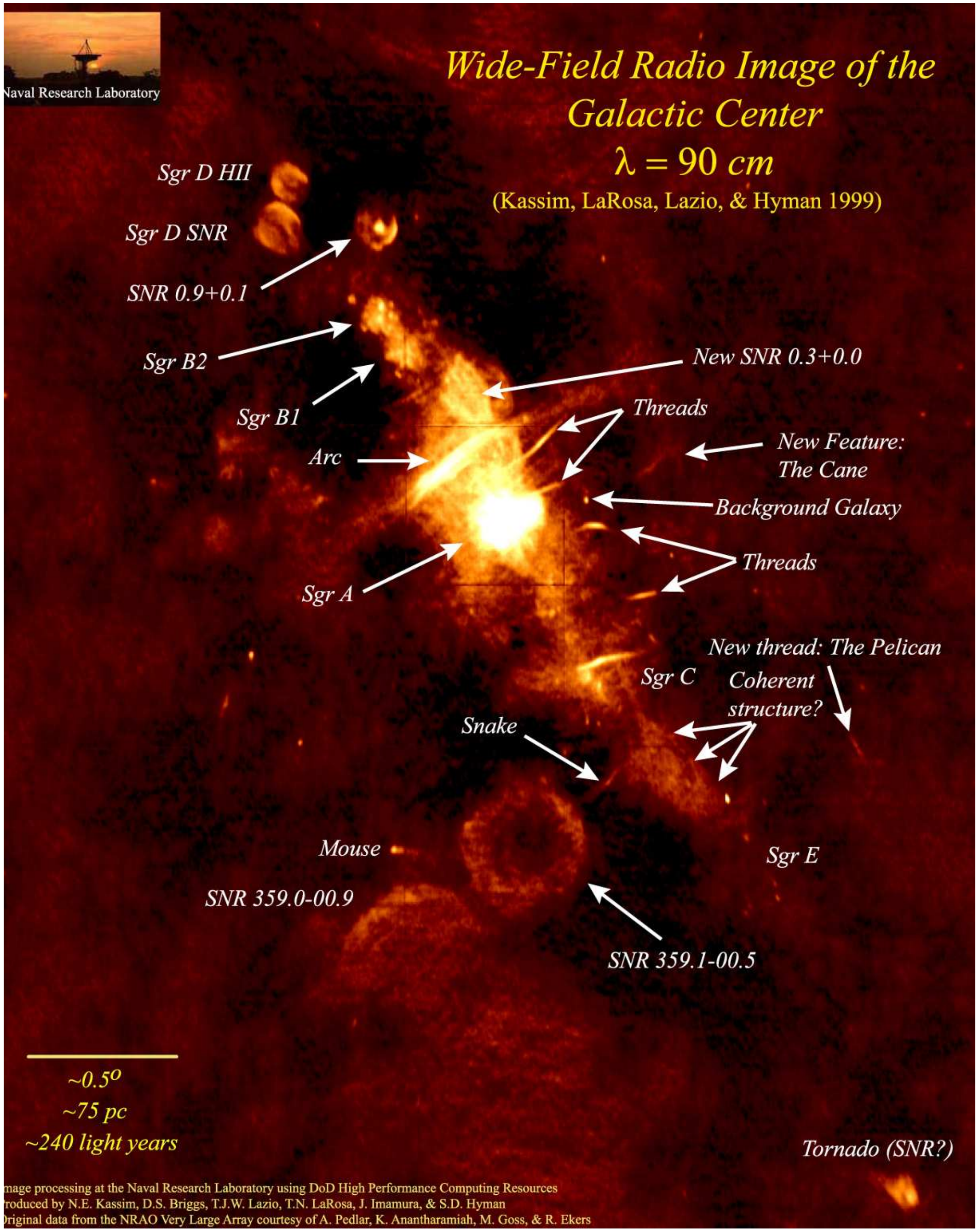
Supernova Remnants



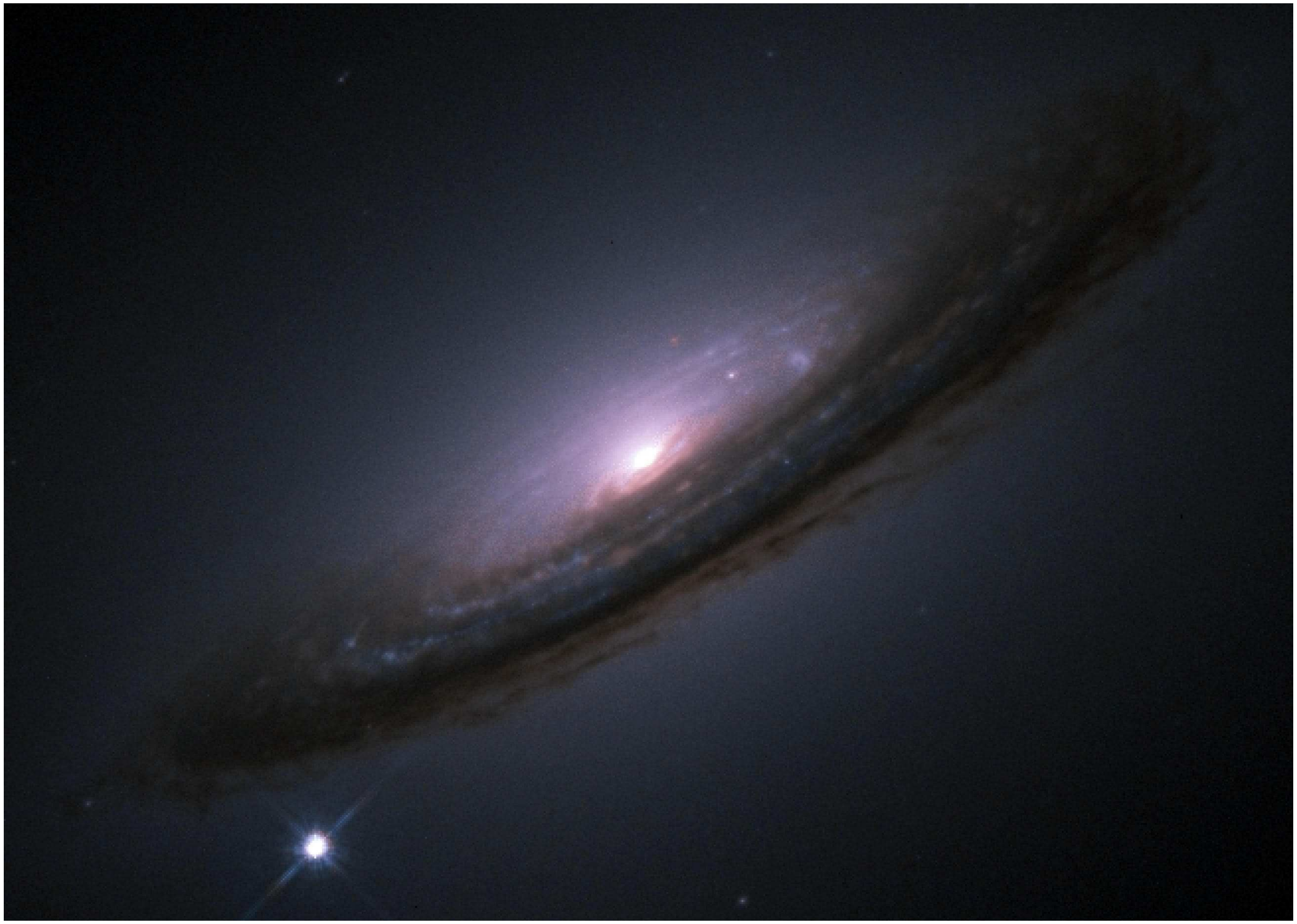
Wide-Field Radio Image of the Galactic Center

$\lambda = 90$ cm

(Kassim, LaRosa, Lazio, & Hyman 1999)

mage processing at the Naval Research Laboratory using DoD High Performance Computing Resources
roduced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
riginal data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

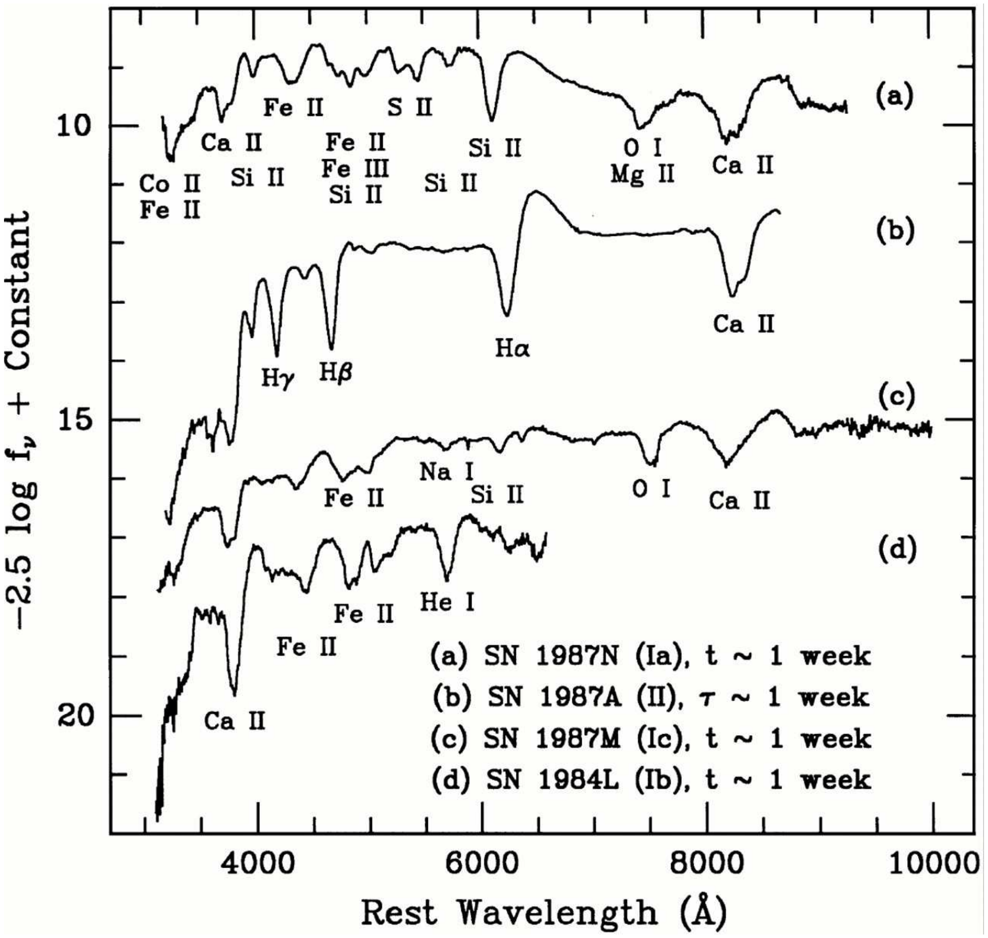
Radio Supernova Remnants in the Galactic Center



SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim\ 10^{51}$ erg/s in light, 100× more in neutrinos (in type-2). Star brightens by $\sim 20^{\mathrm{m}}$.

Classification, I



(Filippenko, 1997, Fig. 1); t: time after maximum light; τ: time after core collapse; P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

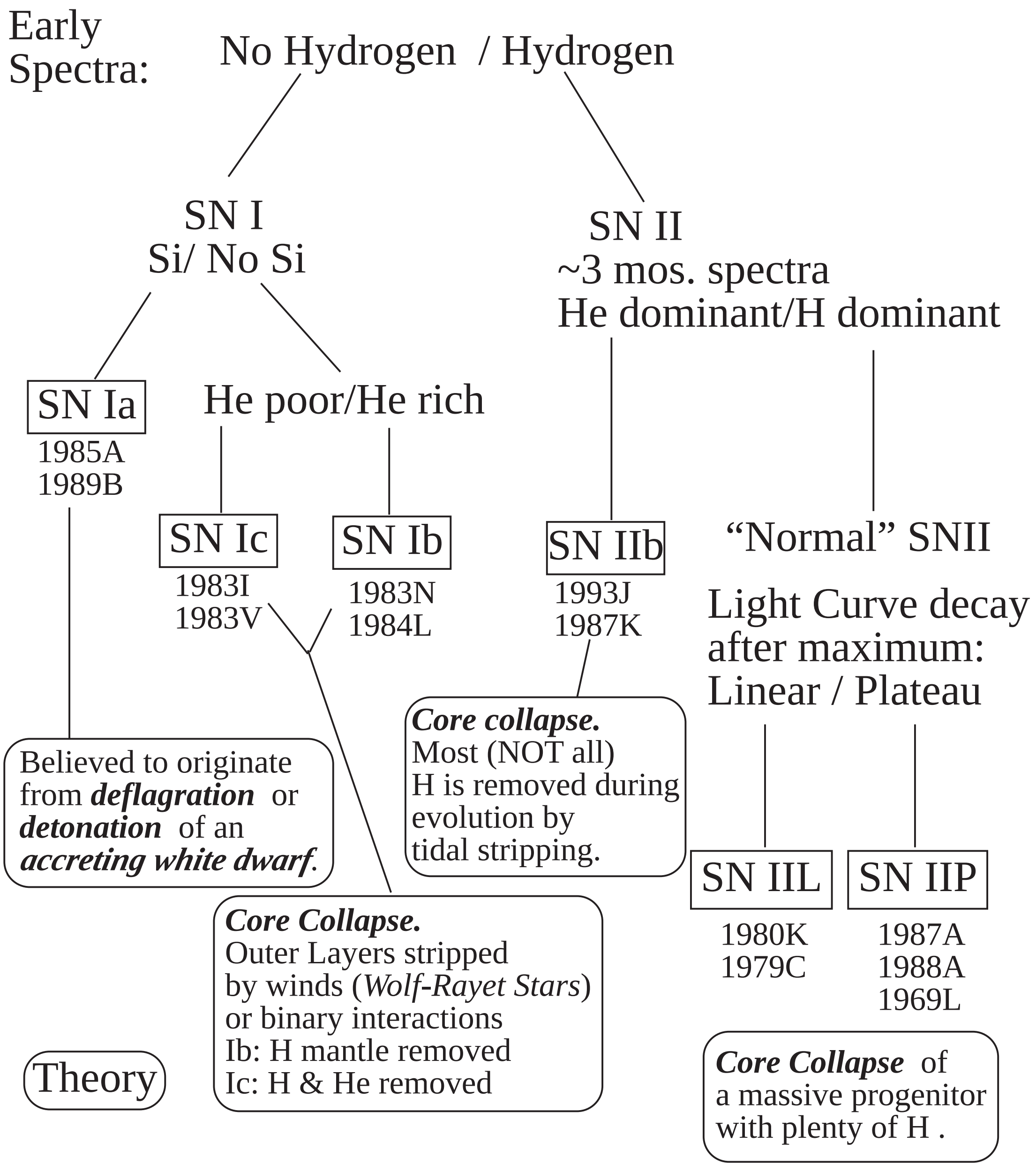
Rough classification (Minkowski, 1941):

Type I: no hydrogen in spectra; subtypes Ia, Ib, Ic

Type II: hydrogen present, subtypes II-L, II-P

Note: pre 1985 subtypes Ia, Ib had different definition of today $\Longrightarrow$ beware when reading older texts.

