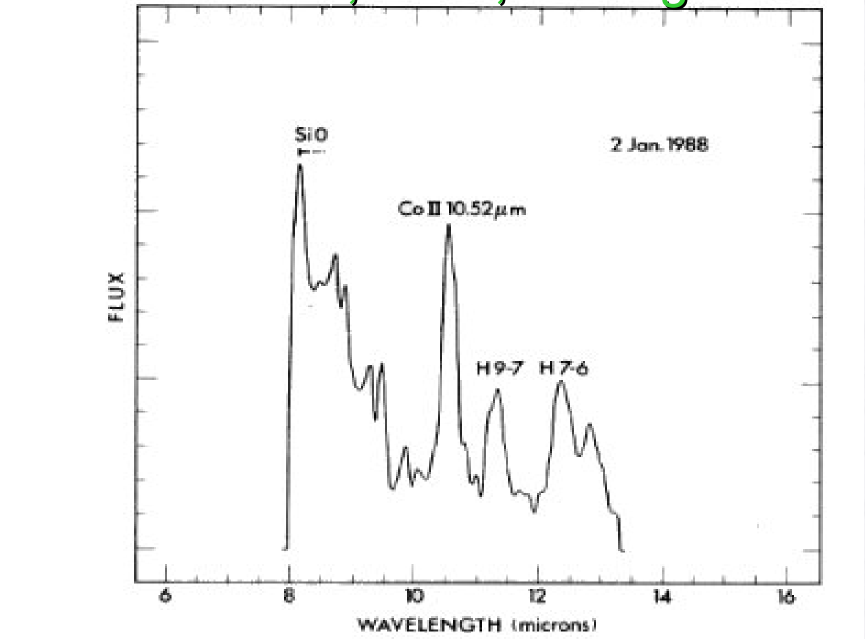
r-process nucleosynthesis requires non-spherical effects in the explosion (Thielemann et al., 1990)

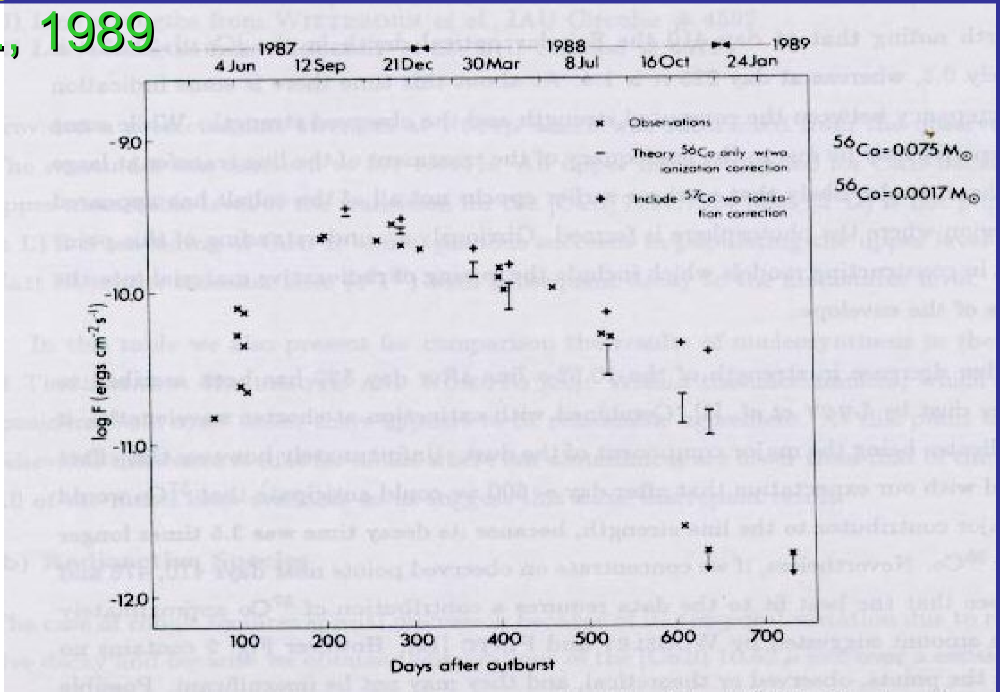
MOLECULES

- Cool, dense, partially ionized envelope ➔ favorable for molecule formation by gas phase chemistry (Dalgarno, 1993).
- CO appeared early (t=112d) (Bouchet et al., 1987); bands optically thick at early times and vibrational level populations not in thermal equilibrium ➔ $M_{CO} \approx 10^{-3} M_o$; T ~4000K (192d) to ~1800K (377d) ; in clumps occupying ~10% of the volume within a sphere expanding at ~2000 kms^{-1} (Liu et al., 1992). He abundance in the CO-emitting region must be very low (otherwise CO is destroyed by He^+ produced by γ-ray illumination - Lepp et al, 1990)
- SiO: 160 < t < 520 d (Danziger et al., 1989) : $M_{SiO} \sim 4 \times 10^{-6} M_o$ (Roche et al., 1993)
- H_2^+ (Miller et al., 1992) and H^- (Culhane & McCray, 1993) → H_2, survive collisional dissociation when T ≤ 3000K
- H_3^+? (T_{exc} must be ≤ 2000K); $M(H_3^+) \sim 10^{-7} M_o$ (Miller et al., 1992)

The 10.52 μm [CoII] line

Bouchet et al., 1989; Danziger et al., 1989





- Insensitive to temperature, transparent window, no blending, and most of the Co was singly ionized: Simple nebular theory after it became optically thin led to the MOST DIRECT determination of the mass of cobalt.

- Temporal behaviour consistent with the radioactive decay of 56Co, but leaving at later times a residual that could be safely ascribed to 57Co whose decay rate is much longer

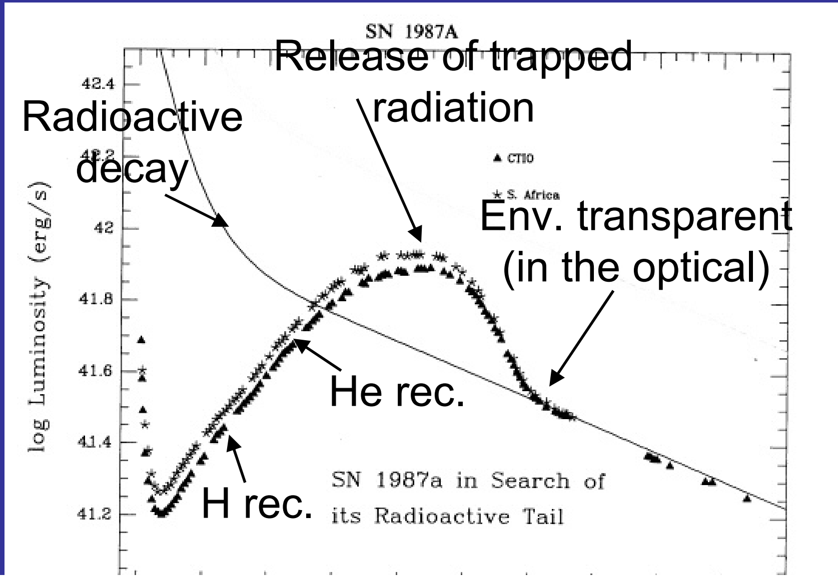
Light Curve Evolution

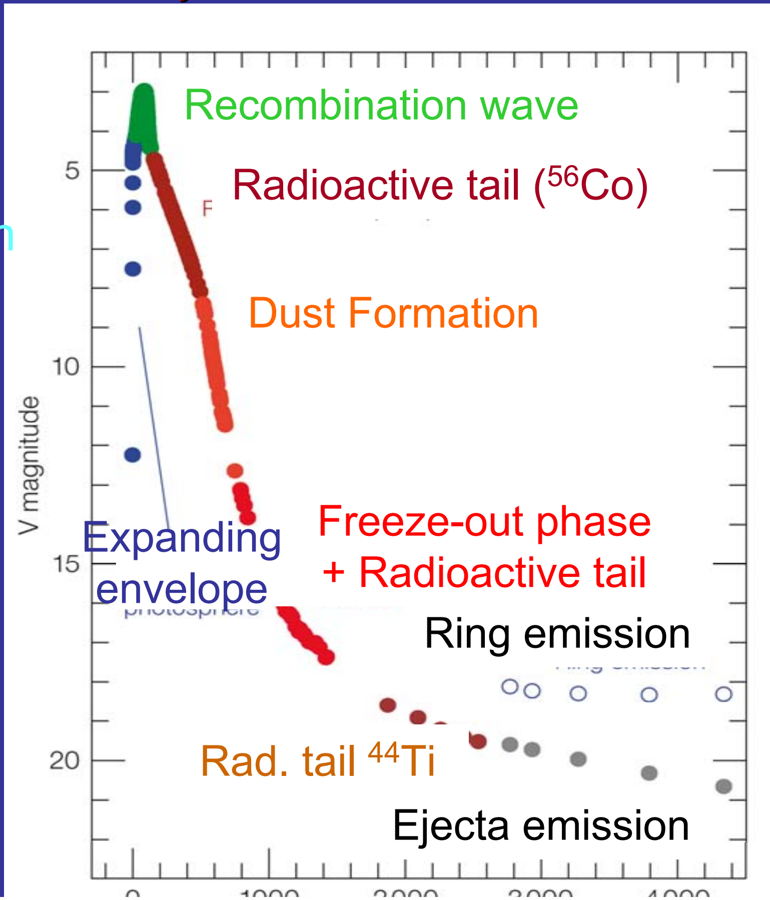
- Shock breaks through the surface: T~3x10^5 K ➔ UV flash ➔~3h, R X 10 ➔ V ~ 6.4

- As envelope expands it flows through a recombination front (“antiflamme”): ordinary diffusion far too inefficient ➔ Radiation doesn’t diffuse to photosphere but photosphere moves to radiation

- Energy released BY recombination: mostly FROM the shock: thermal radiation must deplete the internal energy faster than it can be replenished by diffusion from below

- After H, He recombination releases energy (shock, recombination itself, and radioactivity that had diffused out while “awaiting” the recombination front.)
- Radioactive energy deposition comes from Compton scattering of γ-ray lines (^{56}Co 847, 1238 keV)

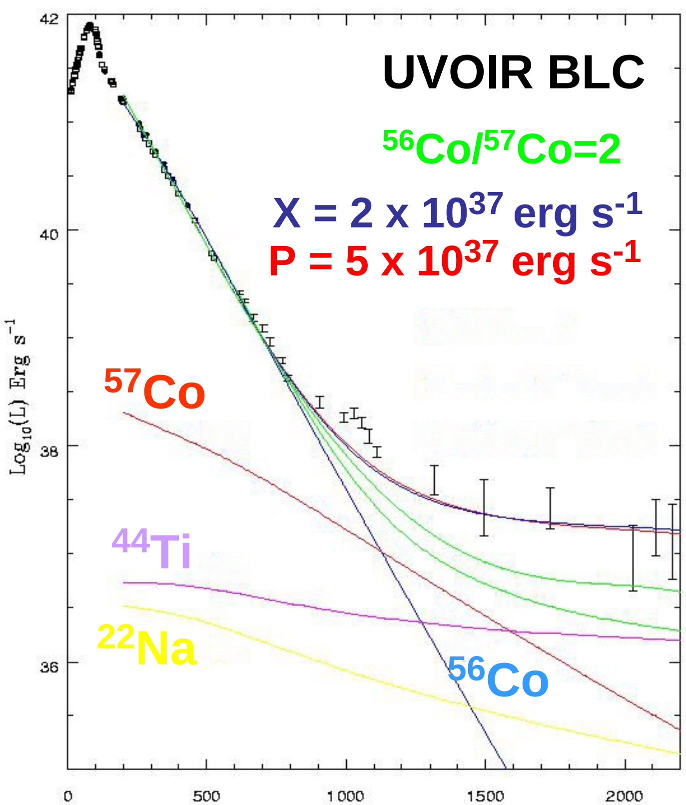




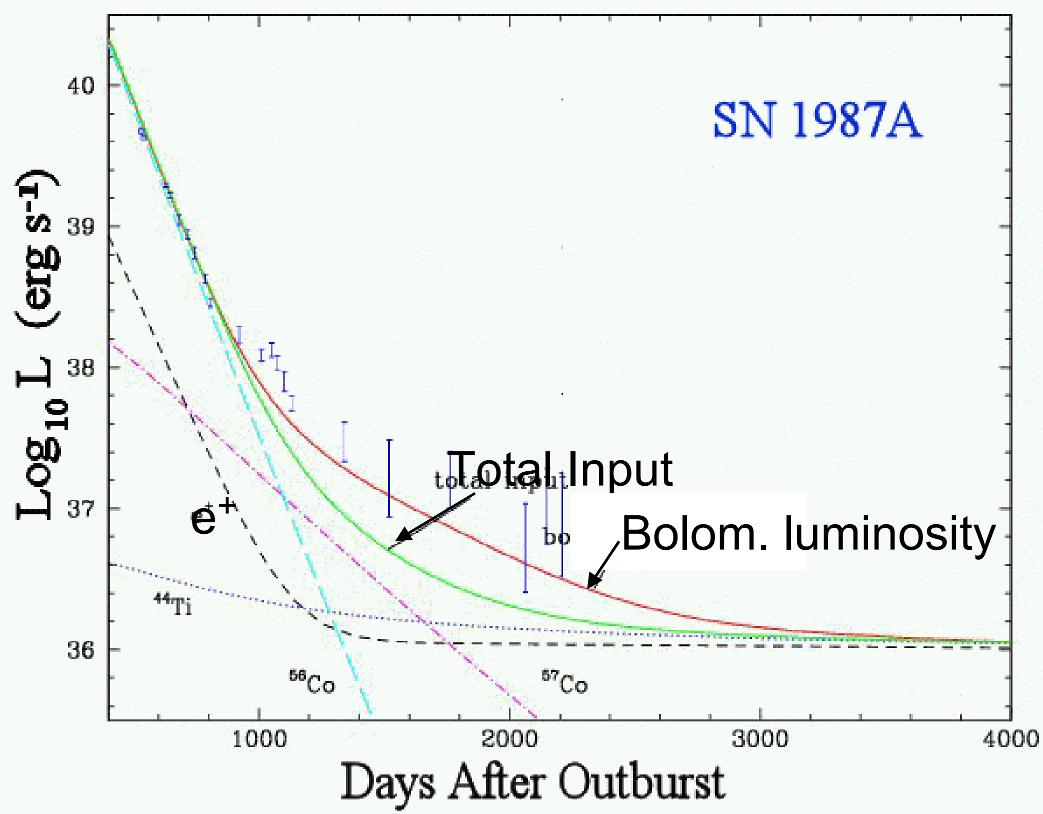
$$S_{nuc} = M(^{56}Ni) \times [3.9 \times 10^{10}\, e^{-t/\tau(Ni)} + 7.2 \times 10^{9}\, (e^{-t/\tau(Co)} - e^{-t/\tau(Ni)})\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

FREEZE-OUT

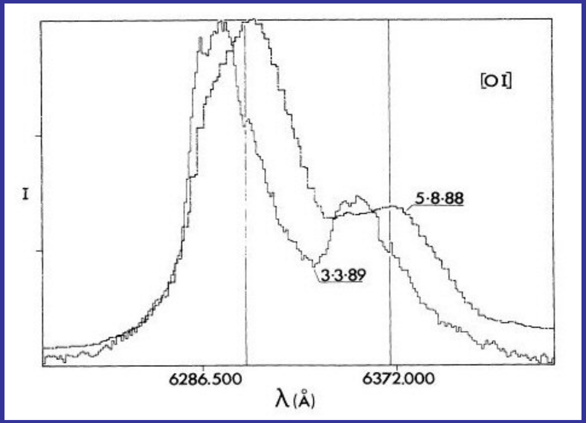
The recombination & cooling time scales comparable with the expansion time scale ➔ the gas is not able to recombine and cool at the same rate as radioactivity takes place: some of the stored energy is finally released ≡ emitted luminosity remains greater than instantaneous radioactive power deposition (Fransson & Kozma, 2002)



Bouchet et al., 1996



The Dust



IAUC4746

March 1, 1989

- Clumps
- Silicates?

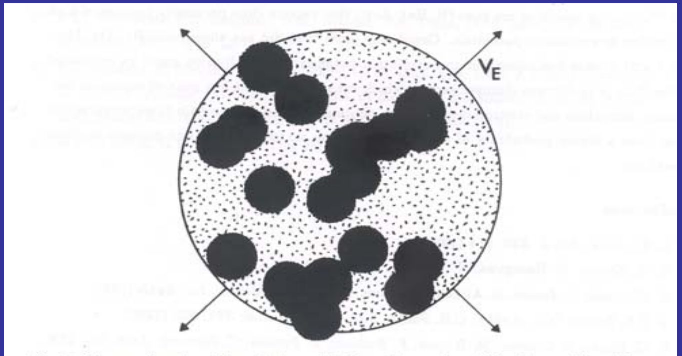
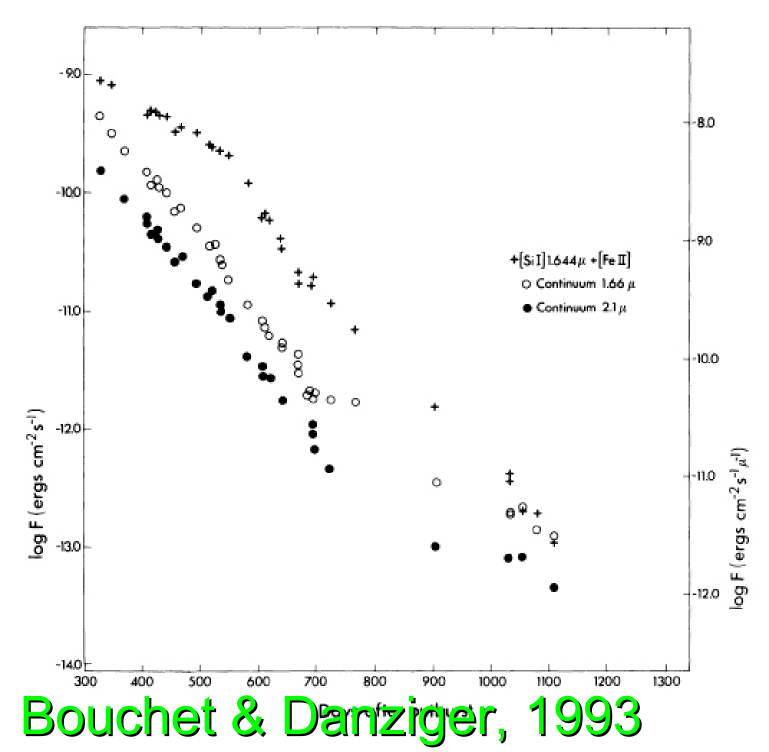
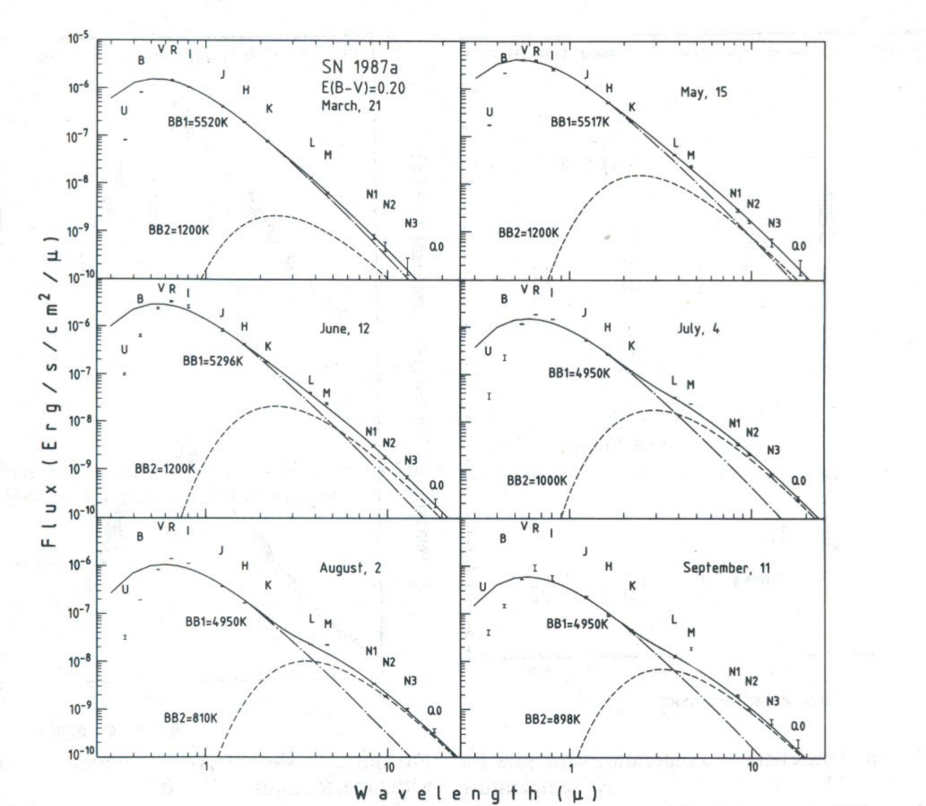


Fig. 7. Opaque clouds – diffuse dust model. Here the number of clouds $n = 20$ and have radii such that $\tau_c = 0.4$.

Lucy, Danziger, Gouiffes & Bouchet, 1989, 1991



Bouchet & Danziger, 1993



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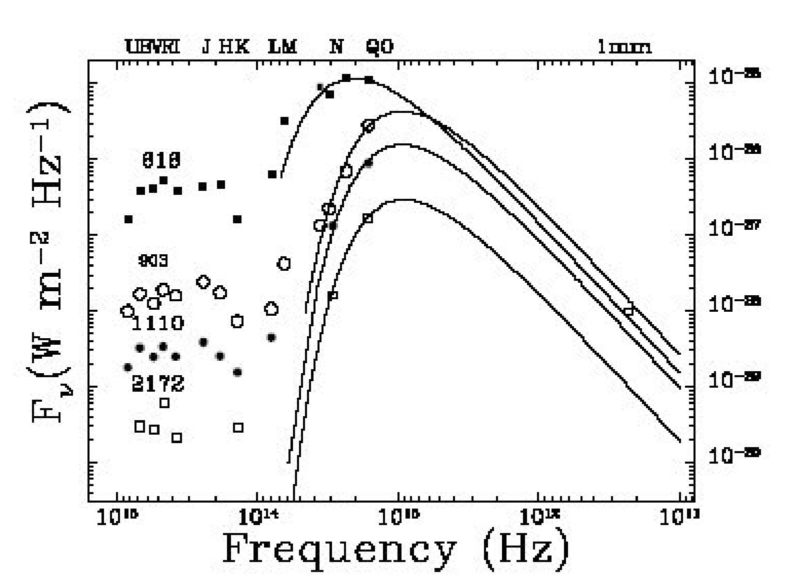
SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

I. J. Danziger, C. Gouiffes, P. Bouchet and L. B. Lucy, European Southern Observatory, report: "During 1988 Aug.-Oct., the emission line profiles of O I (630.0, 636.3 nm) and C I (982.4, 985.0 nm) became asymmetric with peak emission blueshifted by 500-600 km/s. Similar behavior is seen in the Na I and H-alpha profiles. This effect is attributed to extinction by dust within the metal-rich ejecta. Comparisons with theoretical line profiles indicate that the dust is widely distributed in the ejecta and extends out to the innermost part of the hydrogen envelope. At 650 days, the O I blueshift requires 1 mag of extinction to the center, implying a condensation efficiency of only 10E-6 (Dwek 1988, Ap.J. 329, 814; Kozasa et al. 1988, preprint). Clumpiness allows higher efficiencies, and obscuration by a dust clump might account for the pulsar's non-recovery (IAUC 4735, 4743). This interpretation of the blueshifts requires that the accelerated decline of optical light after day 530 (Burki et al. 1989, preprint; Catchpole et al. 1988, preprint) is due in part to dust extinction rather than entirely to the increased escape of gamma- and x-ray photons. The re-emission of this optical light by grains in equilibrium with the ambient radiation field accounts for the observed infrared radiation longward of 8 microns (ESO data). Roche et al. (1989, Nature 337, 533) attribute the increasing 10-micron emission after day 450 to a thermal echo from dust behind the supernova. But the corresponding scattering echo is not evident in optical lightcurves."



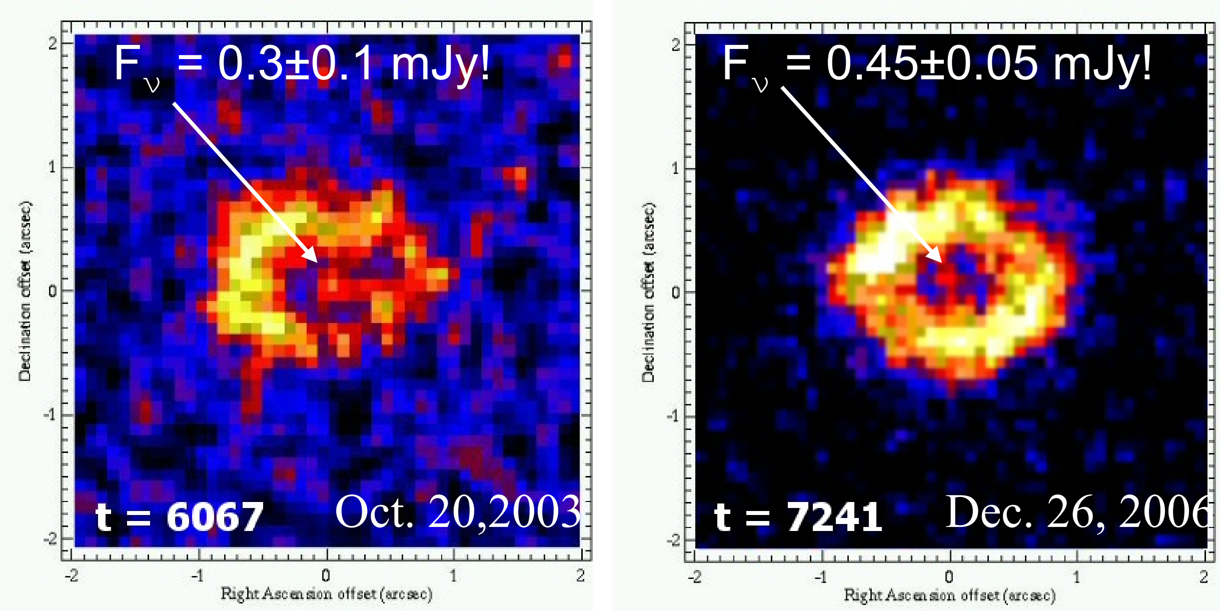
Ejecta emission = "Hot" dust

- Dust detected at day 6067 (Bouchet et al., 2004), still present at day 7241
- 90 K < $T_{Dust,Ejecta}$ < 100 K
- $M_{Dust,Ejecta}$ = 0.1-2 x 10^{-3} M_o
- L_{IR} = (1.5±0.5) x 10^{36} $ergs^{-1}$

Ring emission = shock heated dust

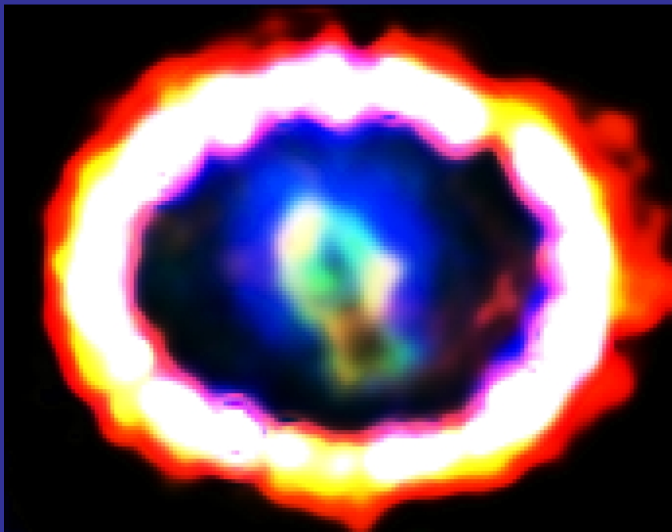
- T_{Ring} = (180±15) K
- M_{Ring} = (0.1-1) x 10^{-5} M_o

N: 10.36μm (Δ=5.30μm) T-ReCS/Gemini-South



Flux increase due to heating by Reverse Shock?