Classification, II



Early Spectra:

No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

“Normal” SNII

Light Curve decay
after maximum:
Linear / Plateau

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf***.

Core collapse.
Most (NOT all)
H is removed during
evolution by
tidal stripping.

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

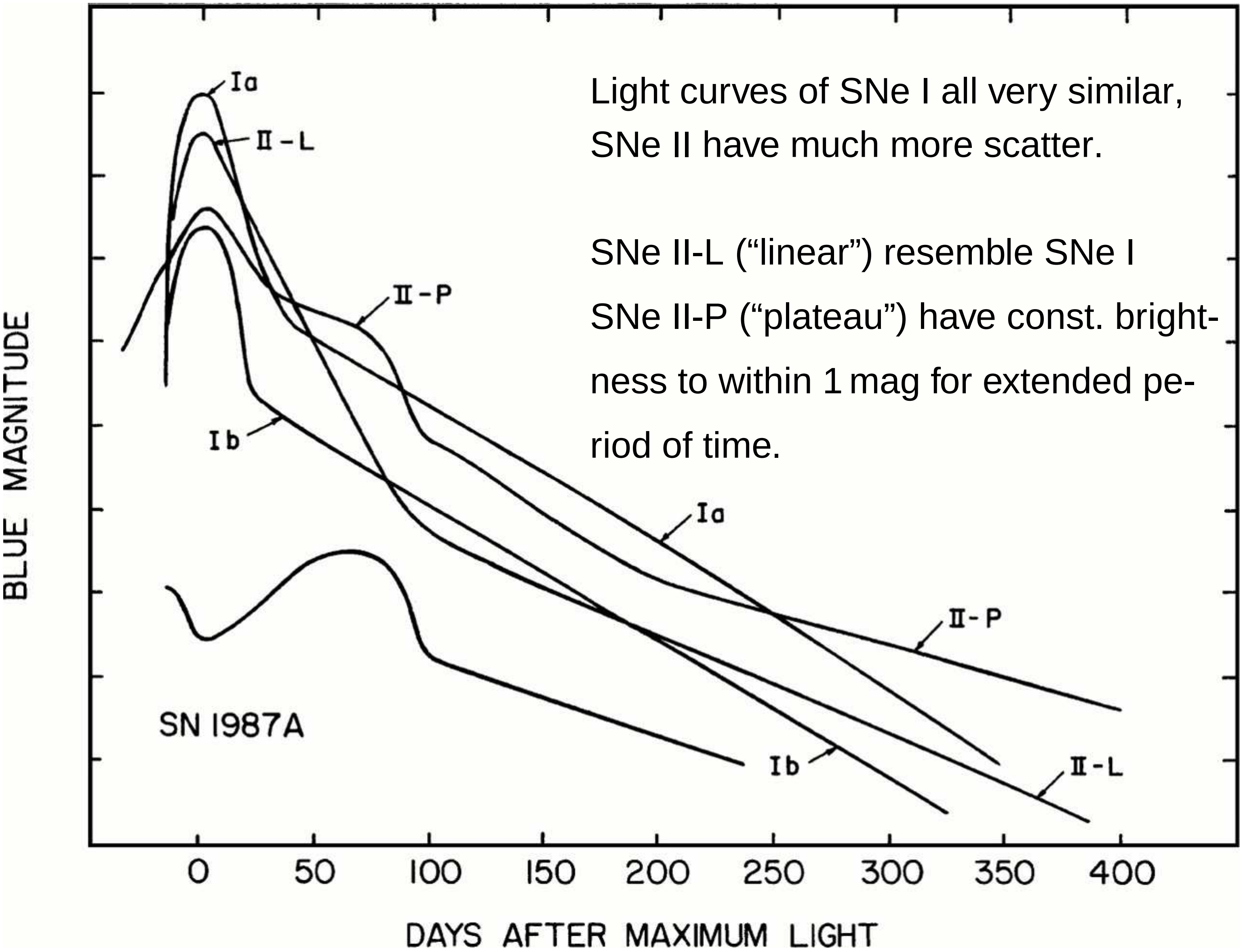
Core Collapse.
Outer Layers stripped
by winds (*Wolf-Rayet Stars*)
or binary interactions
Ib: H mantle removed
Ic: H & He removed

Theory

Core Collapse of
a massive progenitor
with plenty of H .

courtesy M.J. Montes

Classification, III



Light curves of SNe I all very similar, SNe II have much more scatter.

SNe II-L (“linear”) resemble SNe I

SNe II-P (“plateau”) have const. brightness to within 1 mag for extended period of time.

(Filippenko, 1997, Fig. 3)

Models

Clue on origin from supernova statistics:

- SNe II, Ib, Ic: never seen in ellipticals; rarely in S0; generally associated with spiral arms and H II regions.

$\Longrightarrow$ progenitor of SNe II, Ib, Ic: massive stars ($\gtrsim 8\,M_\odot$) $\Longrightarrow$ core collapse

- SNe Ia: all types of galaxies, no preference for arms.

$\Longrightarrow$ progenitor of SNe Ia: accreting carbon-oxygen white dwarfs, undergoing thermonuclear runaway $\Longrightarrow$ lightcurves all very similar $\Longrightarrow$ cosmological standard candles!

courtesy ESO


courtesy ESO

SN 1987A

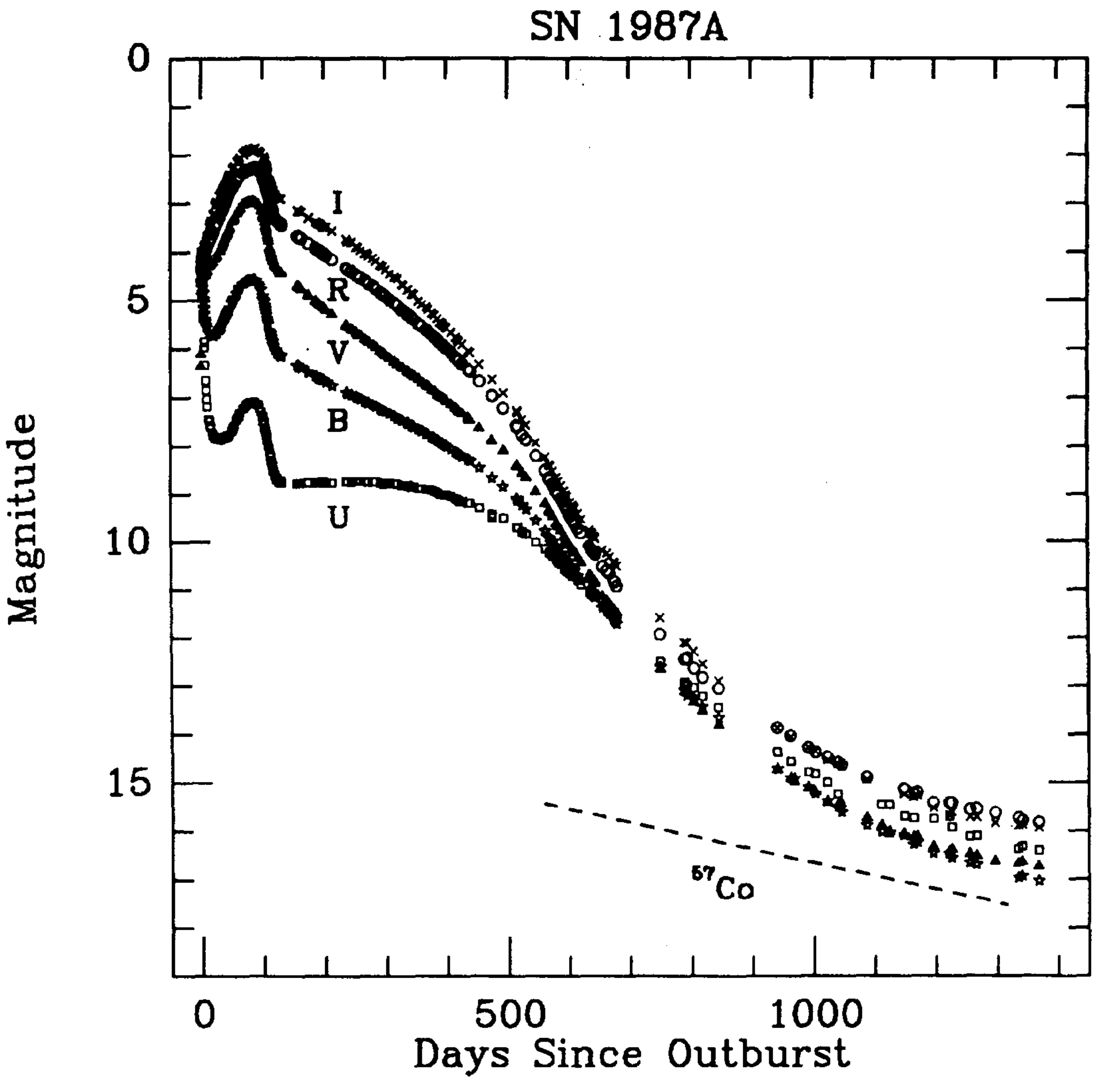
1987 February 23: Explosion of blue supergiant in the LMC

Sandulaek -69°202; closest (observed) supernova since Kepler (1604)

© Anglo-Australian Observatory

courtesy AAO

SN 1987A

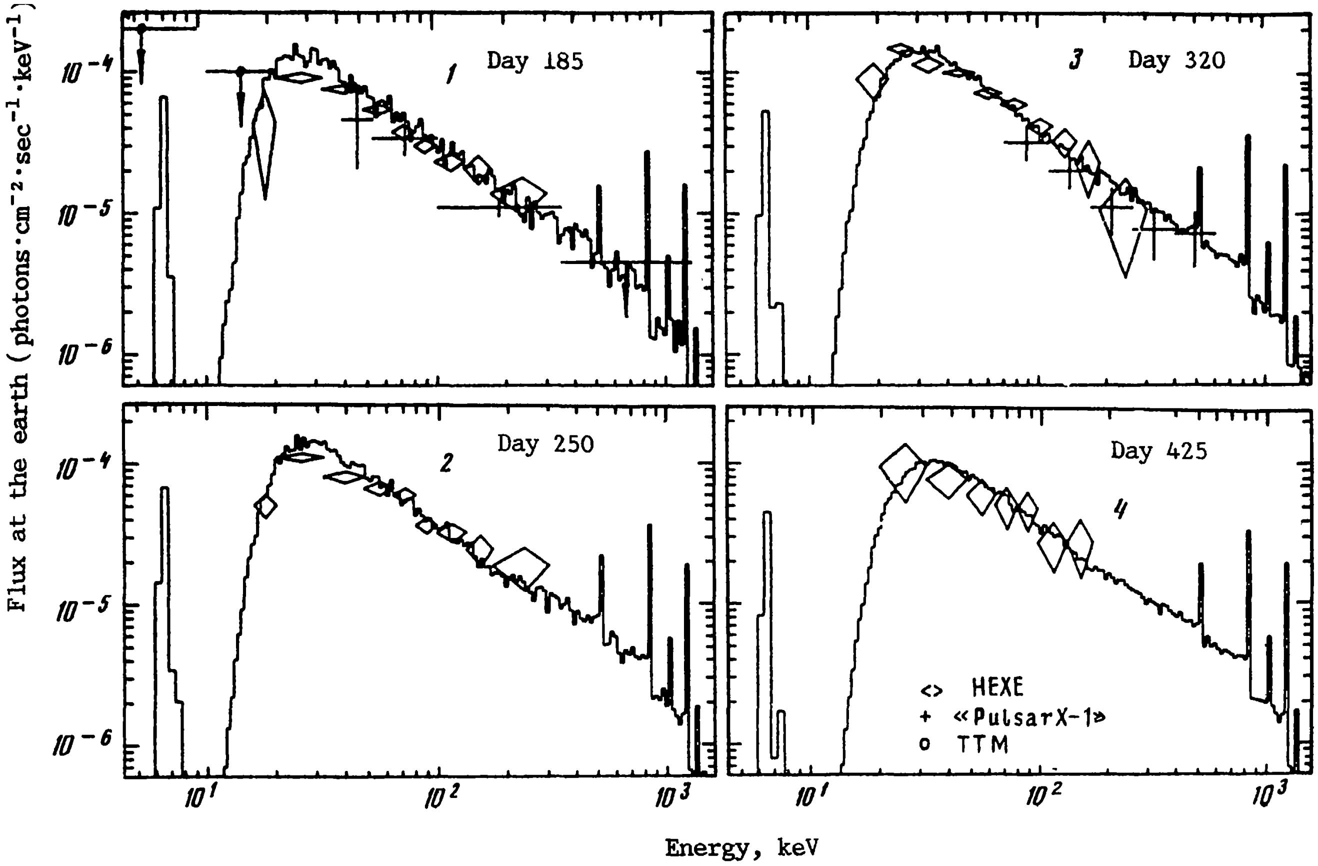


UVOIR (UV, optical, infrared) light curve resembles SNe II-P, although peak much lower than typical (progenitor was blue supergiant, not red supergiant).

Exponential decay of bolometric luminosity after first few 100 days $\Longrightarrow$ Radioactive decay

(Suntzeff et al., 1991, Fig. 2)

SN 1987A



(Sunyaev; 1991)

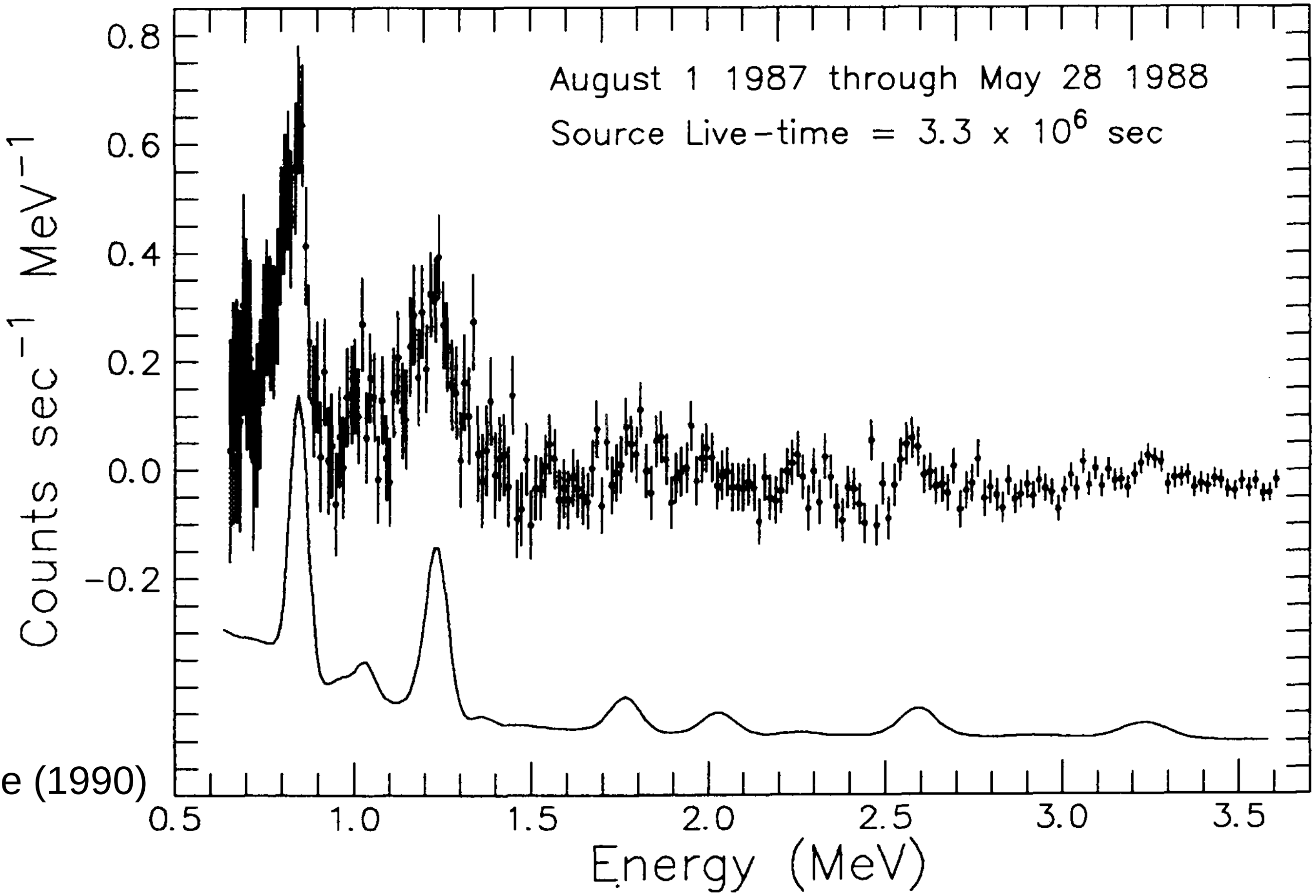
During SN explosion: formation of ^{56}Ni. Then radioactive decay:

$$^{56}\mathrm{Ni} \xrightarrow[t_{1/2}=6.1\,\mathrm{d}]{\mathrm{EC}} {}^{56}\mathrm{Co} \xrightarrow[t_{1/2}=77.12\,\mathrm{d}]{81\%\mathrm{EC},19\%\beta^+} {}^{56}\mathrm{Fe} \quad \text{emission of } \gamma\text{-ray lines}$$

Optically thick medium $\Longrightarrow$ downscattering and thermalization $\Longrightarrow$ continuum spectrum.

1987: Mir-HEXE: Observed X-ray spectrum agrees with radioactive decay picture.

SN 1987A

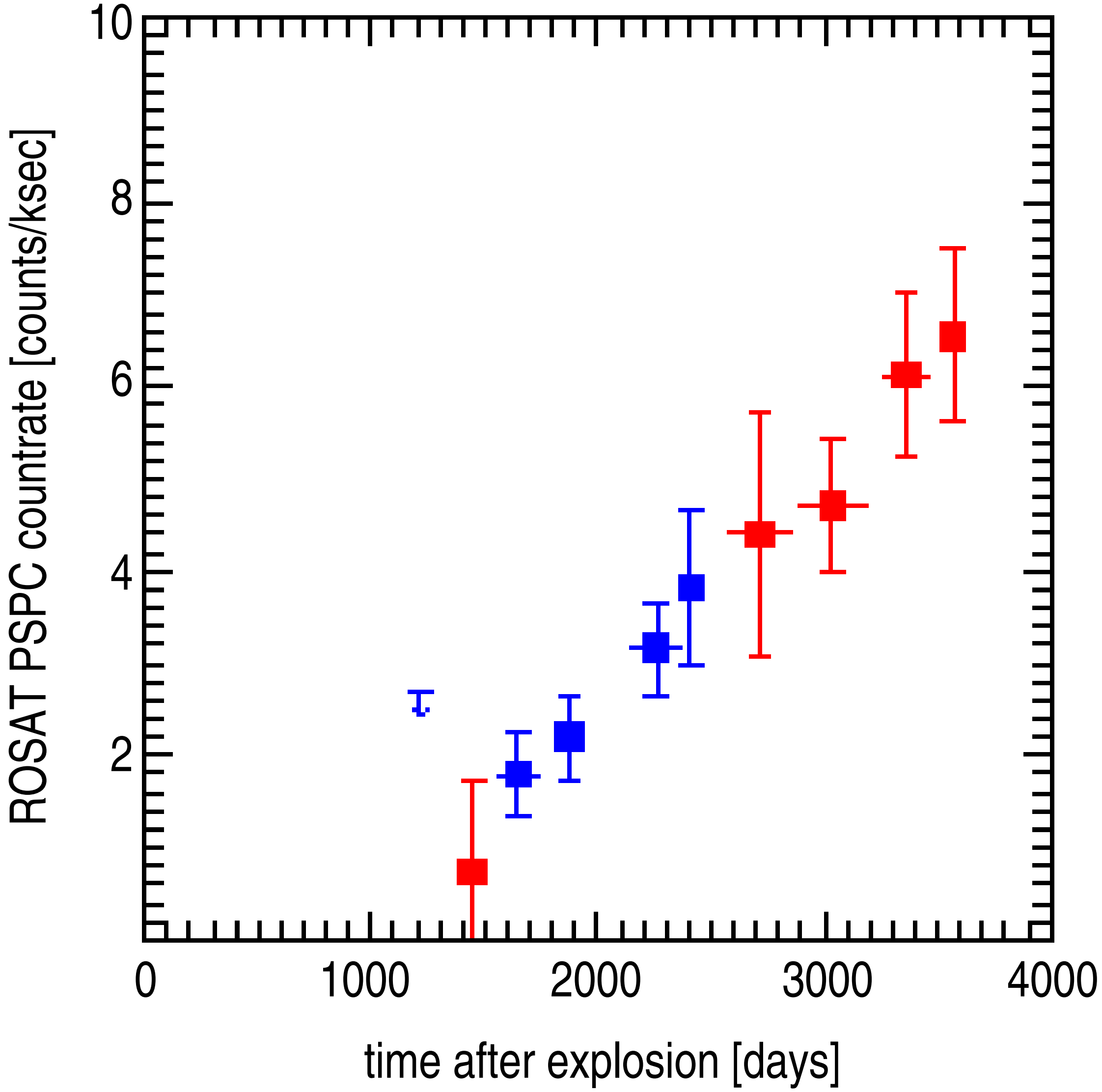


Leising and Share (1990)

Solar Maximum Mission: high resolution γ-ray mission; direct spectroscopy of 847, 1238, 2599, and 3250 keV lines from ^{56}Co decay

SMM finds about 0.07 $M_\odot$ in cobalt.

SN 1987A

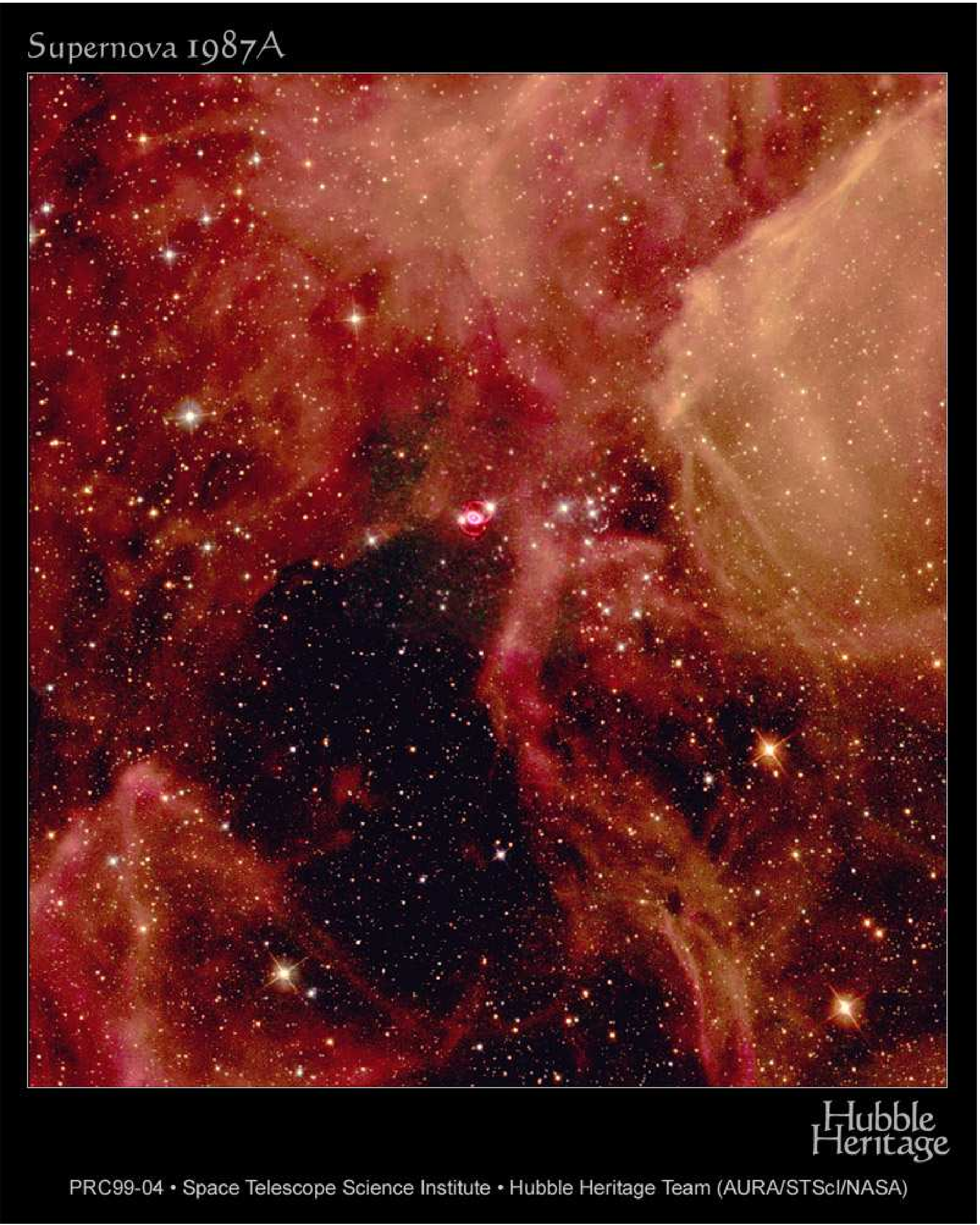


(Hasinger, Aschenbach & Trümper, 1996, Fig. 3)

$\sim$1000 d after explosion: the X-ray luminosity of SN 1987A started to brighten again ($L_X \propto t^2$).