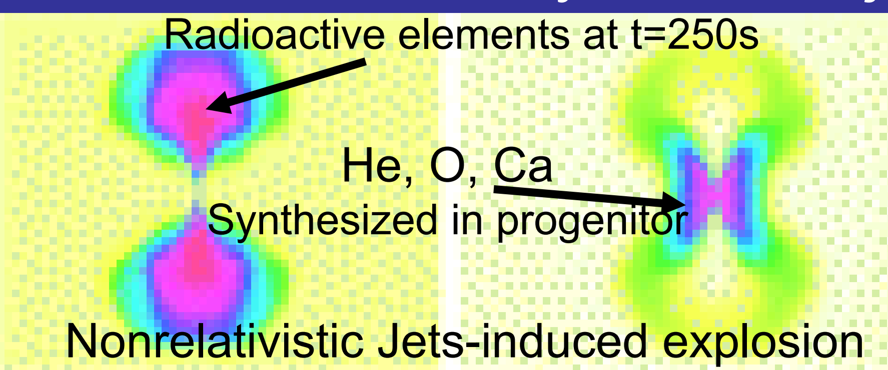
Inner Debris

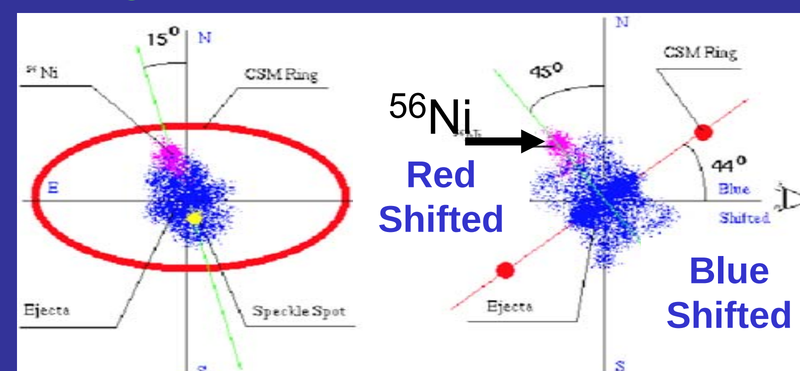


- Glowing: ^{44}Ti decay
- Interior dust clouds
- Cold! < 300 K
- Stirred, not blended

- Fe bubbles: ~1% of mass, ~50% of interior volume

Axisymmetric ejecta: Wang et al., 2002

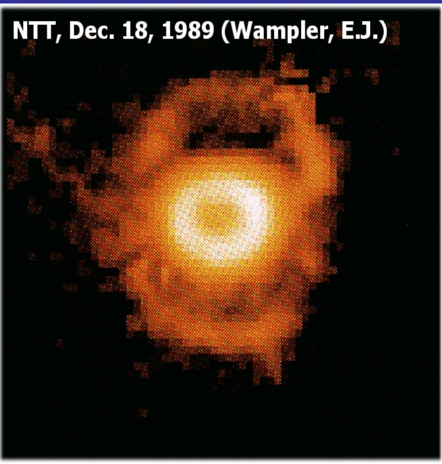


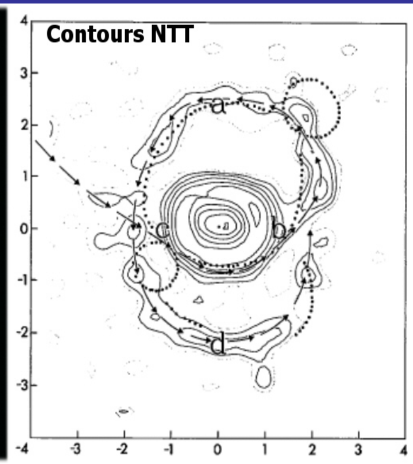


Why don't we see a compact object?

- Optical, near IR: obscured by black cloud?
- X-rays: < cooling neutron star. Debris may be opaque at 1 keV.
- Absorbed luminosity should emerge as far IR.

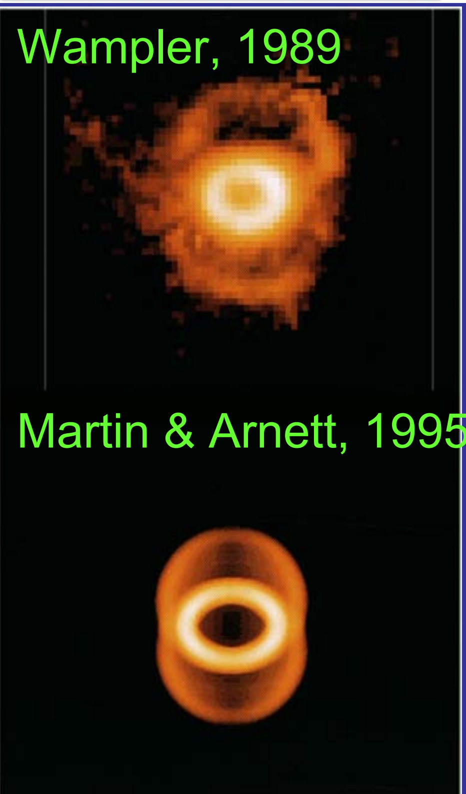
Circumstellar Structure





- Radius: R ~ 0.6 lt yr
- Expanding: V ~ 10 km s^{-1}
- Density ~ 3 x 10^3 – 3 x 10^4 cm^{-3}
- Glowing mass ~ 0.1 M_{Sun}
- Nitrogen-rich

(Michael et al. 2003)

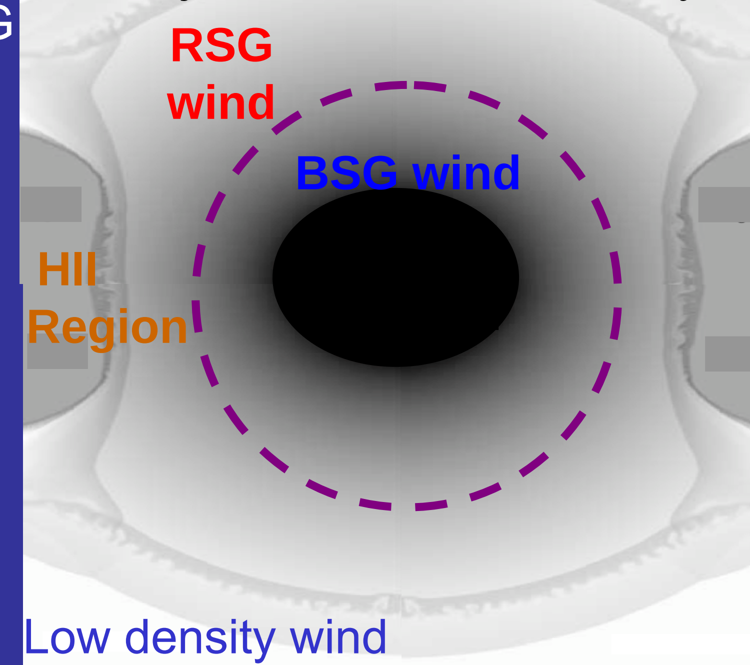


Model Standard

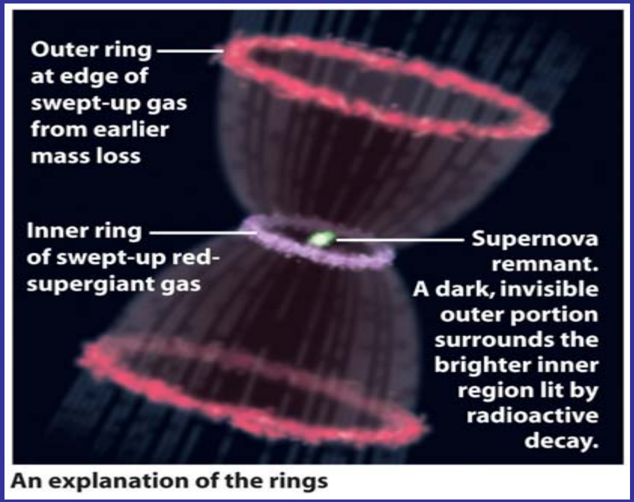
- RSG → outer envelope →BSG
- Dense slow RSG wind, (550kms^{-1}) concentrated into equatorial plane
- High-velocity low-density isotropic BSG wind for final ~20 000 yr
- Faster BSG wind overtook RSG wind
- BSG photoionizes RSG wind

(Chevalier & Dwarkadas 1996)

Hydro simulation of the interaction of the ejecta with CSM at t=13 yr



Triple Ring system

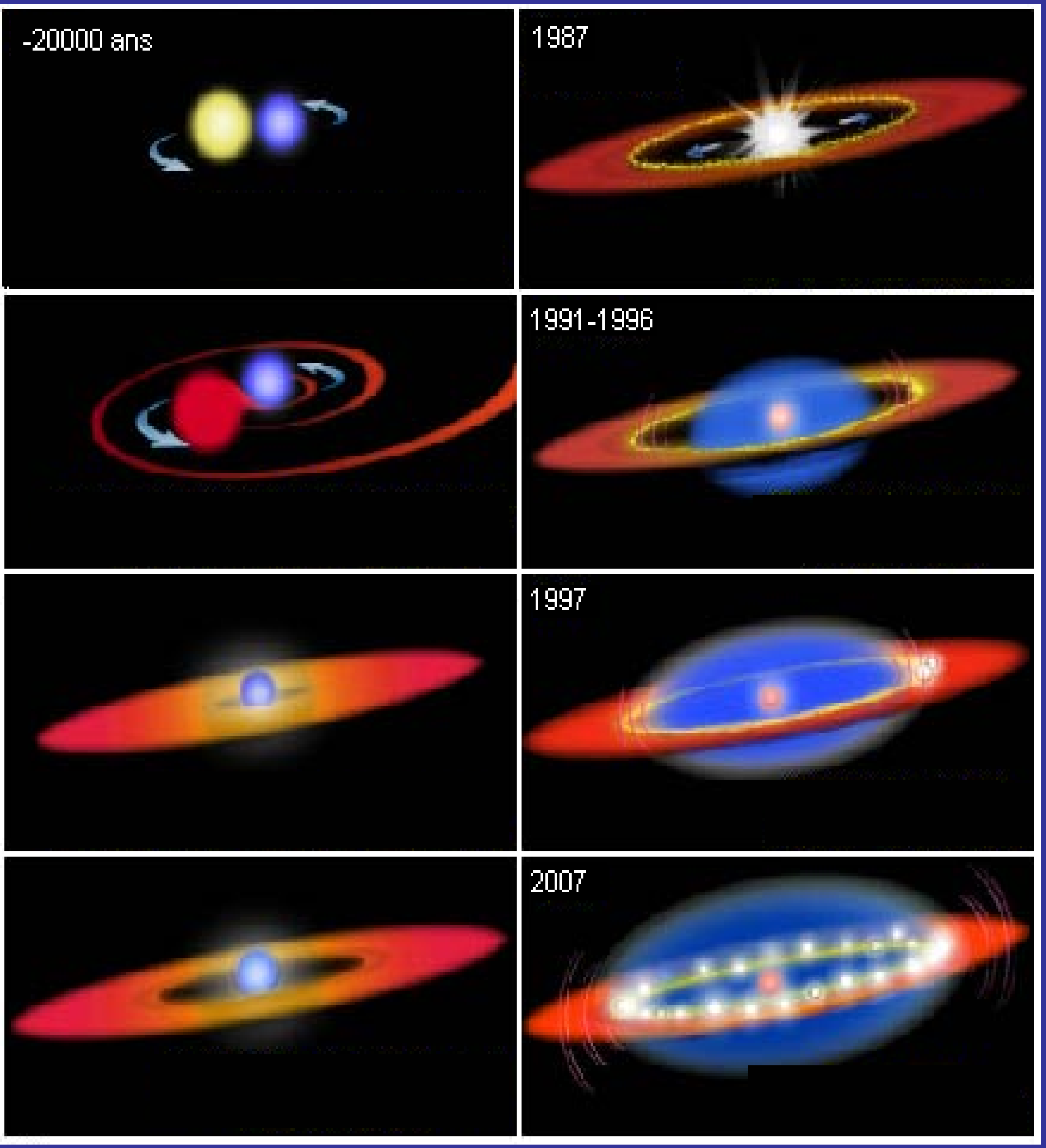


An explanation of the rings

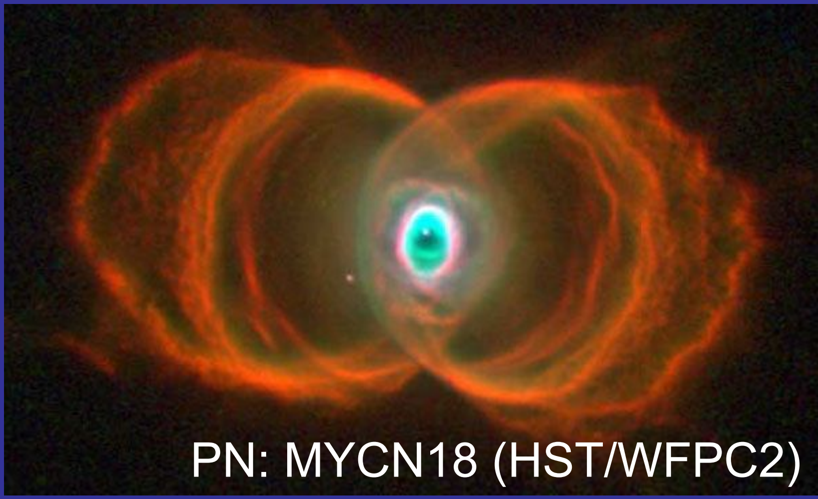
Why three rings?