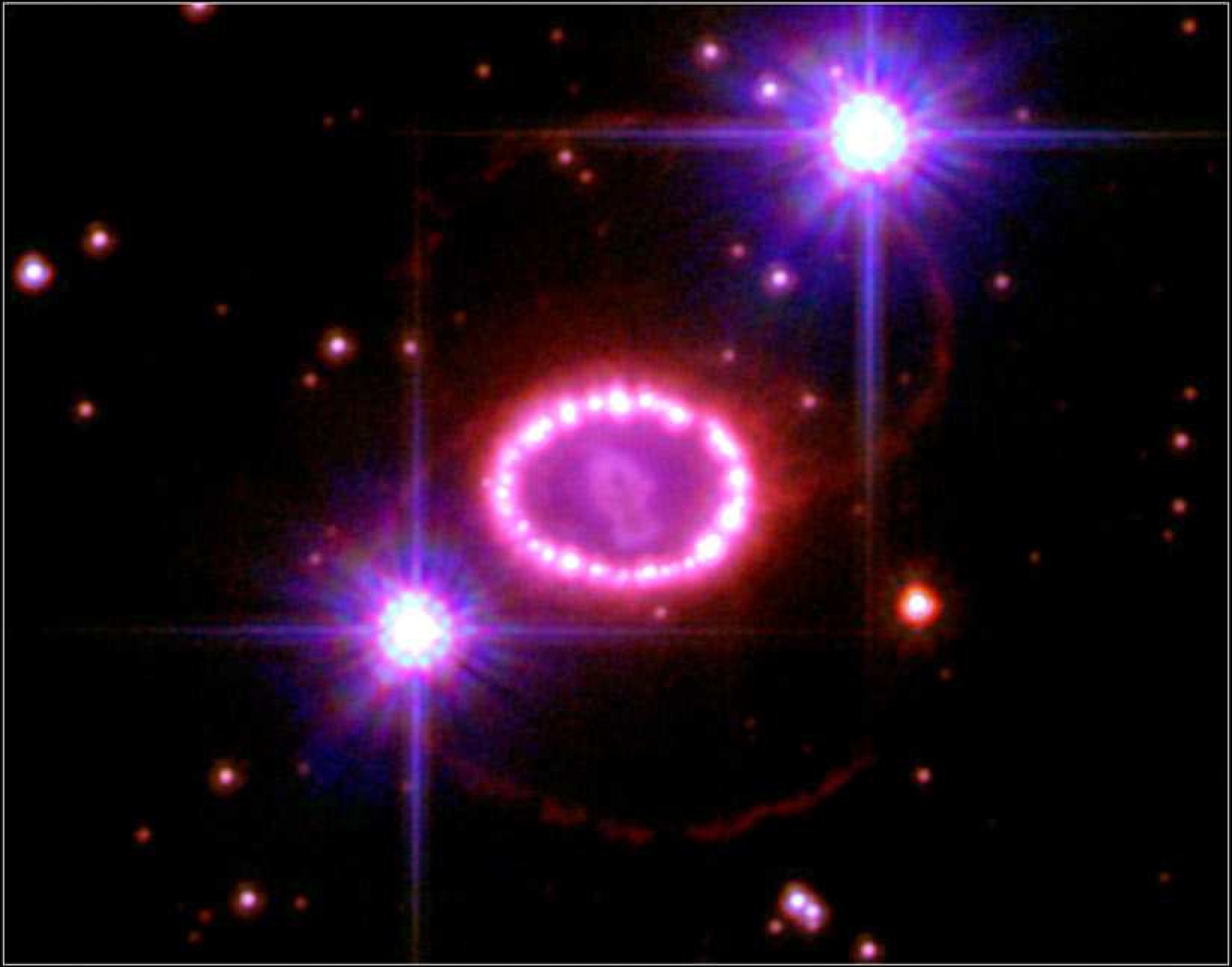
Most likely explanation: interaction between SN blast wave and interstellar medium (mainly progenitor stellar wind)

$\Longrightarrow$ Supernova remnant!


Supernova 1987A

PRC99-04 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

Additional features seen in the optical: central ring due to impact of blast wave on circumstellar material and outer rings, possibly due to ionization of material illuminated by SN blast. Material possibly from bipolar outflow during blue supergiant phase (fast blue SG wind colliding with slower RG wind); material ejected $\sim$20000 years before explosion.



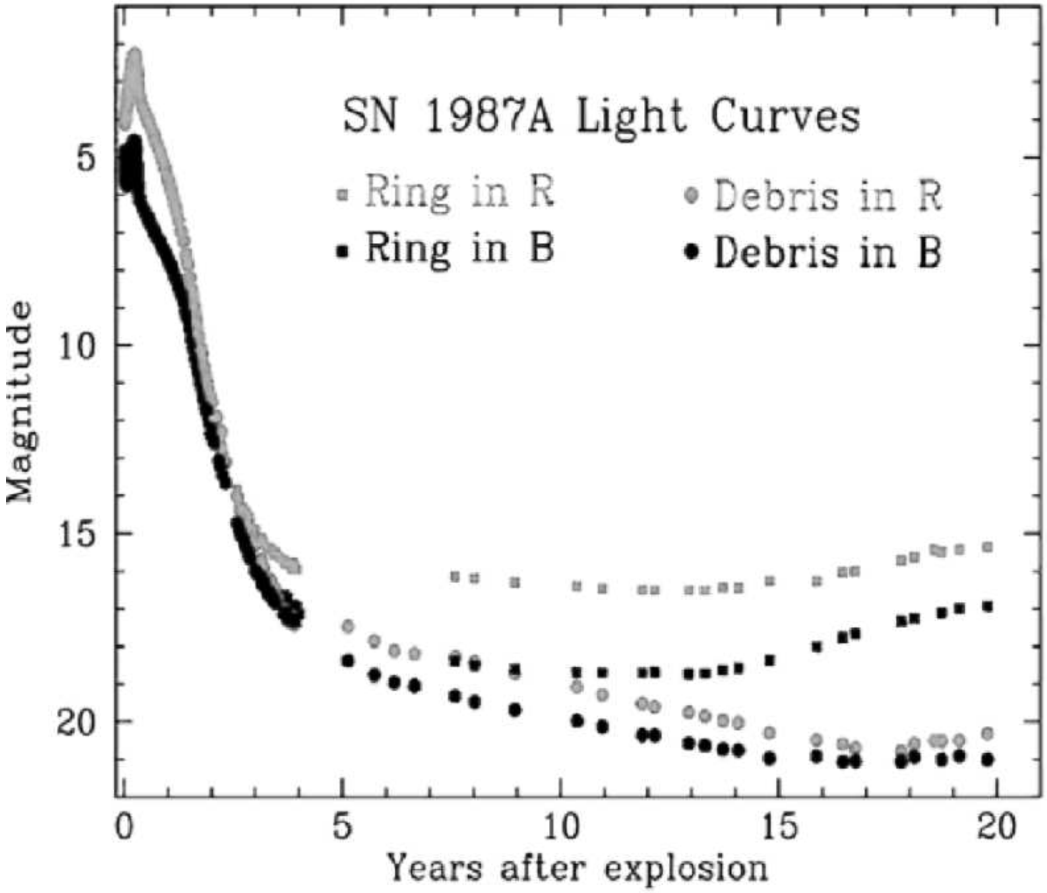
Supernova 1987A • December 2006

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

STScI-PRC07-10

SN 1987A



McCray 2007, Fig.3

Late time light curve due to radioactive decay of Cobalt.

- Day 125–1100: dominated by decay of ^{56}Co
- After $\sim$ 3 years: radioactive decays of long-lived ^{57}Co and later of ^{44}Ti start to heat the system
- Today: Light curve almost flat and $\sim\ 10^{-7}$ fainter than at maximum! Ring still brightening!

SN 1987A has made the transition to a young Supernova Remnant!

Introduction to SNRs, I

After Supernova Explosion: Formation of Supernova Remnant (SNR)

Explosion energy goes into kinetic energy of ejecta:

$$E = \frac{1}{2} M v_{\text{ej}}^2 \tag{4.1}$$

Therefore

$$v_{\text{ej}} = 10^4\,\text{km}\,\text{s}^{-1} E_{51}^{1/2} \left(\frac{M_{\text{ej}}}{M_\odot}\right)^{-1/2} \tag{4.2}$$

$$\sim 10^{-2}\,\text{pc}\,\text{yr}^{-1} E_{51}^{1/2} \left(\frac{M_{\text{ej}}}{M_\odot}\right)^{-1/2} \tag{4.3}$$

where $E_{51} = E/10^{51}\,\text{erg}\,\text{s}^{-1}$.

$\Longrightarrow$ Fast material smashes into stationary ISM $\Longrightarrow$ shock!

Typical temperatures via thermalization:

$$E \sim NkT = \frac{M}{m_{\text{p}}} kT \quad \Longrightarrow \quad T \sim 10^9\,\text{K} \Longrightarrow \mathrm{X-ray\ emission!} \tag{4.4}$$

Introduction to SNRs, II

Simplified computation if fluid approximation possible, i.e., mean free path $\ll$ size of system

Two possible candidates: 1) Ionization length scale, 2) Magnetic length scale

Ionization length scale: Need $\sim$50 eV to collisionally ionize hydrogen; cross section: $\sigma_{\mathrm{ion}} \sim a_0^2 \sim 10^{-17}\,\mathrm{cm}^2$. For protons: $10^4\,\mathrm{km\,s^{-1}} \mathrel{\hat{=}} \sim 2\,\mathrm{MeV}$; assume $n_{\mathrm{H}} = 1\,\mathrm{cm}^{-3}$

$\Longrightarrow$ typical stopping length:

$$l_{\mathrm{ion}} \sim \frac{\text{Energy}}{\text{E Loss/Ionization}} \cdot \text{mfp btw collisions} \tag{4.5}$$

$$\sim \left(\frac{2\,\mathrm{MeV}}{50\,\mathrm{eV}}\right) \frac{1}{n_{\mathrm{H}}\sigma_{\mathrm{ion}}} \sim 10^3\,\mathrm{pc} \tag{4.6}$$

$\Longrightarrow$ l_{ion} is too large

Magnetic length scale given by Larmor radius ($B \sim 3\,\mu\mathrm{G}$)

$$R_{\mathrm{L}} = \frac{qB}{mc} \sim 2 \times 10^{10}\,\mathrm{cm} \sim 10^{-8}\,\mathrm{pc} \tag{4.7}$$

$\Longrightarrow$ R_{L} is small enough

Use fluid approximation to study SNR evolution!

Introduction to SNRs, III

Generally, four phases of SNR evolution:

Free expansion : velocity very large with respect to ambient medium, swipe up large fraction of the medium

Sedov phase : Expansion driven by conversion of internal energy into kinetic energy

Snowplough phase : energy loss due to radiative cooling becomes important, shock becomes isothermal, shell moves with constant radial momentum (“snow plough”).

Merging phase : speed of expansion $<$ speed of sound, SNR dissolves into ISM

Will now look at these phases in detail.

Phase I: Free Expansion, I

Free Expansion: Material moves with uniform velocity, $r \propto t$.

Possible until sweptup mass $\sim$ ejected mass:

$$M_{\text{sweptup}} \sim \frac{4\pi}{3}\rho_{\text{ISM}} r_f^3 = M_{\text{ej}} \tag{4.8}$$

(assuming constant density around SN)

Therefore

$$r = \left(\frac{3}{4\pi}\right)^{1/3} M^{1/3} \rho^{-1/3} \tag{4.9}$$

$$= 2\,\text{pc}\,\left(\frac{M_{\text{ej}}}{M_\odot}\right)^{1/3} \left(\frac{\rho_{\text{ISM}}}{2\times 10^{-24}\,\text{g}\,\text{cm}^{-3}}\right)^{-1/3} \tag{4.10}$$

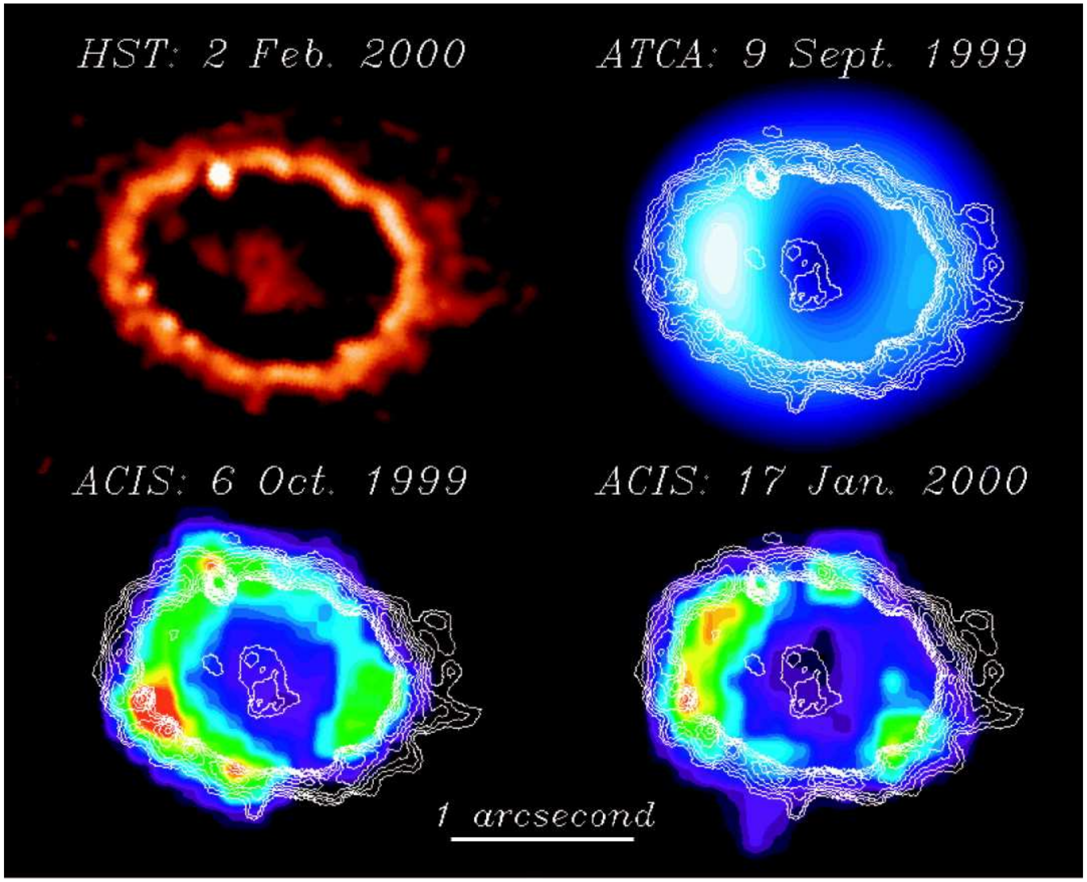
Corresponding time scale

$$t \sim \frac{r}{v_{\text{ej}}} \sim 200\,\text{yr}\,\left(\frac{M_{\text{ej}}}{M_\odot}\right)^{5/6} E_{51}^{-1/2} \rho_{24}^{-1/3} \tag{4.11}$$

(using Eq. 4.2).