Rotation needed for the equatorial plane, and RSG are too big
➔ Podsiadlowski
BUT Woosley, Chevalier, Dwarkadas, Martin, Arnett, Meyer …

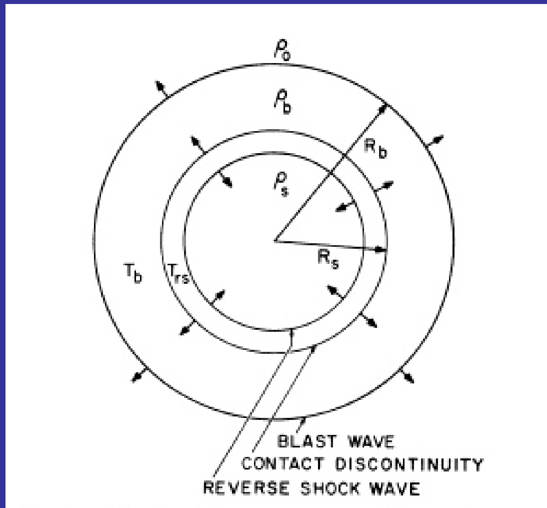
- Single rotating star: hydrodynamic formation due to ionization and heating of the cool RSG wind (Meyer, 1997, 1999)
- Binary system: impulsive mass loss from primary star, formation of a thin dense shell, and the expansion of 2 jets (Soker, 2002)
- Binary mergers: mass loss from a rotationally distorted envelope following rapid in-spiral of a companion inside a common envelope (Podsiadlowski, 1992; Morris & Podsiadlowski, 2006)
- LBV: unstable LBV eject and shape their nebulae when BSG (Smith, 2007)



Morris & Podsiadlowski, 2006 (Document STSCI)

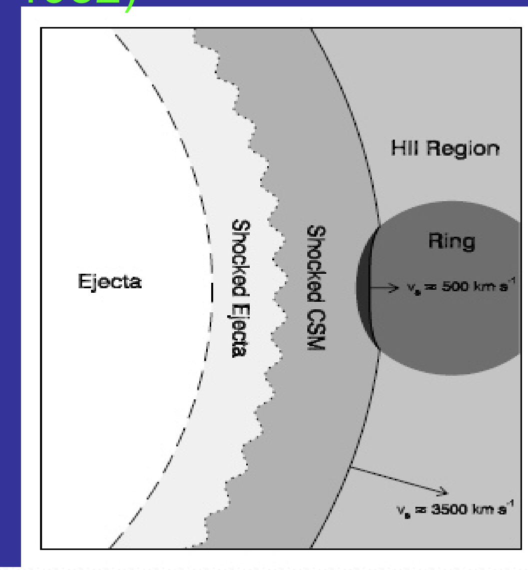


The Reverse Shock



McKee, 1974: Expanding debris are decelerated by the CSM which causes a shock to propagate inward through the SN material RS (+ Chevalier, 1982)

← Note: until the RS has shocked a significant fraction of the SN shell, it will actually move outward vs. fixed coordinates

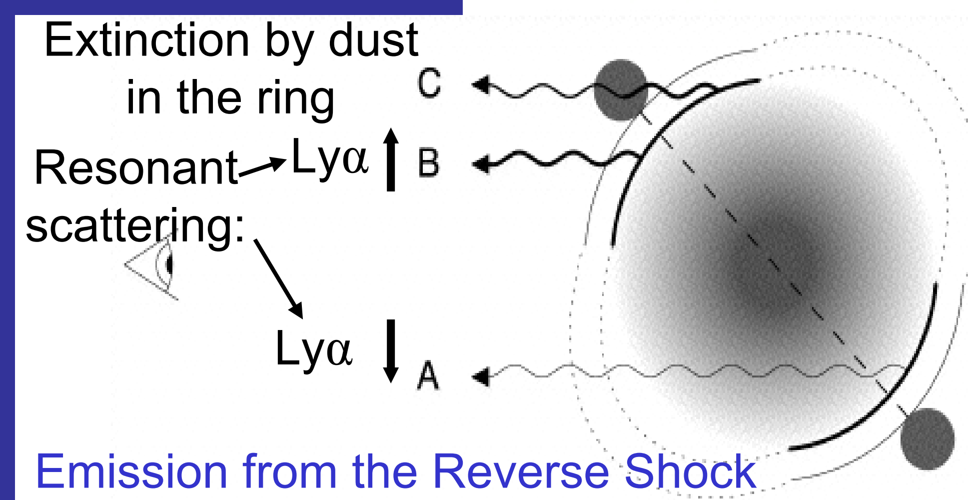


- High velocity debris cross the RS at velocities ~ 12 x 10^3 kms-1
- "Shock velocity": freely streaming H atoms in the RS rest frame (~ 8000kms^{-1})
- Post-shock ions = 2000 kms^{-1}

➔ **Fast atoms & Slow ions**

- No cylindrical symmetry
- Flux of H atoms is increasing

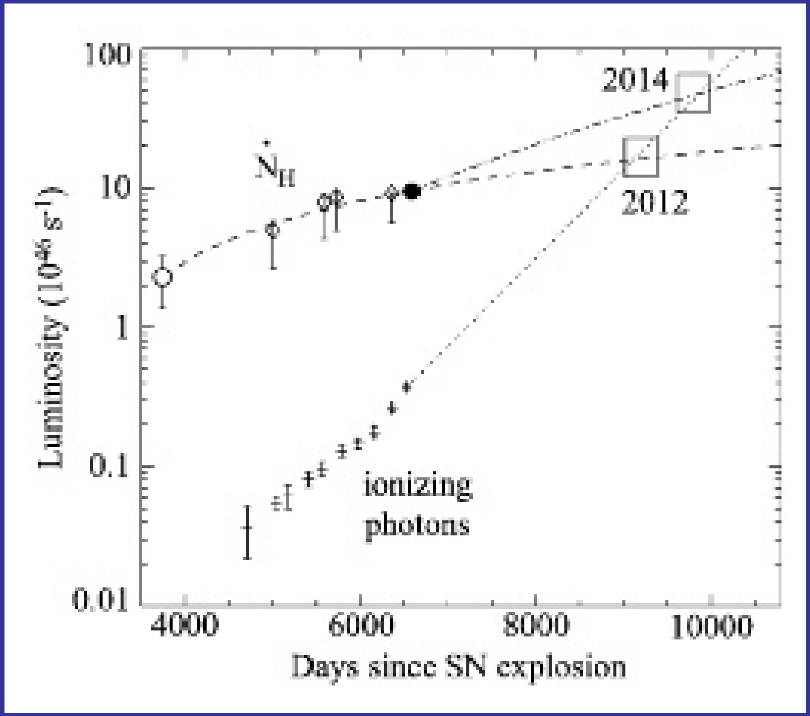
Heng et al., 2007; Smith et al., 2005



Michael et al., 2003

The "Bleach Out" of the Reverse Shock

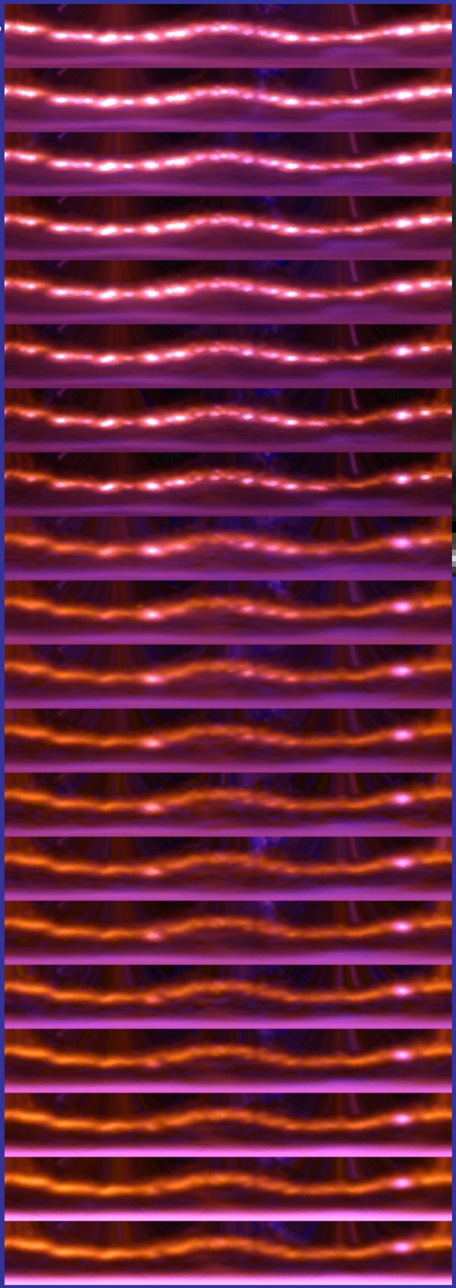
- Non radiative shock seen as very broad, high-velocity Lyα & Hα emission
- Results from the collisional excitation of neutral H from the debris crossing the RS
- At t=18 yr, the total RS $L_{H\alpha} \sim 15 L_o$ ➔ flux of $2.3 \times 10^{-3}\ M_o\ yr^{-1}$ (x 4 since 1997)
- Lα continuum from gas shocked by the forward blast wave ionize neutral H in the debris before they reach the RS: when the inward flux of ionizing photons exceeds the flux of H approaching the RS ➔ Preionization shut off the RS emission



Smith et al., 2005

Hotspots!

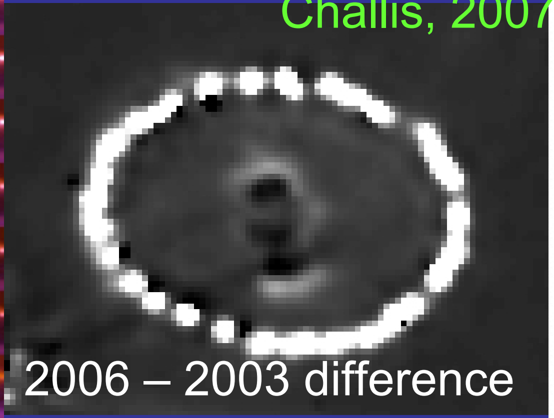
2007



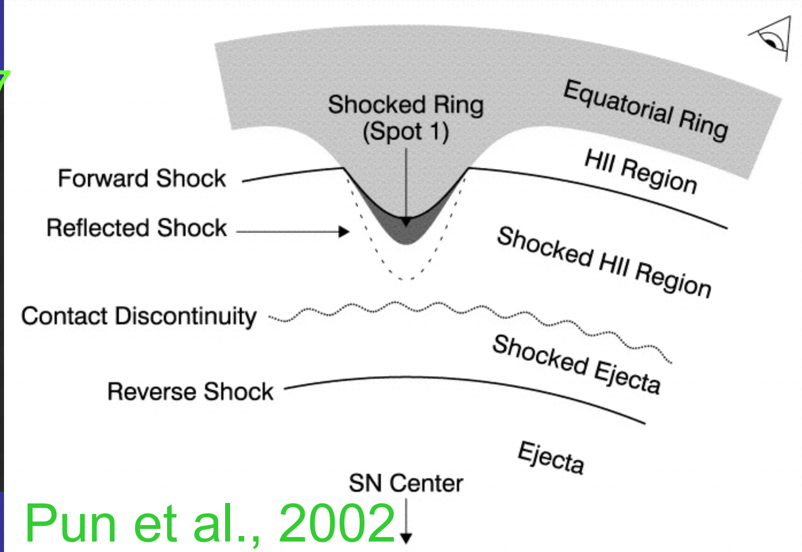
1994

Unfolding the ring! (Garnevich, 2006)