SN 1987A is only close remnant in free expansion phase.

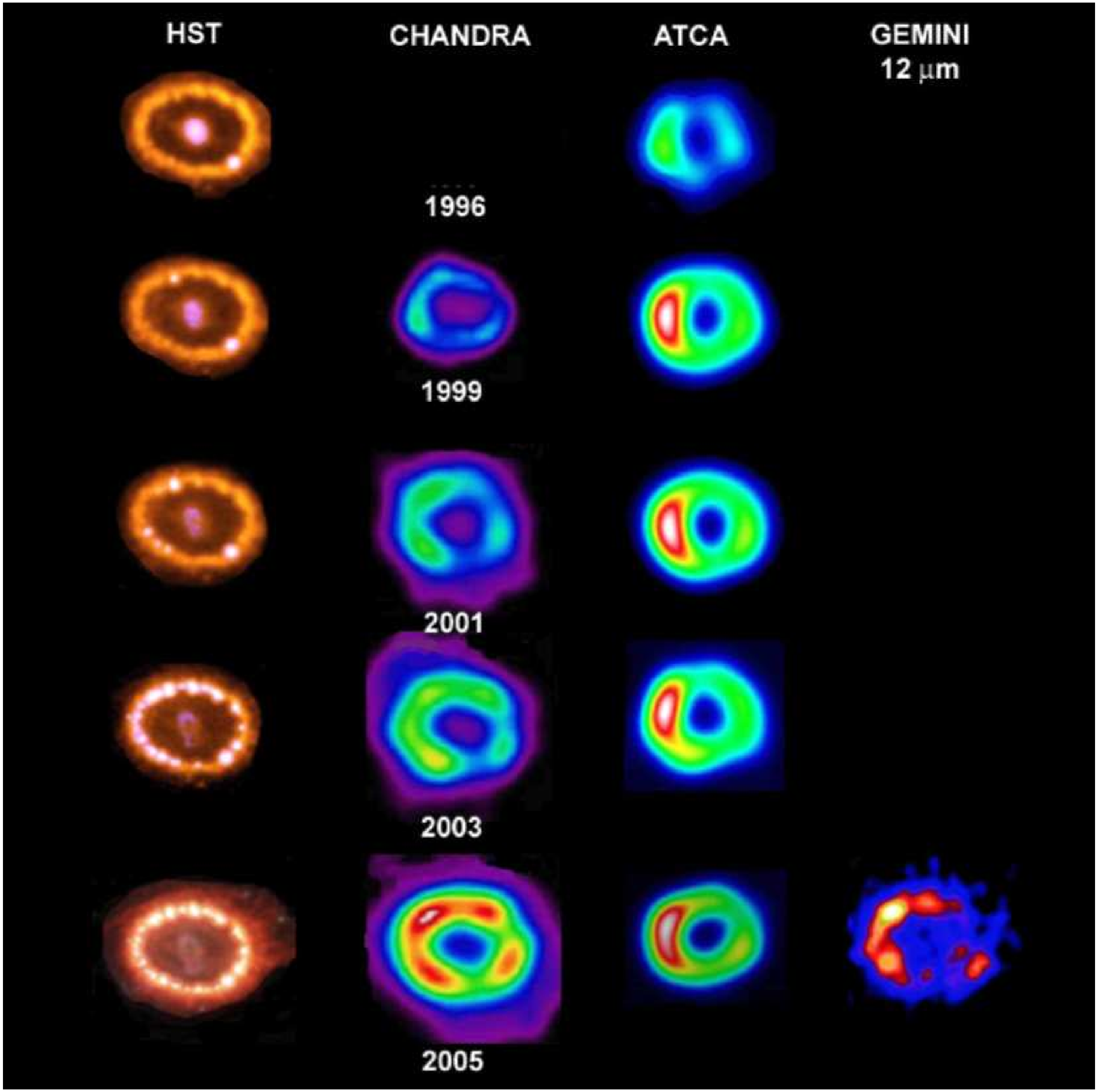
Phase I: Free Expansion, II



(Burrows et al., 2000, Fig. 1)

Ring ($1.66'' \times 1.21''$) around SN 1987A from shock heating at point of first contact between blast wave and equatorial ring from stellar wind of progenitor. Mainly ionized C and N.

Bright spots brightened first (1997) $\Longrightarrow$ “bullets” within faster than normal blast wave; 2000: many more spots $\Longrightarrow$ rest of blast wave has reached location of ring.


HST
CHANDRA
ATCA
GEMINI
12 μm
1996
1999
2001
2003
2005

Phase II: Sedov Phase, I

After free expansion: kinetic (expansion) energy is transfered into internal energy of the system. The total energy stays roughly constant (adiabatic expansion) $\Longrightarrow$ Sedov phase or blast wave phase.

Energy constancy translates to

$$E \sim \underbrace{\frac{1}{2}\left(\frac{4\pi}{3}\right)\rho r^3 v^2}_{\text{kinetic energy}} + \underbrace{A\left(\rho v^2\right)\left(\frac{4\pi}{3}\right) r^3}_{\text{internal energy}} \propto \rho r^3 v^2 \overset{!}{=} \text{const.} \tag{4.12}$$

where A is a constant. Solving for $v = \mathrm{d}r/\mathrm{d}t$:

$$\frac{\mathrm{d}r}{\mathrm{d}t} \propto \left(\frac{E}{\rho}\right)^{1/2} r^{-3/2} \tag{4.13}$$

Separation of variables gives

$$r \propto \left(\frac{E}{\rho}\right)^{1/5} t^{2/5} \tag{4.14}$$

Detailed theory (Padmanabhan, Vol. 1, Sec. 8.12) shows that the constant of proportionality is ~ 1 for $\gamma = 5/3$ ($p \propto \rho^\gamma$; γ depends on dof).

Note that these equations assume $\rho =$ const., which is not true since remnant expands; still, good enough for order of magnitude computations.

Phase II: Sedov Phase, II

Inserting numbers into Eq. (4.14) gives:

Radius of the shell:

$$r \approx \left(\frac{E}{\rho}\right)^{1/5} t^{2/5} \sim 0.3\,\mathrm{pc}\,E_{51}^{1/5} n_{\mathrm{H}}^{-1/5} t_{\mathrm{yr}}^{2/5} \tag{4.15}$$

Velocity of the shell:

$$v = \dot{r} = \frac{2}{5}\left(\frac{E}{\rho}\right)^{1/5} t^{-3/5} \tag{4.16}$$

Solving Eq. (4.15) for t and inserting

$$= \frac{2}{5}\left(\frac{E}{\rho}\right)^{1/5} r^{-3/2}\left(\frac{E}{\rho}\right)^{3/10} \tag{4.17}$$

$$\sim 5000\,\mathrm{km\,s}^{-1}\left(\frac{r}{2\,\mathrm{pc}}\right)^{-3/2} E_{51}^{1/2} n_{\mathrm{H}}^{-1/2} \tag{4.18}$$

Phase II: Sedov Phase, III

Temperature of the shell follows from assuming thermalization, i.e., $m_\mathrm{p}v^2/2 = NkT$ ($\Longrightarrow T \propto v^2$):

$$T \sim 6 \times 10^8\,\mathrm{K} \left(\frac{r}{2\,\mathrm{pc}}\right)^{-3} E_{51} n_\mathrm{H}^{-1} \tag{4.19}$$

$$\sim 10^6\,\mathrm{K}\, E_{51}^{2/5} n_\mathrm{H}^{-2/5} \left(\frac{t}{3 \times 10^4\,\mathrm{yr}}\right)^{-6/5} \tag{4.20}$$

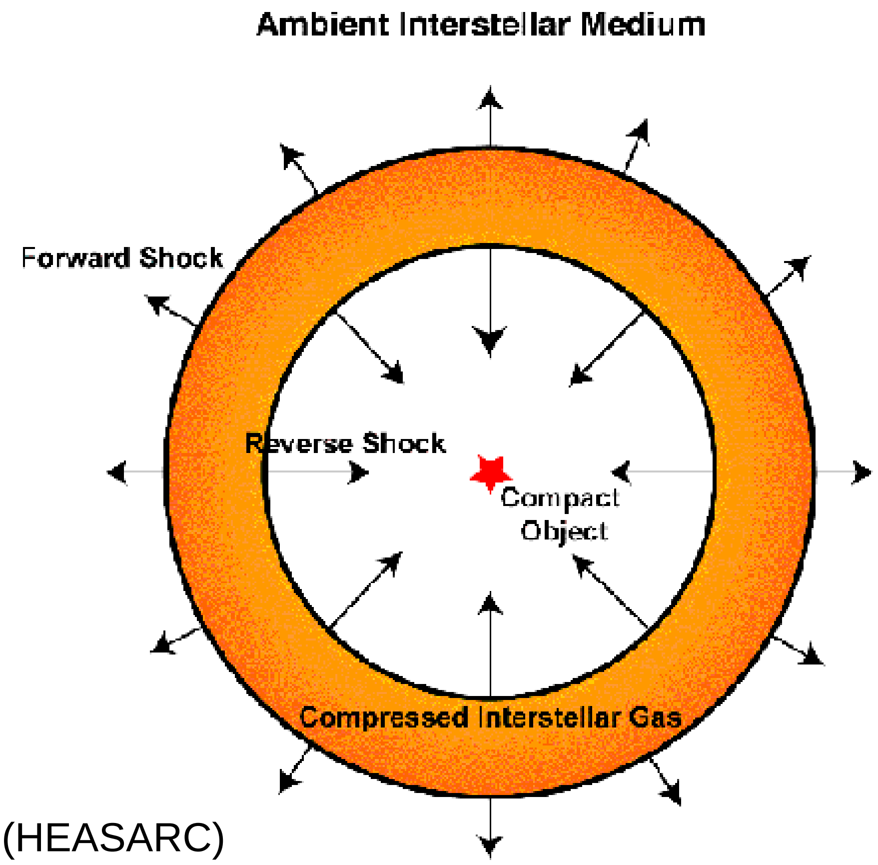
Mainly bremsstrahlung emission with $T \sim 10^6\,\mathrm{K} \Longrightarrow$ X-ray emission!

Measuring r, v, and T allows to determine age of supernova remnant from Sedov time scale.

$$t_\mathrm{sedov} \sim 3 \times 10^4 T_6^{-5/6} E_{51}^{1/3} n_\mathrm{H}^{-1/3}\,\mathrm{yr} \tag{4.21}$$

Example Cygnus Loop: $R \sim 20\,\mathrm{pc}$, $v \sim 115\,\mathrm{km\,s^{-1}} \Rightarrow t \sim 65000\,\mathrm{yr}$.

Phase II: Sedov Phase, IV



(HEASARC)

Nature of shock: “contact discontinuity”:

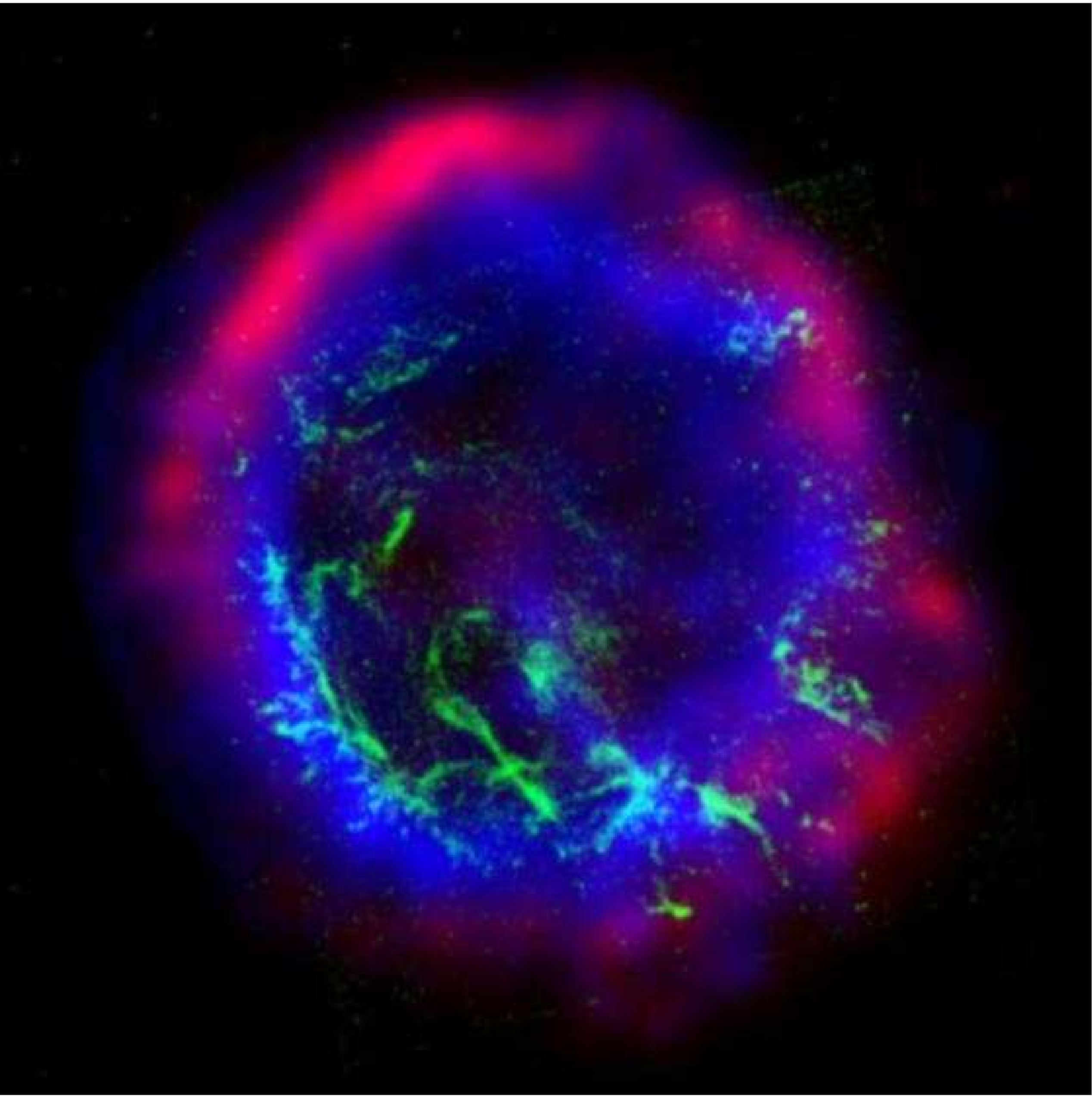
forward shock outside of which ISM has not yet reacted to SN blast wave

reverse shock where information from ISM has traveled backwards into SN ejecta

Between two shocks ($\delta r \sim 25\%$): hot material.

These remnants are called shell-like remnants.

Note: limb-brightening due to shell-structure (longer path through bright edge $\Longrightarrow$ ring)



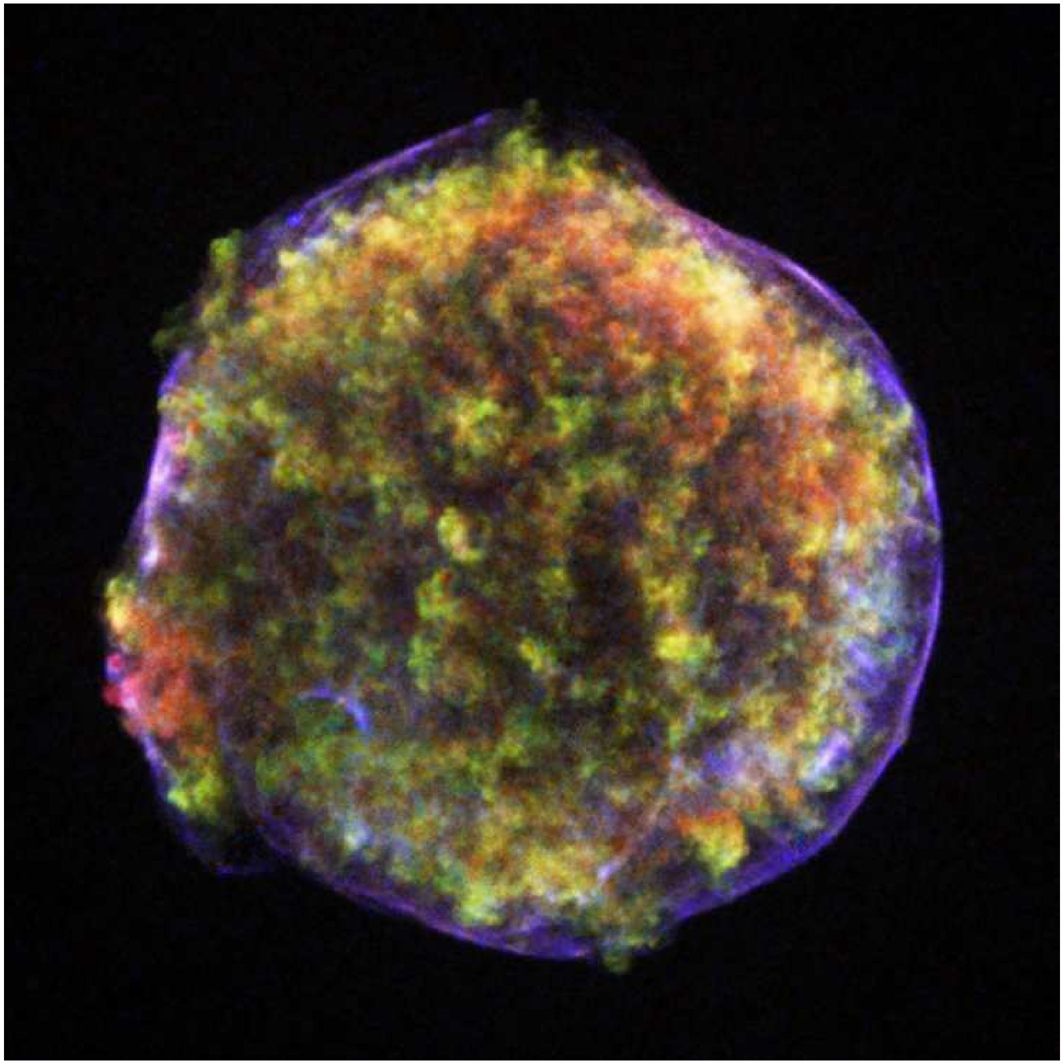
blue: X-rays (Chandra), red: radio (ATCA), green: optical (HST)

Best example for contact discontinuity: E0102−72.3:

forward shock bright in radio emission

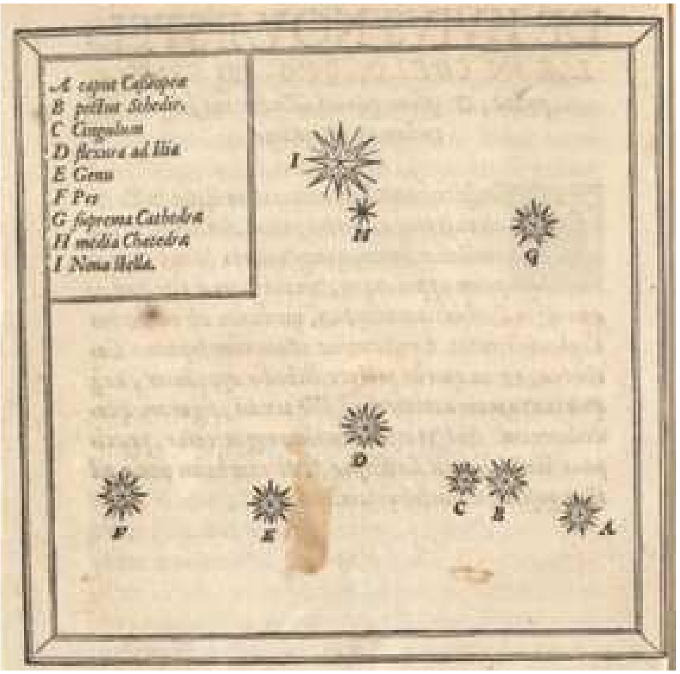
reverse shock bright in X-ray emission

Optical emission only visible as filaments.



red 0.95-1.26 keV, green 1.63-2.26 keV, blue 4.1-6.1 keV

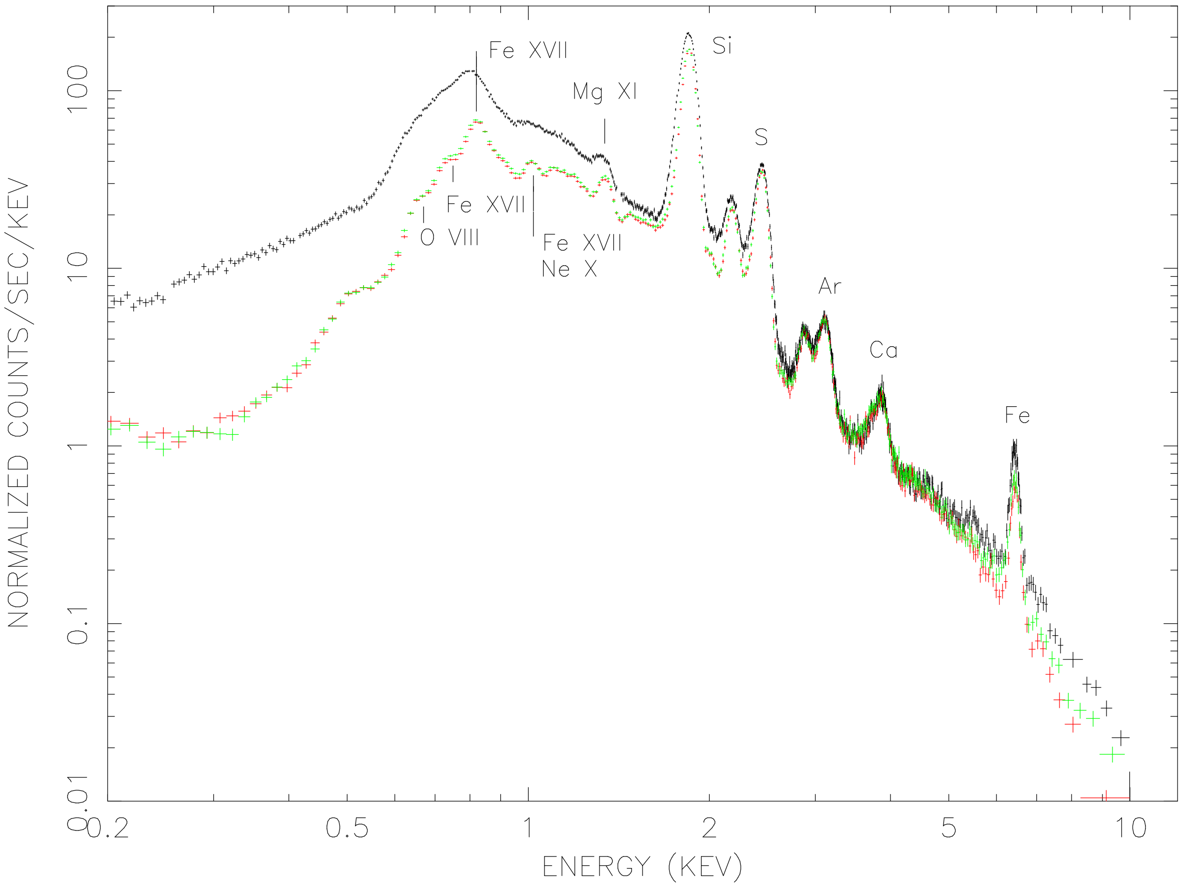
NASA/CXC/Rutgers/J.Warren & J.Hughes et al.



Brahe, De Stella Nova

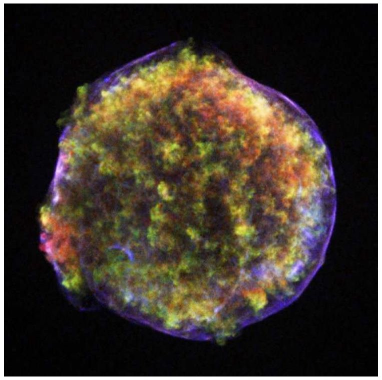
Tycho’s supernova remnant:
1572 November 11, first naked eye supernova for a long time, now very difficult to see in optical.