Challis, 2007

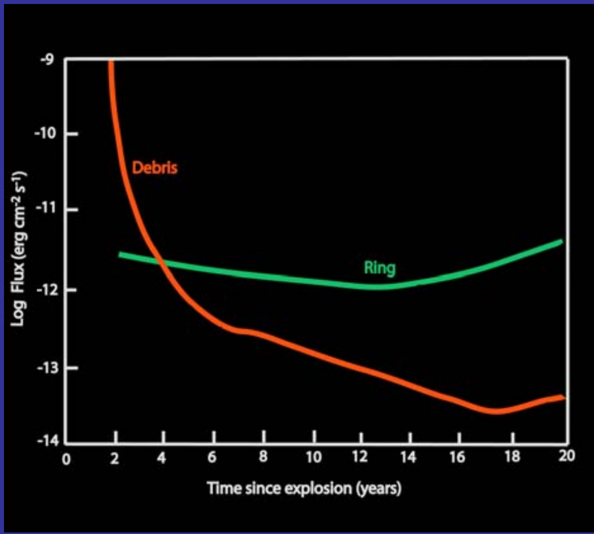


2006 – 2003 difference



Pun et al., 2002

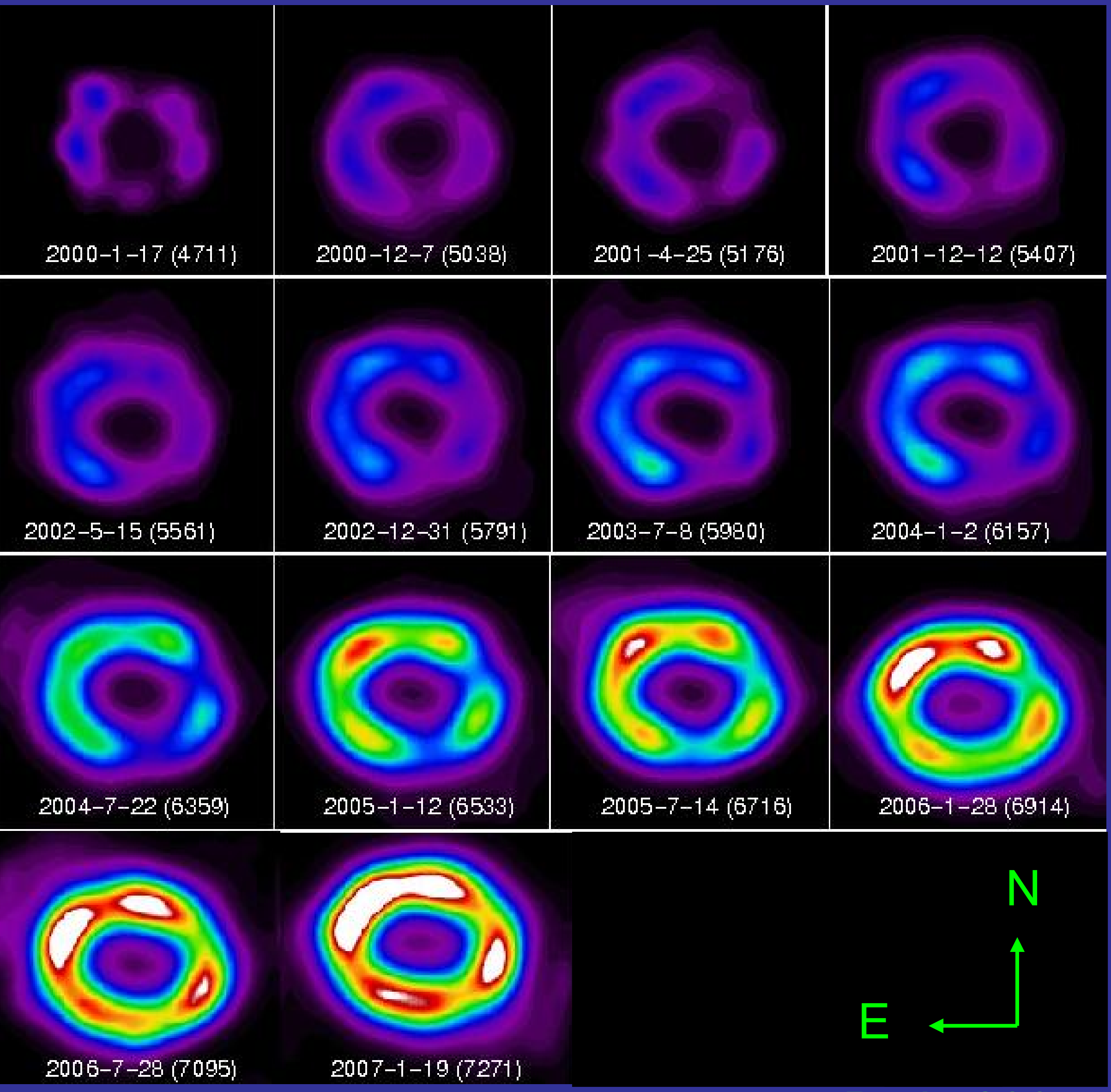
- Ring has brightened by factor ~ 3
- Hotspots still unresolved
- Have not fully merged
- Did the last spots show up in the dark regions in 1994? ➔ are they more dense that the regions where the spots first appeared?



What caused fingers?
Why so regularly spaced?

ACIS Images 2000–2007

Park, 2007



1 arcsec

Park, 2007

Ring-like

Asymmetric intensity

Developments of X-ray spots

→ becoming a complete ring as the blast wave arrives the inner ring!

Surface brightness increase

→ Now ~18 x brighter than 2000

L_X $_{(0.5\text{-}2\mathrm{keV})}$ = 2.1×10^{36} ergs/s

No point source at center

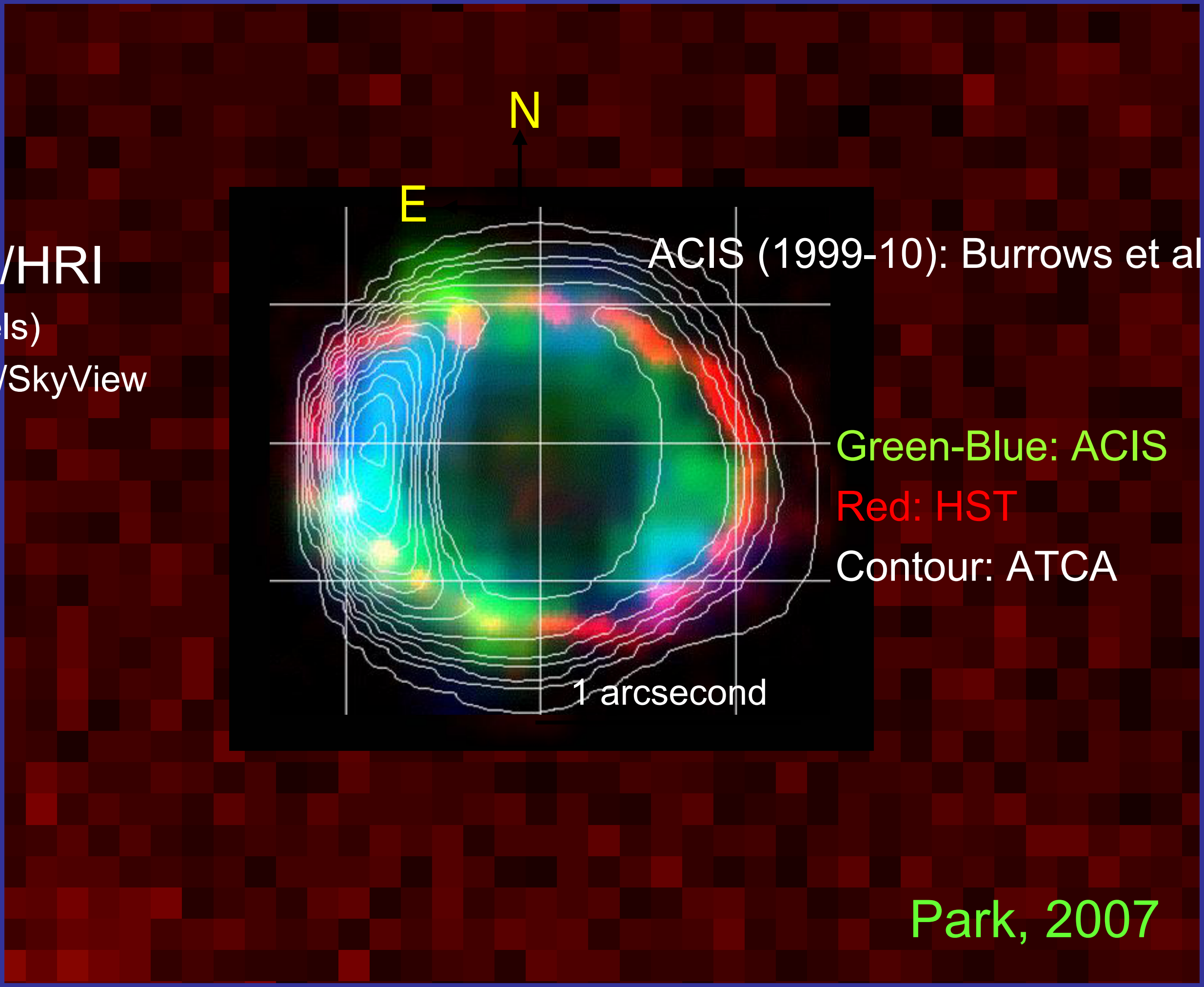
Elemental abundances (x solar)

(from simultaneous fit of 6 spectra)

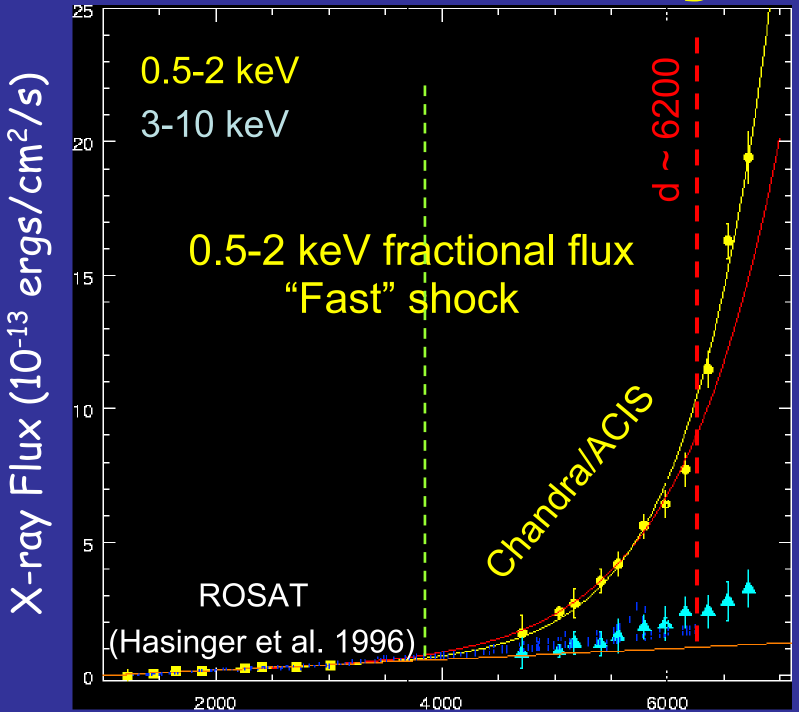
He = 2.57	N = 0.37	S = 0.84
C = 0.09	O = 0.09	Fe = 0.15
Ar = 0.54	Ne = 0.20	
Ca = 0.34	Mg = 0.14	
Ni = 0.62	Si = 0.32	

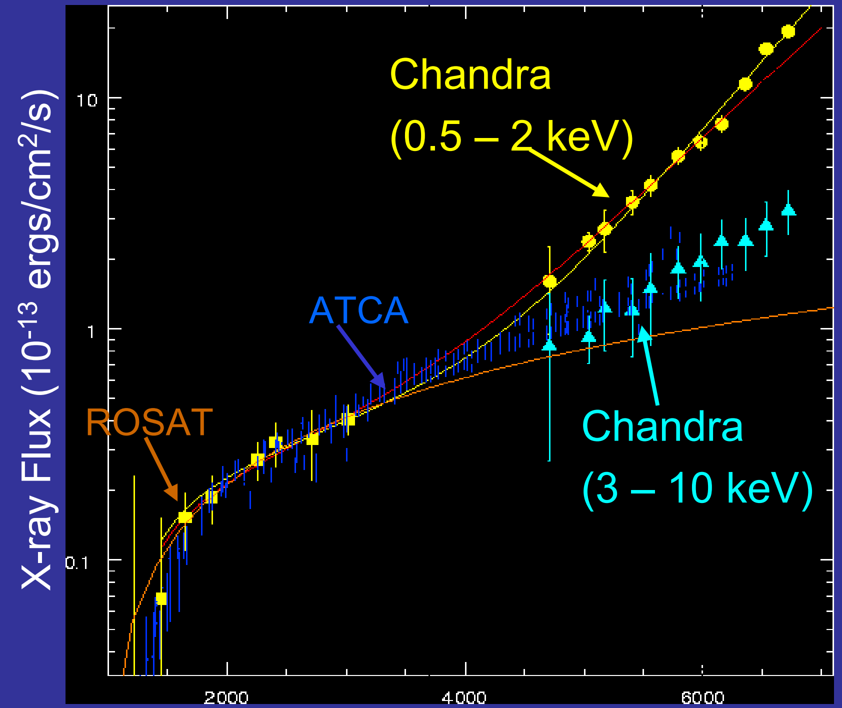
First X-ray Images

ROSAT/HRI
(5” pixels)
HEASARC/SkyView

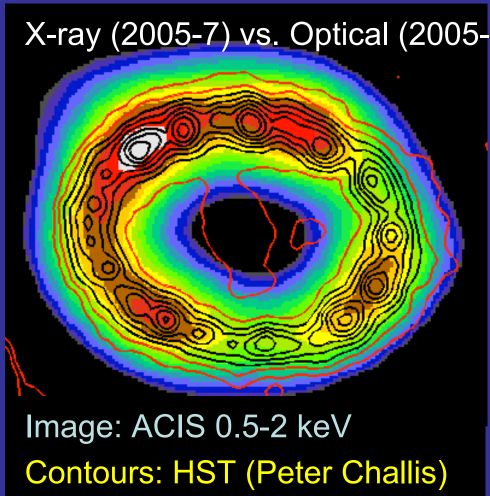


X-Ray Light Curves





Forward shock enters a "wall"?

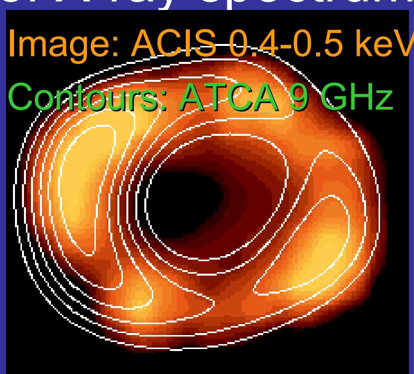


(Park et al., 2004, 2005, 2006)

Similar rates of hard X-ray and radio

➔The same origin for them?