Phase II: Sedov Phase, VII



XMM EPIC spectrum of Tycho's SNR

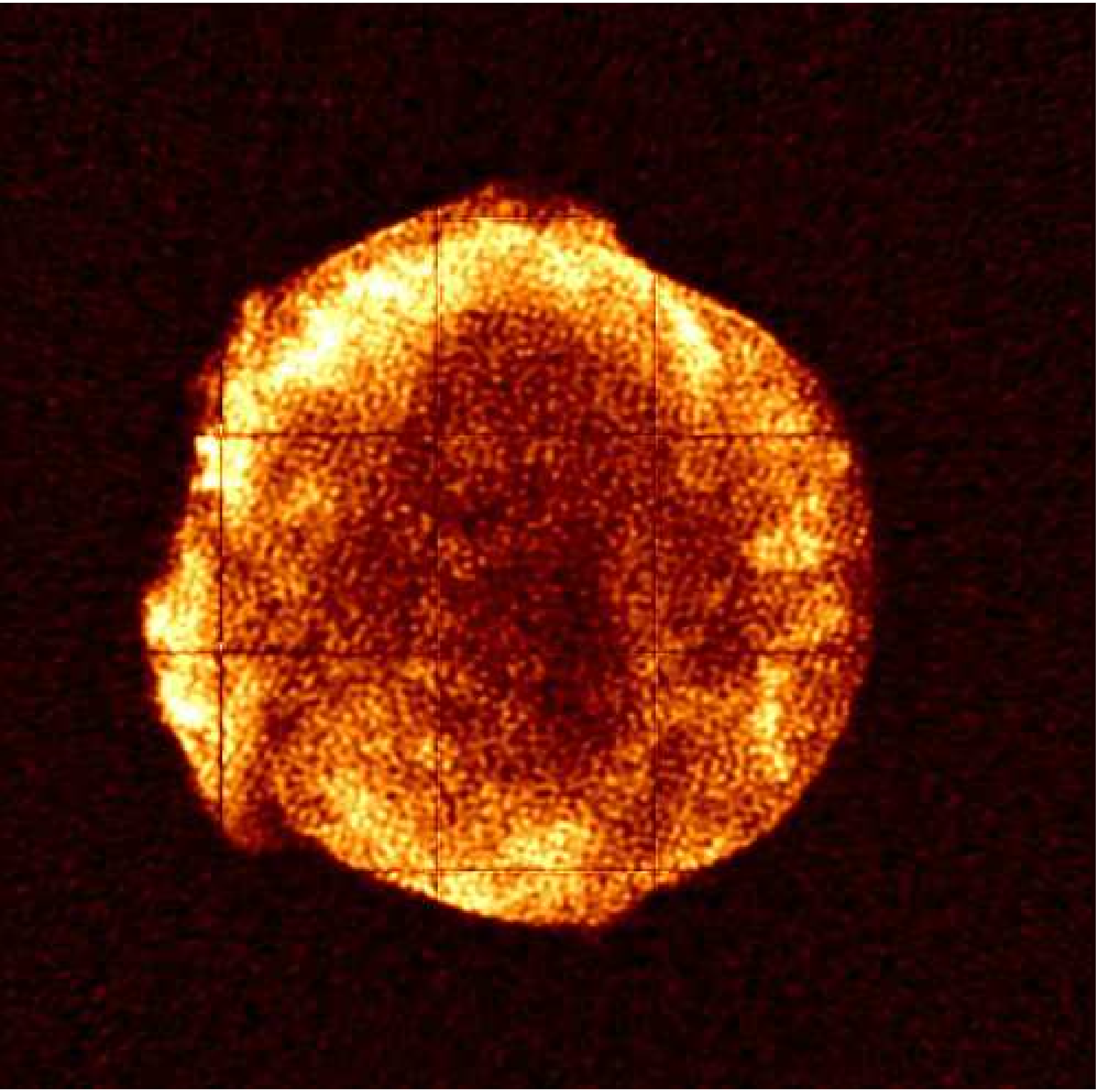
(Decourchelle et al., 2001, Fig. 1a)



Low-energy X-ray spectrum is line dominated $\Longrightarrow$ interior emission from shock excited plasma of stellar debris; outer rim from continuum emission.

Mass estimate from X-ray spectroscopy and radio: $1\ldots2\,M_\odot \Longrightarrow$ $\sim$1.4 $M_\odot$?!?
$\Longrightarrow$ remnant of type I explosion?

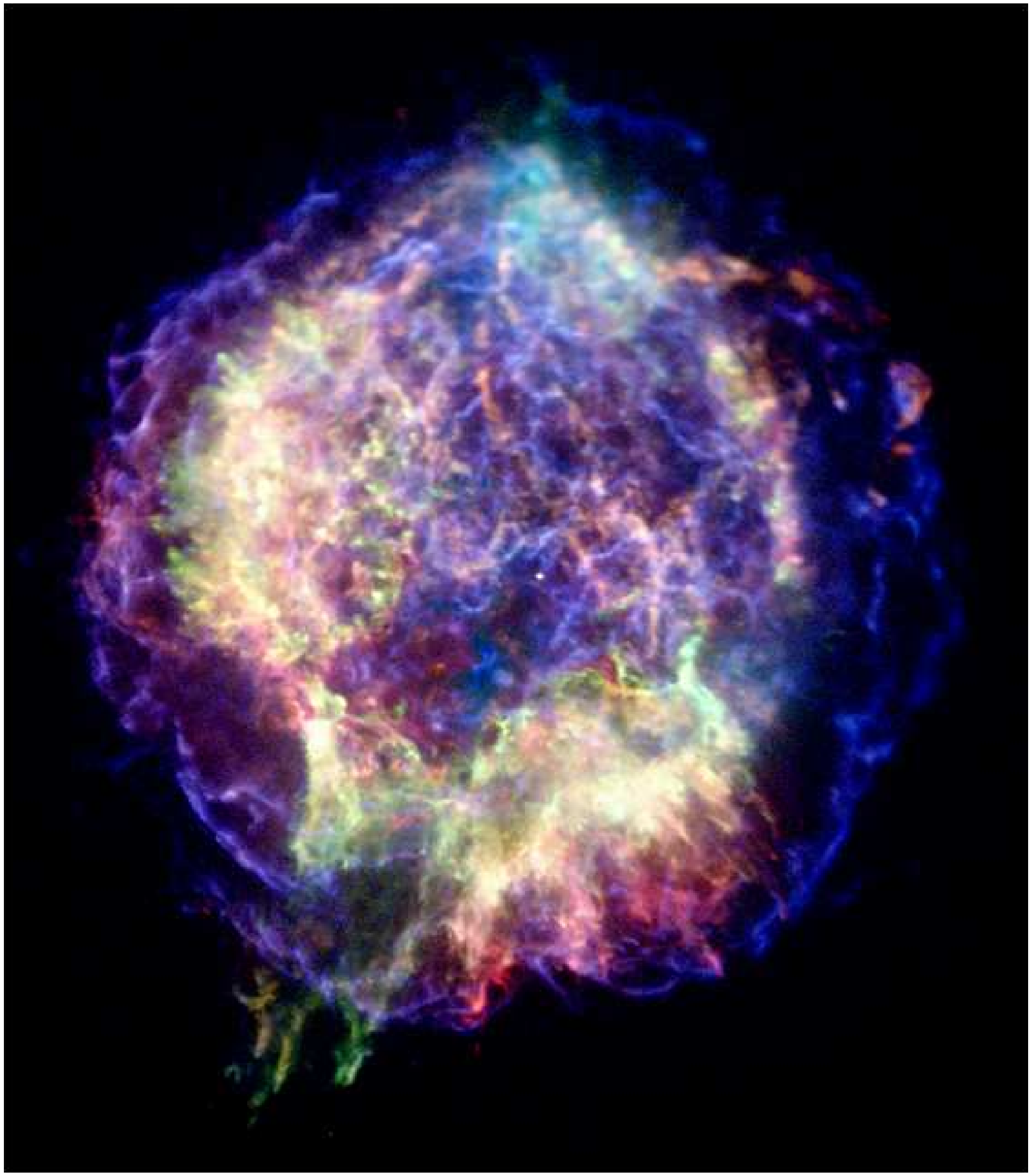
No central X-ray source!



Tycho's SNR, VLA, 0.33 MHz (diameter 7 pc; courtesy F. Lazio)

Tycho is also bright in the radio.

B-field frozen into plasma $\Longrightarrow$ shock produces high B-field regions $\Longrightarrow$ emission of synchrotron radiation



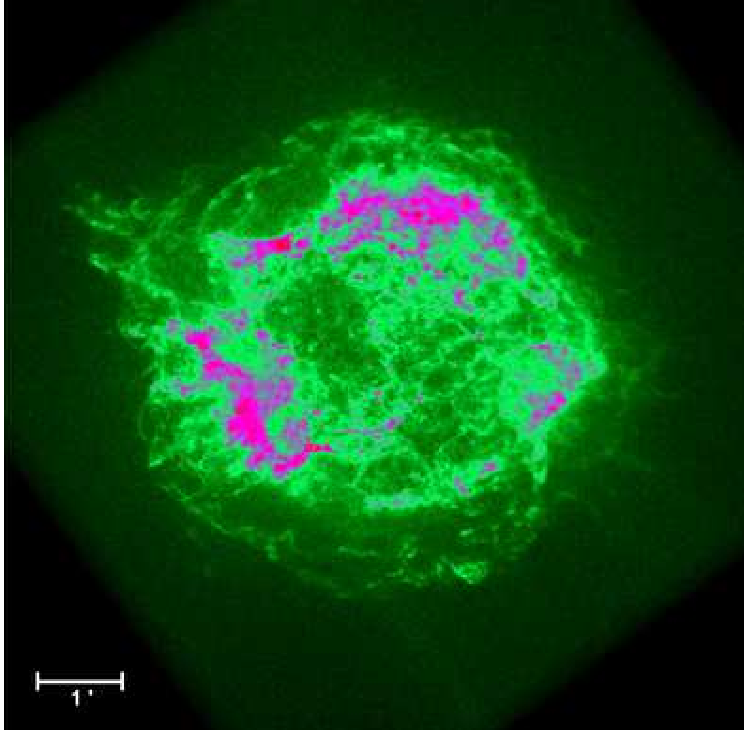
red 0.5-1.5 keV, green 1.5-2.5 keV, blue 4.0-6.0 keV

NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.

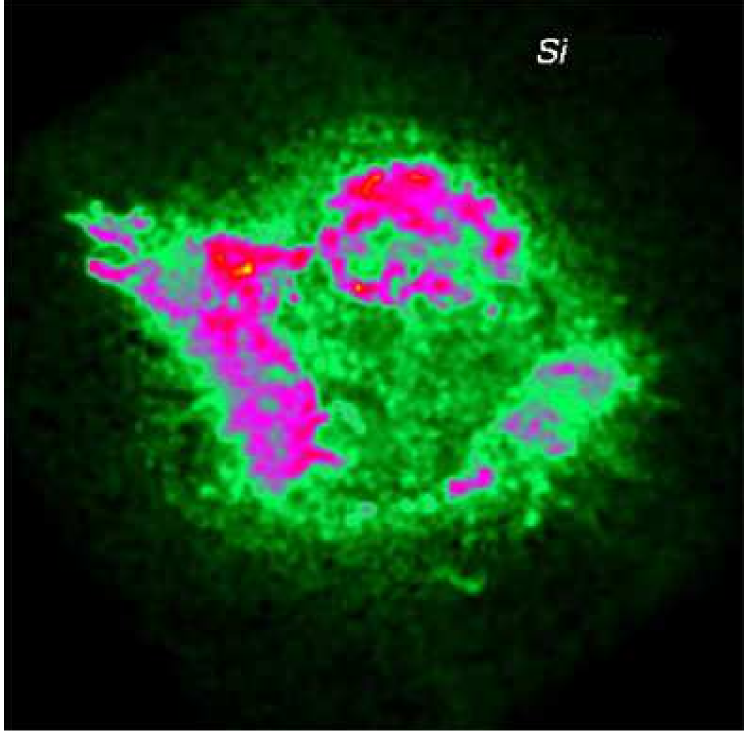
Cassiopeia A: Young remnant ($\sim$1670), no optical explosion observed
Mass of ejected material 10–15 $M_\odot \Longrightarrow$ possibly type II?

Type II are also fainter, explaining why explosion has not been reported.

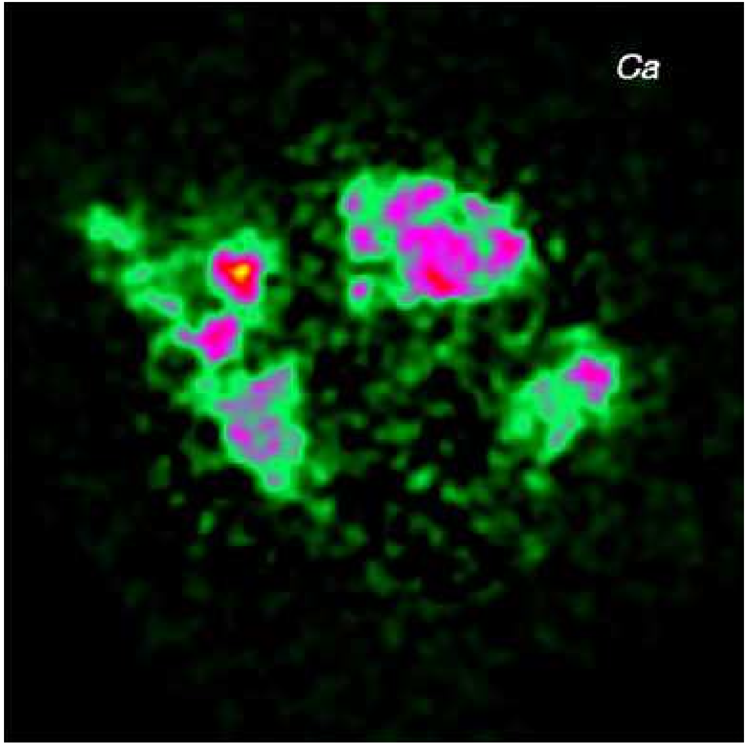
2000: Chandra discovers point-source in center $\Longrightarrow$ neutron star $\Longrightarrow$ confirming type II assumption!