~~➔due to softening of X-ray spectrum?~~



Radio image:

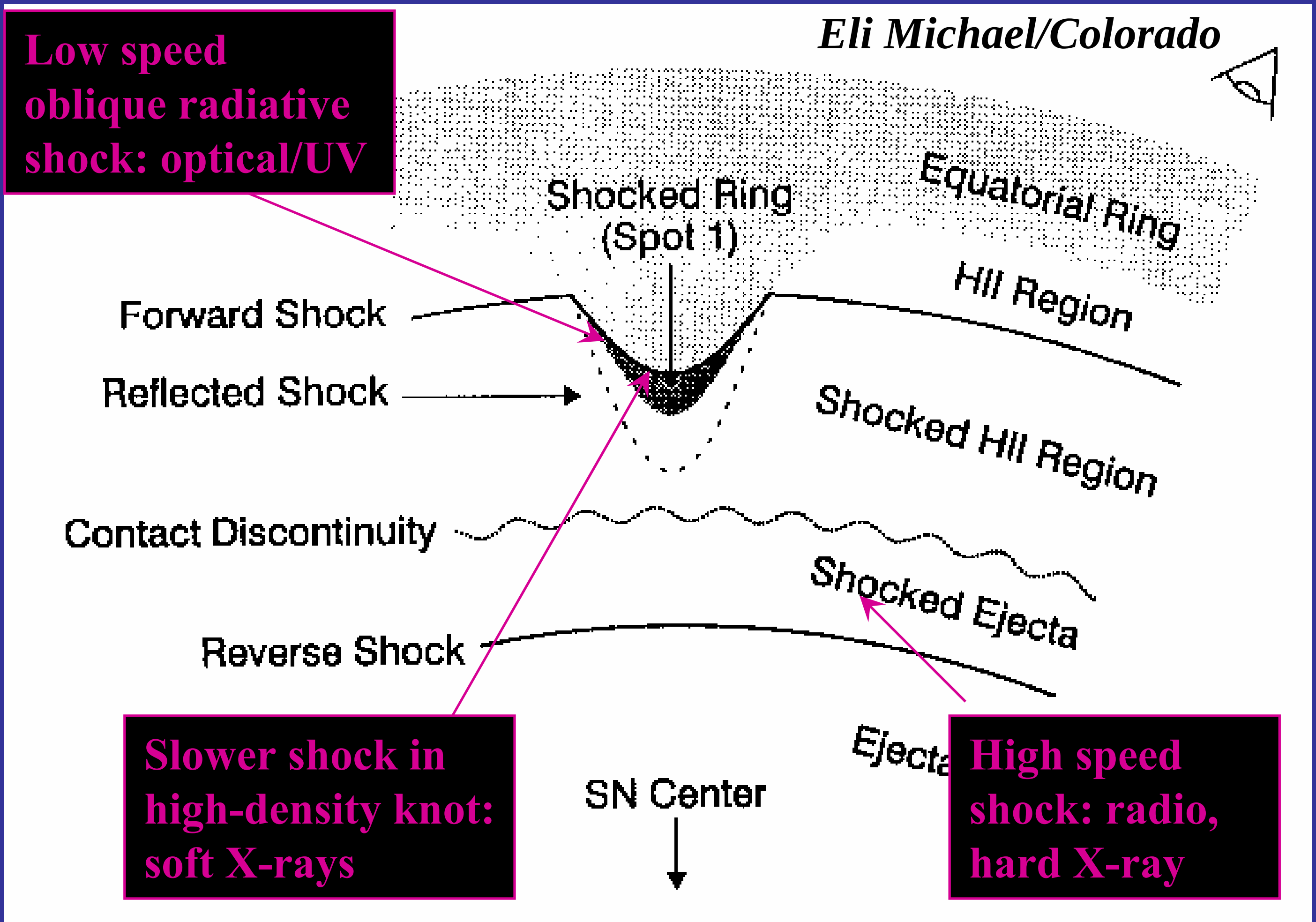
B. Gaensler & L. Staveley-Smith

PHYSICAL INTERPRETATION

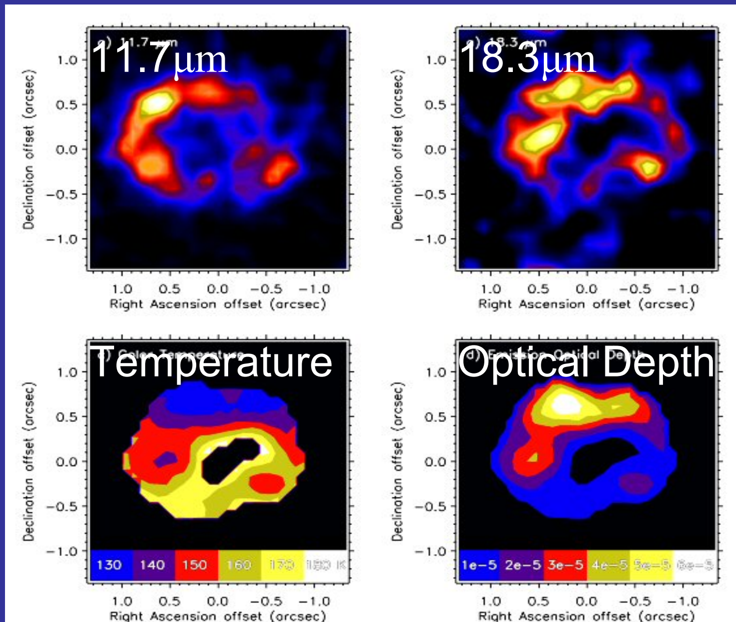
Park et al., 2002, 2004; Zhekov et al., 2005 ➔ 2-shocks model

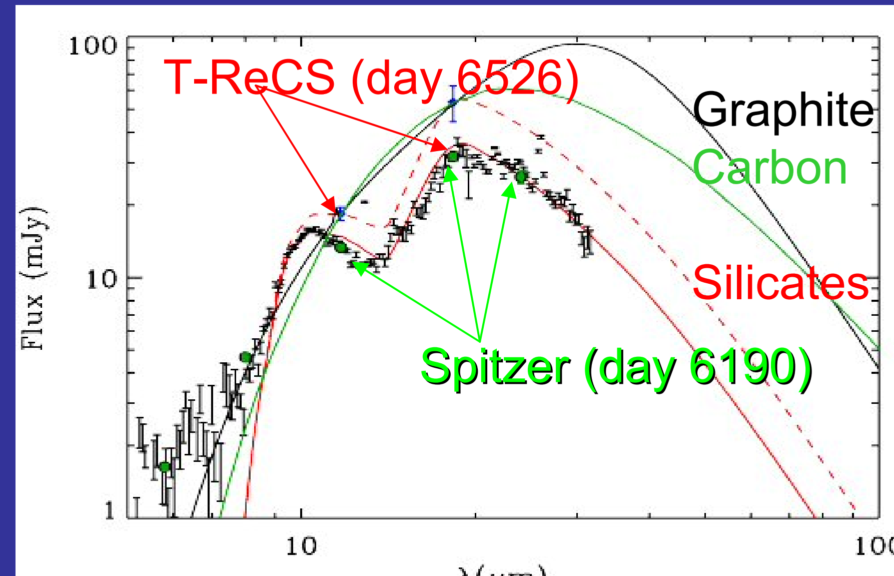
At t = 18 yr:

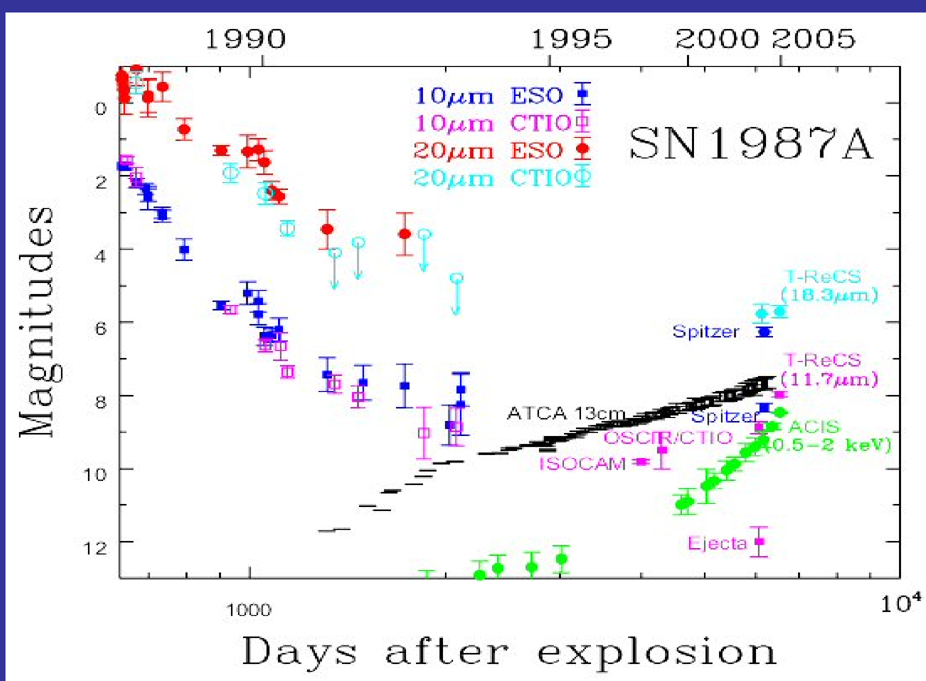
1. Soft X-Ray = Decelerated, slow (300-1700 kms^{-1}); kT=0.51keV; ne~6300 cm^{-3}
2. Hard X-Ray = High-speed (3700±900 kms^{-1}); kT= 2.7 keV; n_e ~ 280 cm^{-3}



MID-IR Emission







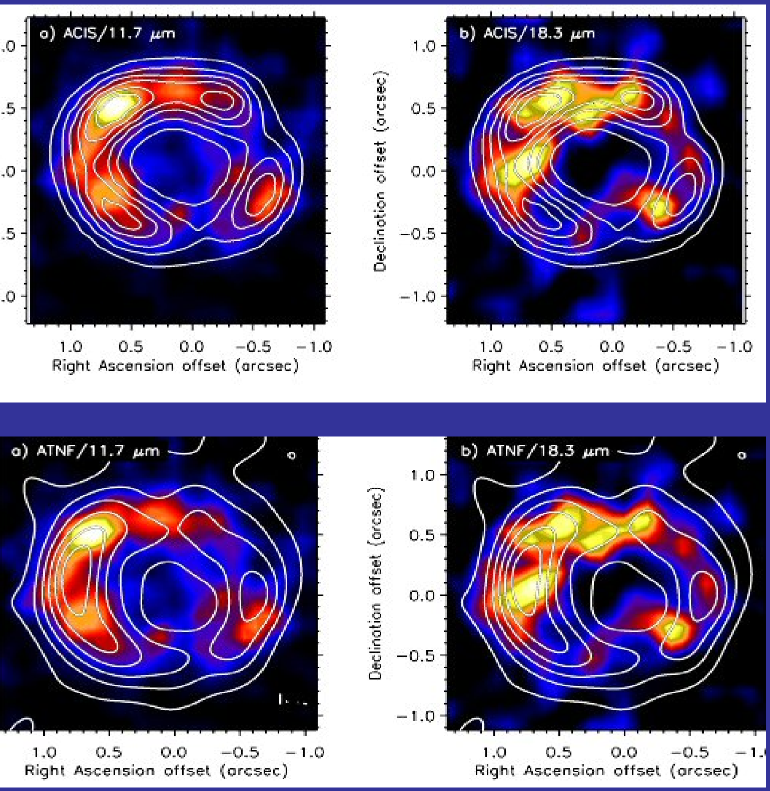
Thermal emission from shock-heated silicate dust

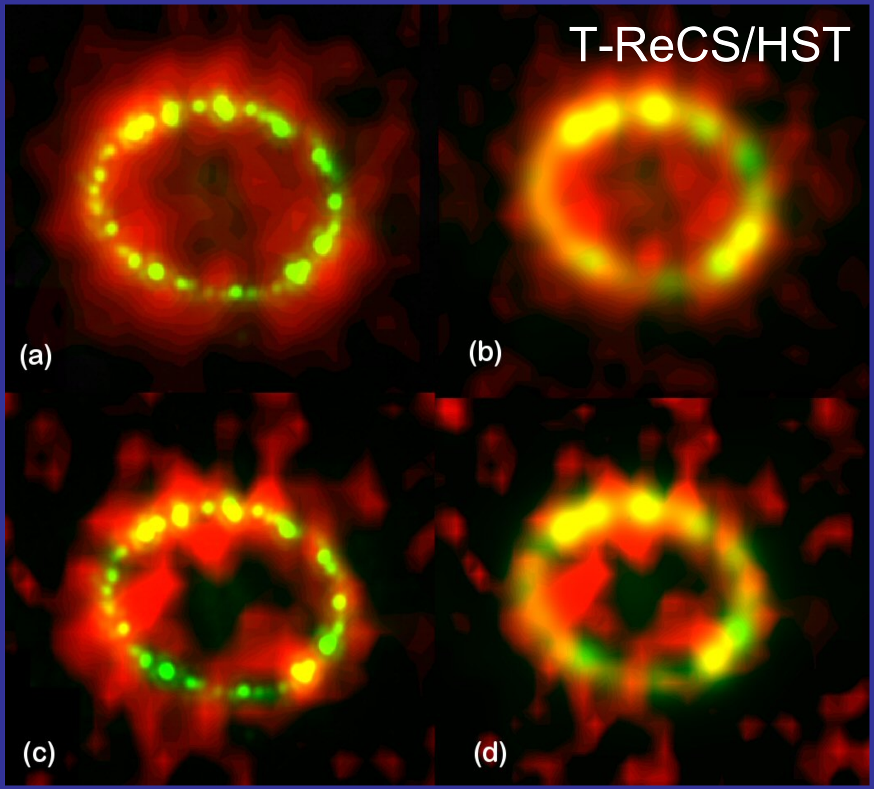
T_{Dust} = (160±15) K

M_{Dust} = (3 ±1) x 10^{-6} Mo

Bouchet et al., 2006

Dust Heating Mechanism





Where is the dust?

1. In the X-ray emitting gas?
2. In the denser UVO emitting knots?

What heats the dust?

1. Collisional heating?
2. Radiative heating?

IR-to-X ray flux ratio IRX ≈ 1!

(T_{gas} ≈ 2x10^7 K → IRX ≈ 100)

Dwek, 1987

Dust severly depleted in the shocked gas:

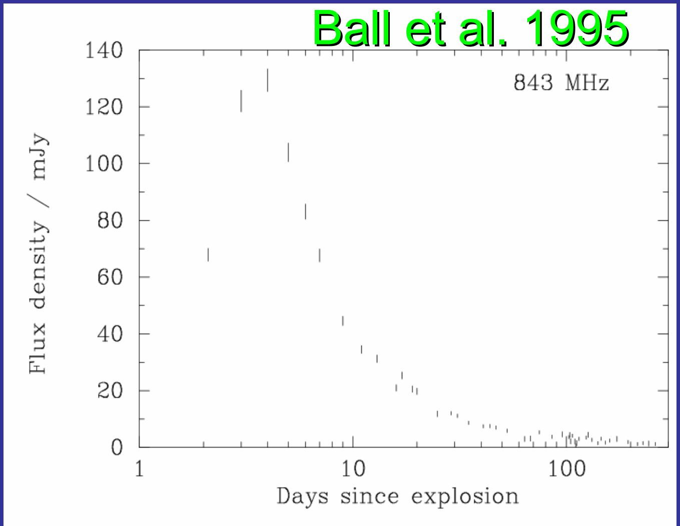
1. Grain destruction by the SN shock wave?
2. Inefficient production in the progenitor wind?

Bouchet et al., 2006

RADIO EMISSION

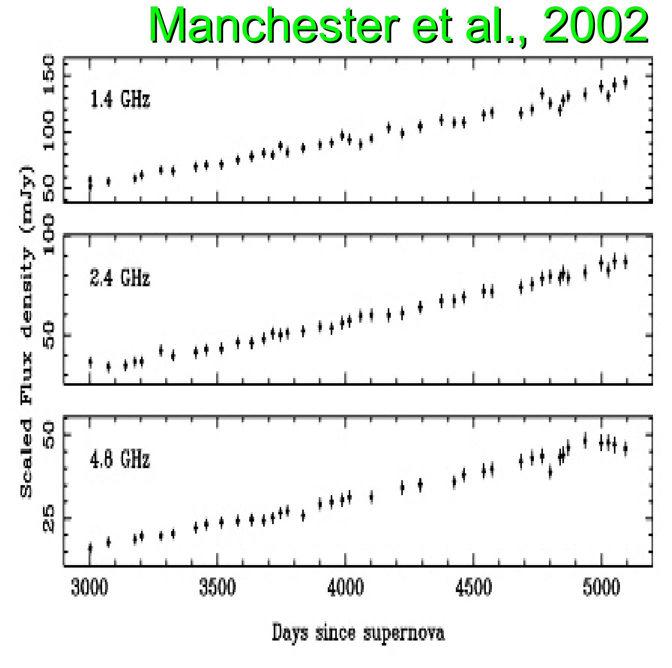
Prompt Phase

- Core collapse on 23 Feb 1987
- Burst of emission seen by MOST on day 2; peaked on day 4 (Turtle et al. 1987)
- Power law decay, faded by day 150
- Synchrotron in BSG wind ($\rho \propto r^{-2}$) (Storey & Manchester 1987; Chevalier & Fransson 1987)
- Hα, VLBI: V ~ 19000 – 30000 $\mathrm{kms^{-1}}$ (Hanuschik & Dachs 1987; Jauncey et al.1988)

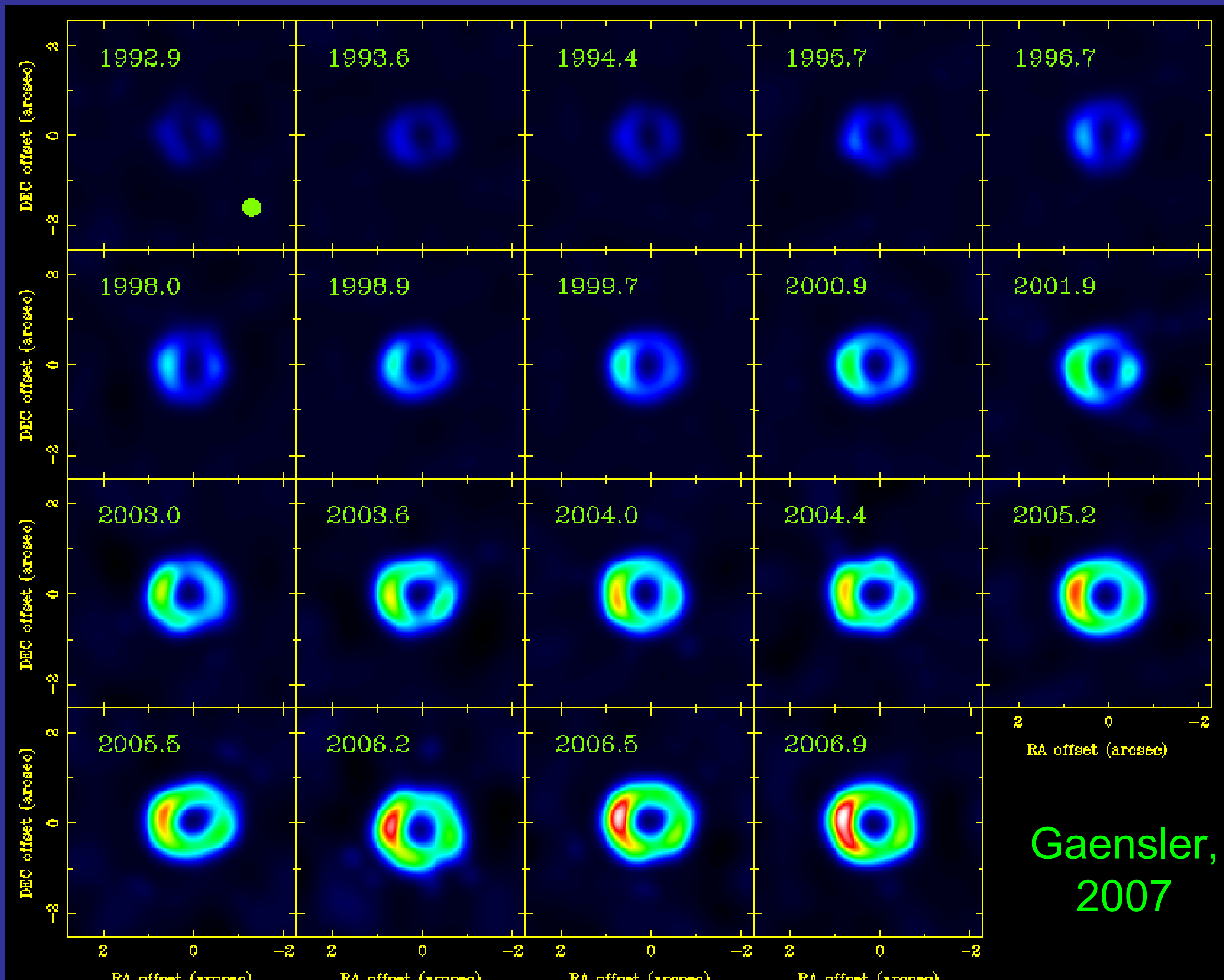


Late Phase (Gaensler, 2007)

- Turn-on after ~3 yr: impact with dense RSG wind
- α ~ -0.9 ➔ optically thin synchrotron emission, steep electron density and small compression ratio in the shock (vs. "canonical" value ~ -0.5)
- Consistent multi-wavelength picture of reverse-shock emitting region: interaction is with dense gas in equatorial plane
- Source now same size as optical ring



Radio Imaging



- Limb brightened
- Bright lobes to east and west
- Eastern lobe brighter than western lobe, & brightening faster

ATCA 9 GHz diffraction limited (0.9 arcsec)

super-resolved (0.15 arcsec)

MAGNETIC FIELD

➔ Radio and hard X-rays come from relatively low density gas between blast wave and reverse shock

How (where) are relativistic electrons accelerated?

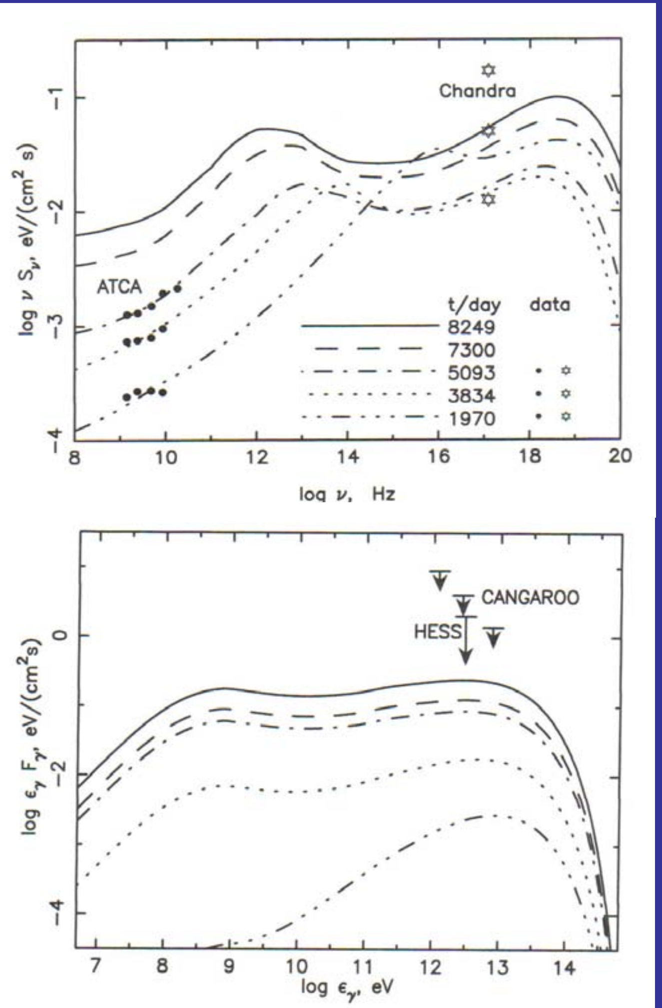
Cosmic Ray acceleration ➔ shock modification and strong magnetic field amplification in ALL the young SNR (Berezhko, 2005)

Berezhko & Ksenofontov, 2000, 2006:

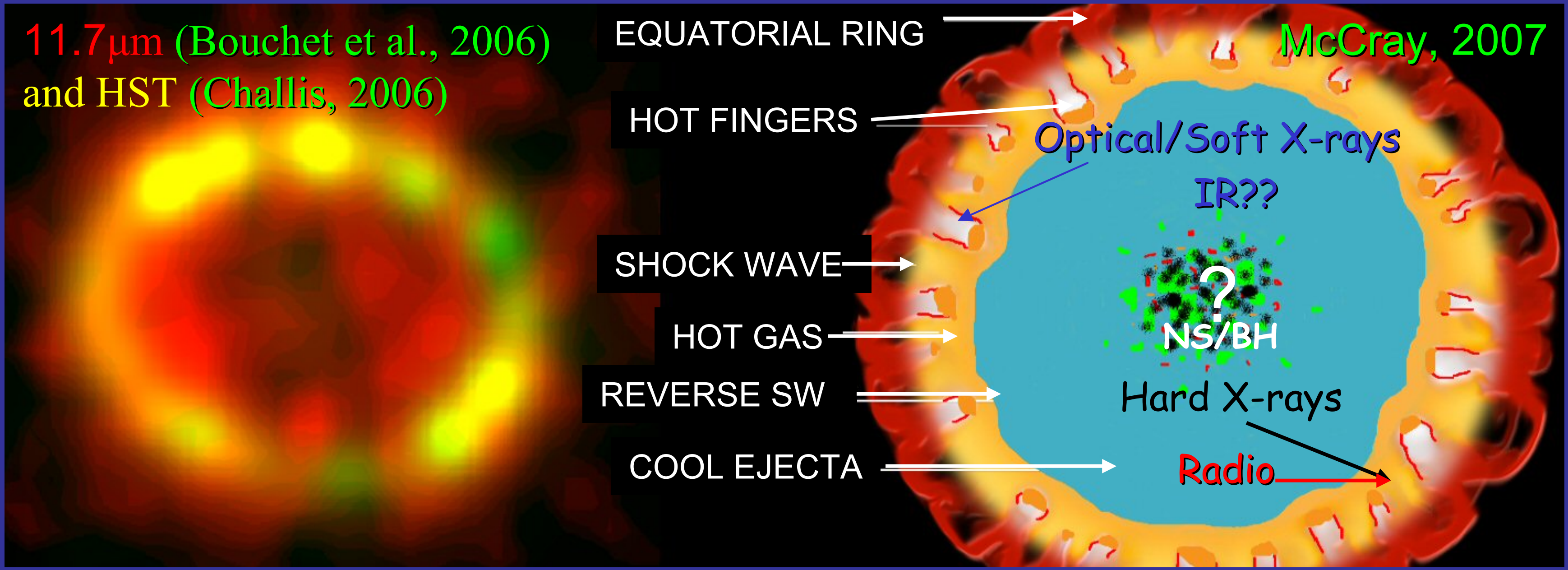
Nonlinear kinetic theory of CR: A large downstream magnetic field (B~10 mG) + strong shock modification due to CR backreaction ➔:

- Radioemission spectrum
- Considerable synchrotron cooling of high energy e^- which reduces their X-ray synchrotron flux
- Expected γ-ray energy flux at TeV-energies is $\sim 2 \times 10^{-13}$ erg $cm^{-2}s^{-1}$

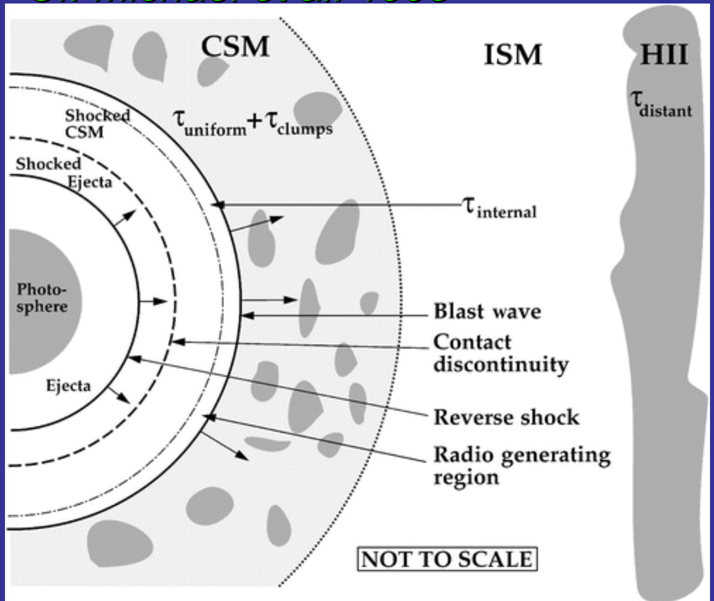
G-SNRs source population of the G-CR

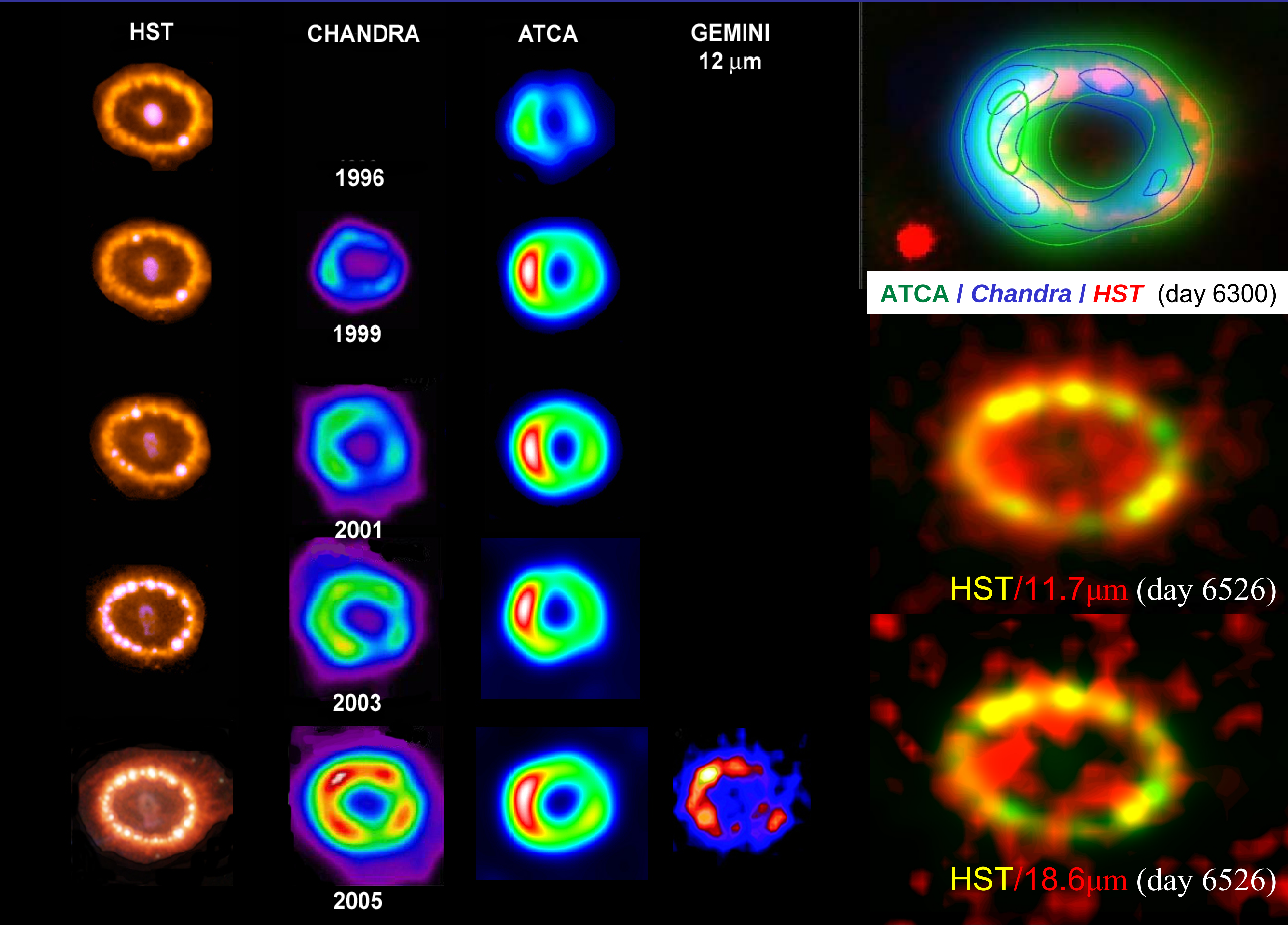


Physical Picture

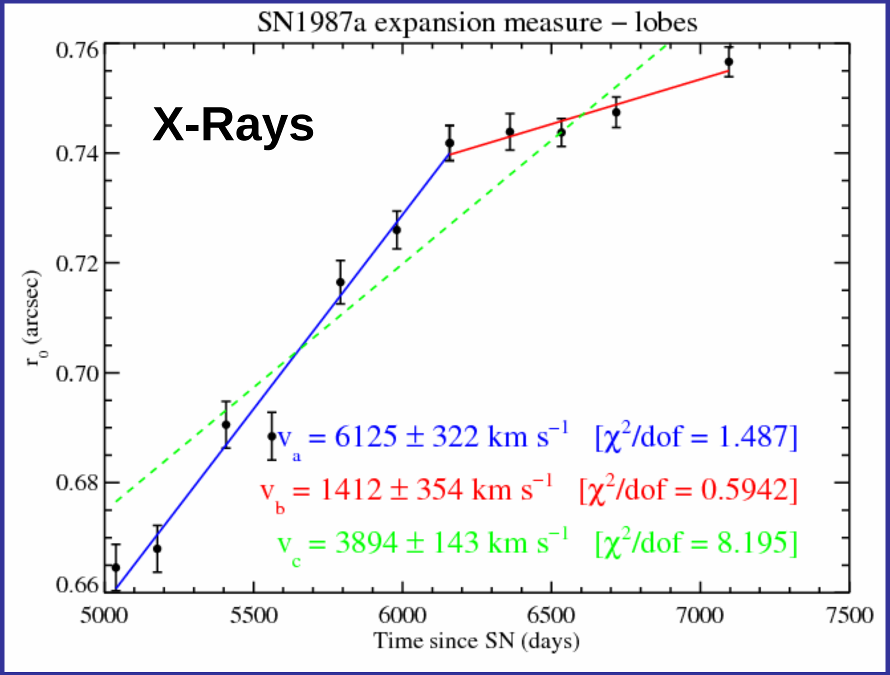


Cf. Michael et al. 1998

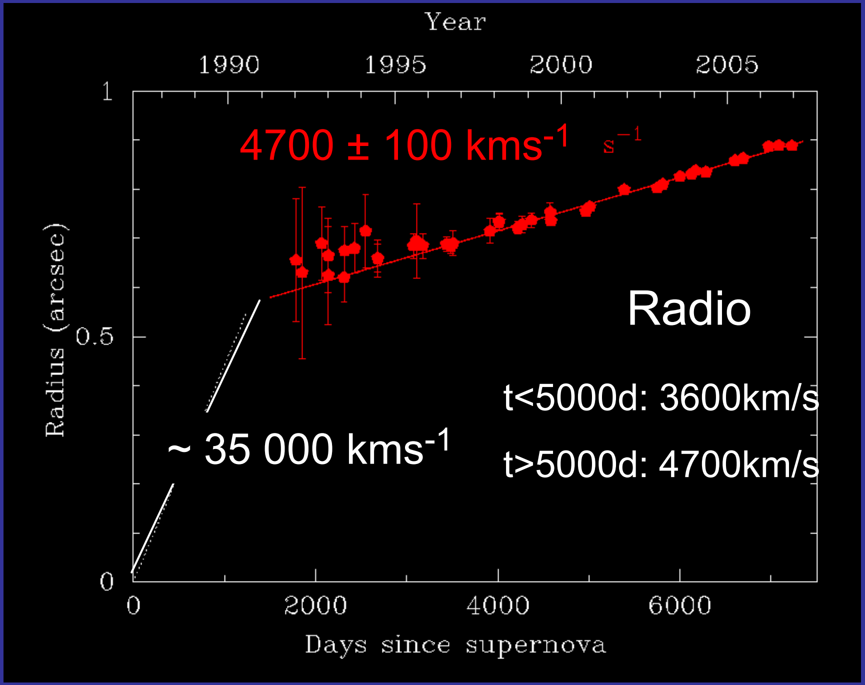



HST
CHANDRA
ATCA
GEMINI
12 μm
1996
1999
2001
2003
2005
ATCA / Chandra / HST (day 6300)
HST/11.7μm (day 6526)
HST/18.6μm (day 6526)

Radial Expansion



Racusin et al. 2007



Gaensler et al., 2007

Rapid deceleration in X ≠ approximatively constant in radio

Discrepancy of radius, velocity & acceleration between radio and X-rays

➔ ???

“New” detection of the Pulsar?

Middleditch et al., 2000:

- Several detections during 1992 – 1996 at different frequencies
- Power faded after 1993; last detected 1996
- Emission with a complex period modulation near 2.14 ms
- Frequency of the signals followed a consistent and predictable spin-down [~(2-3) x 10^{-10} Hz s-1] over the several year
- Modulation of the 2.14 ms period with a ~1000 s period, which complicates its detection
- Precession due to deformation or crustal density distribution not symmetric about the axis of rotation

Santostasi, Johnson, & Frank, 2003:

- possible asymmetric deformation that causes the precession
- main mechanism for the loss of rotational energy due to emission of gravitational radiation

➔ Continuous source of gravitational wave detectable with LIGO II in a few days (10^6 years for LIGO I): 2013

Why No Detection NOW?

• Possible that neutron star has accreted matter and turned into a black hole?: the ^{56}Co ejected which powered the l.c. shows that very little mass could have fallen back + BH truncates a gradually decreasing flux of neutrinos and doesn't produce bursts (Woosley, 1988)

• Possible that the pulsar is not beamed toward us - if slowish pulsar, expected beaming fraction ~ 0.2 (Manchester, 2006)

• Pulsar magnetic field may take time to develop

• A slow, low E pulsar would not pulse at optical or X-ray wavelengths (except maybe thermal emission from NS surface)

• Although outer parts of nebula probably have low optical depth, we really know very little about conditions right in centre - could be absorption/scattering of radio pulses (Manchester, 2007)

Keep searching for a radio pulsar and point X-ray source?

Limits on Properties of a Central Pulsar

- No evidence for central source (PWN or pulsar) at any wavelength: optical luminosity limit ~8 x 10^{33} erg s^{-1} (V>24.6) (Graves et al. 2005), X-ray limit (2-10 keV) ~5 x 10^{34} erg s^{-1} (Shtykovskiy et al. 2005)
- Radio limit of central source from 8 GHz image ~ 1 mJy
- Assume flat spectrum ➔ 20 GHz, L_{PWN} ~ 3 x10^{31} erg s^{-1} ~ 17 mJy
- For the most conservative limit on E of central pulsar, assume PWN only emits at radio frequencies and $L_{PWN} = E_{PSR}$
- For P_o = 200 ms, E_{PSR} = 3 x10^{31} erg s^{-1}, then Bo ~ 6 x 10^{10} G

Manchester, 2007

Well within the range of possible pulsar birth parameters

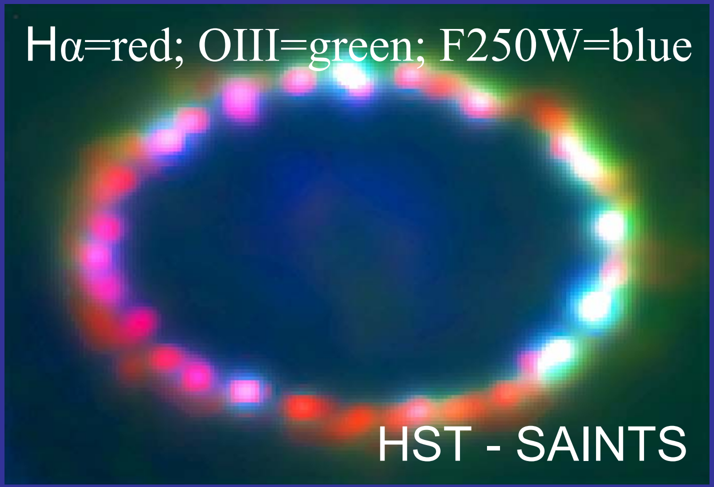
PWN limits do not rule out a perfectly plausible 20-year old pulsar at the centre of SN 1987A

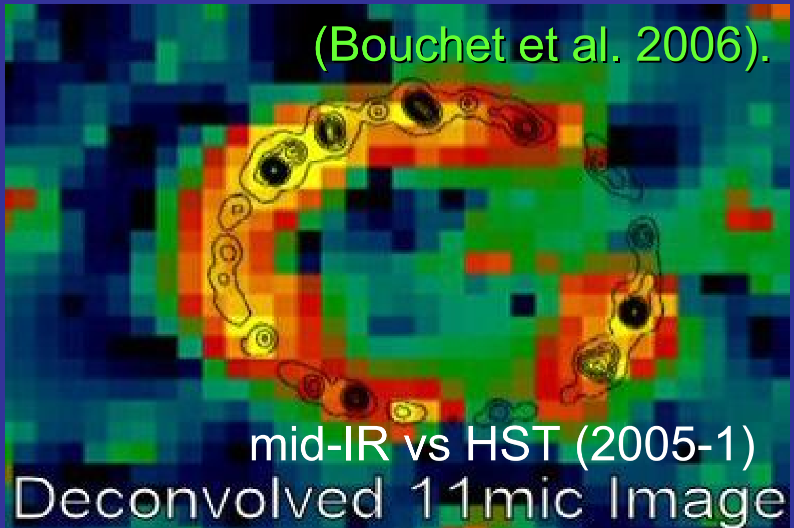
SN 1987A at 20 Years

• Blast Wave at Inner Ring (← $R_{radio} = R_{ring}$)

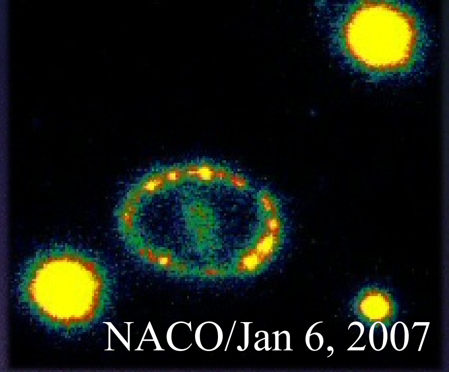
•Reverse shock approaches the central debris (?)

- HST images: optical spots dominate entire inner ring
- Soft X-ray, mid-IR & radio images resemble optical image
- X-rays and radio turned on at 1200d; ratio [hard (> 3keV) X-rays/radio] ~ Cst.
- Inner ring detected in the mid-IR at day 6067: shock-heated silicate dust.
- Soft (~0.5 – 2 keV) X-rays increased rapidly after hotspots appeared; X-ray emission is dominated by the decelerated shock since day ~6000.
- Soft X-ray l.c. makes a turn-up at day ~6200 as ring mid-IR flux at day ~6000
- X-ray radial expansion rate reduces since day ~6200, shock velocity reduces to 1400 km/s; radio expansion constant at ~ 4700 km/s
- Dust still present in the ejecta at day 7241. Mid-IR flux of the ejecta brightens?





Forecasting SN1987A



2017 celebration:

- X-ray, optical ring: ~ 10 x brighter than today
- Hotspots will merge
- Reverse shock emission will vanish
- Interior debris will begin to brighten
- Circumstellar matter will begin to glow
- Spectacular images of NT radio emission from ALMA
- Compact Object: JWST?, ALMA?
- Gravitational waves from LIGO II?

(based on McCray, 2007)

Forecasting SN1987A

2027 celebration:

X-rays, optical: ~ 100 x brighter than today

Will clearly see interior debris and circumstellar matter

Newly synthesized elements will begin to cross reverse shock

McCray, 2007