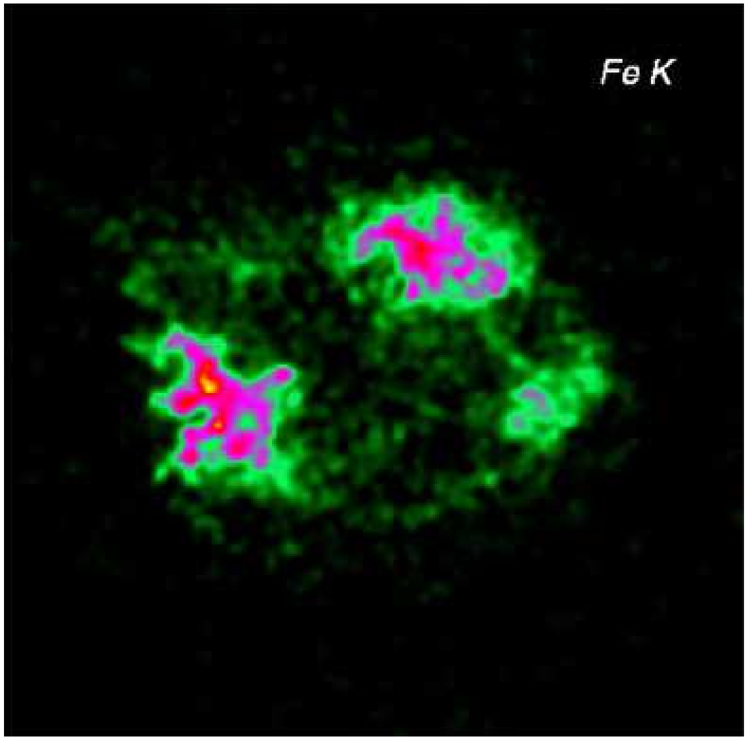
broad band



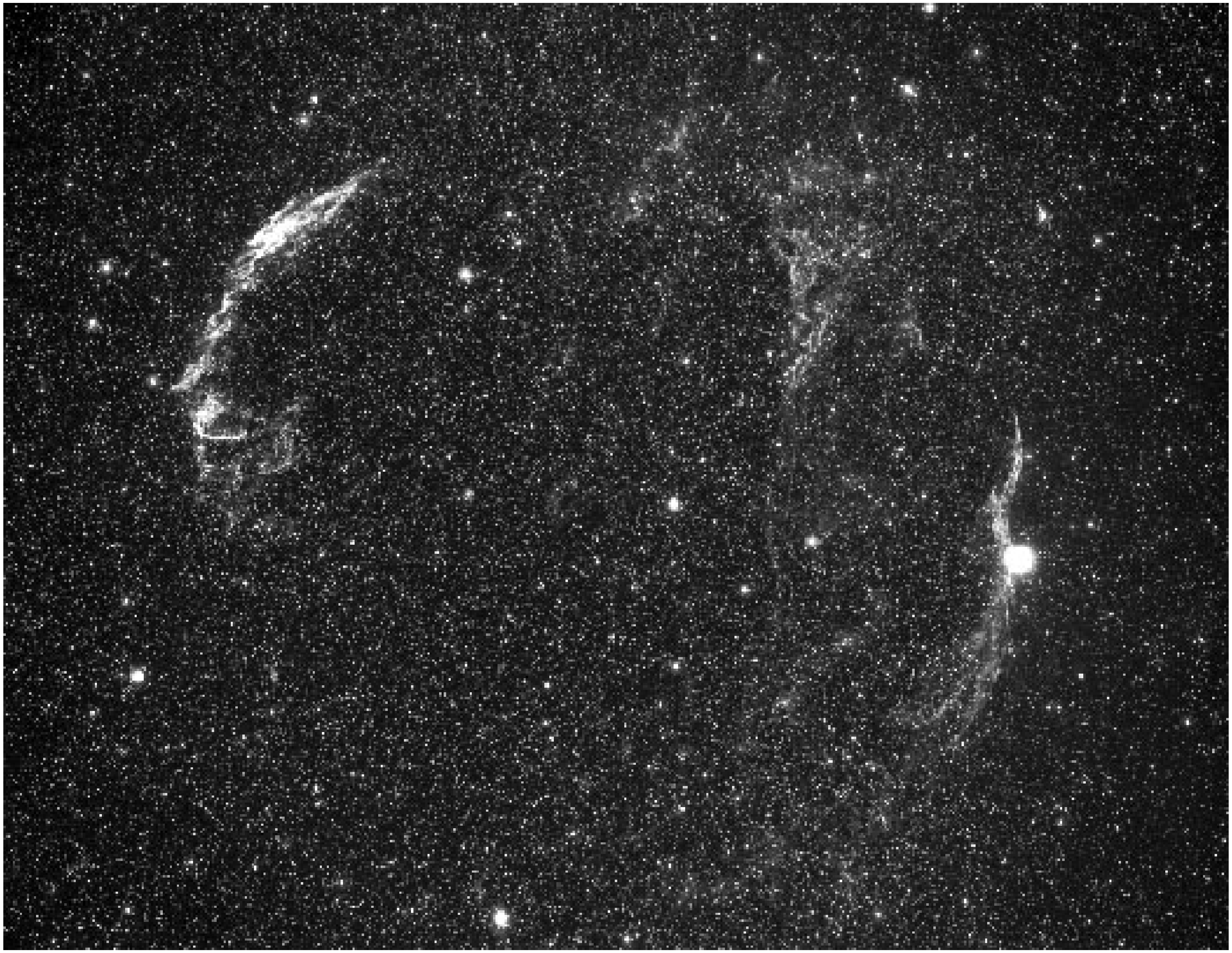
Silicon



Calcium



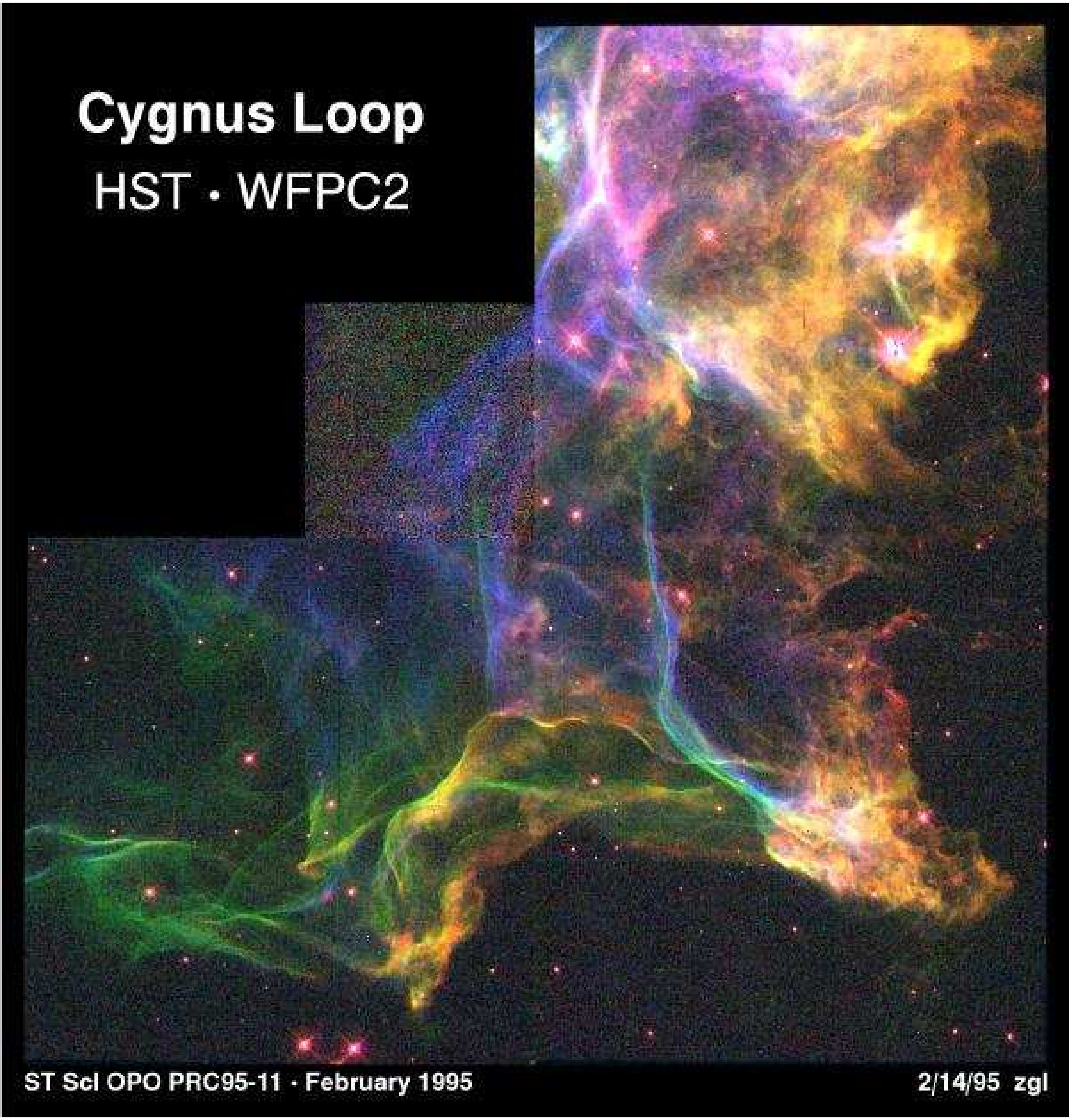
Iron



Cygnus Loop (diameter $\sim 2.5^\circ$; optical; Wallis/Provin)

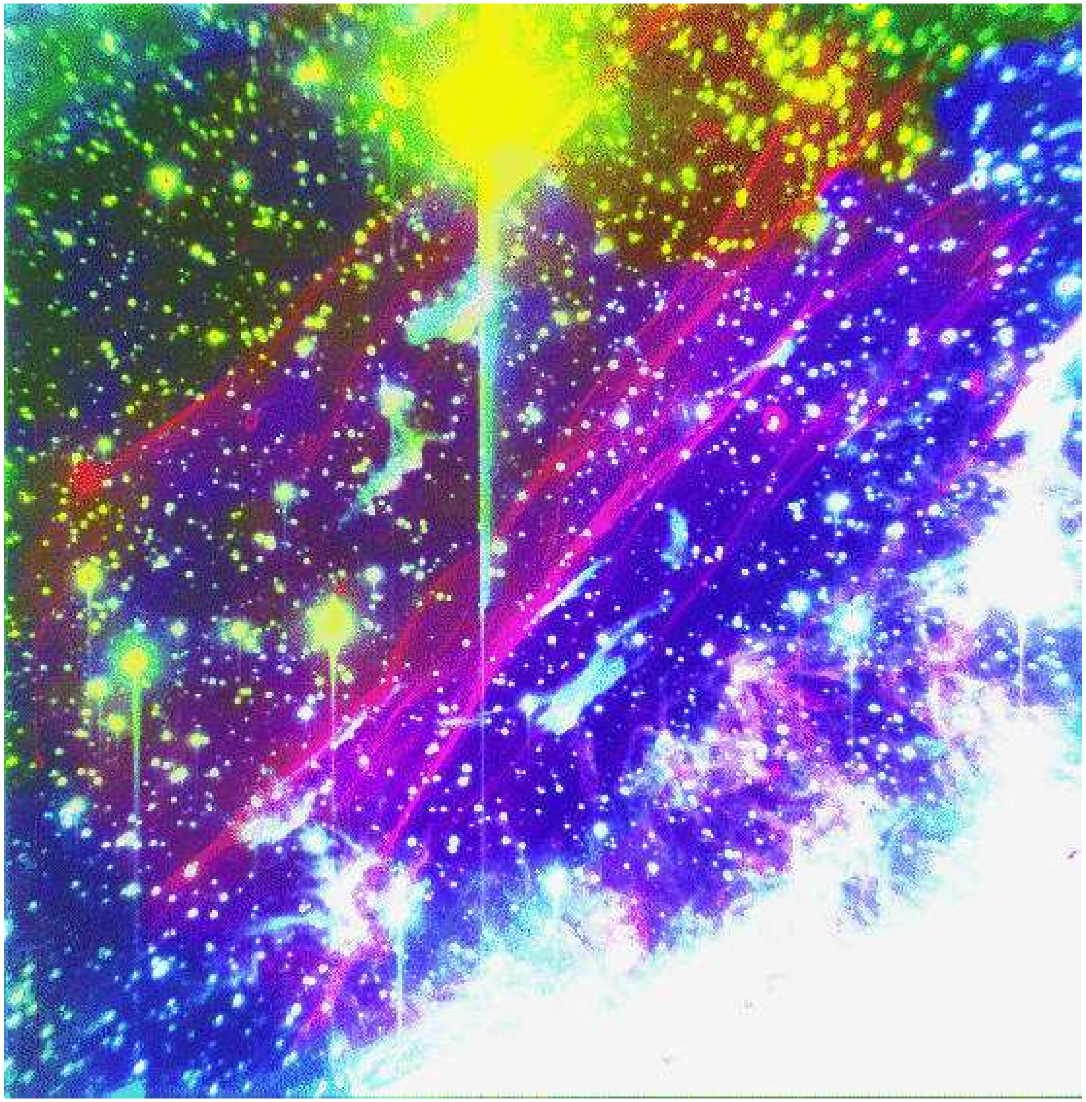
Cygnus loop/Veil nebula: end of Sedov phase ($r \sim 20\,\mathrm{pc}$, $v \sim 115\,\mathrm{km\,s^{-1}}$, estimated age $t \sim 20000\,\mathrm{yr}$)

Interior ($<18\,\mathrm{pc}$) empty of material (swept free by progenitor wind).



Light shocked ISM gas on top of dense gas; deceleration of gas as effective gravity $\Longrightarrow$
Rayleigh Taylor instability!

Phase II: Sedov Phase, XIII



optical/X-ray composite of Cygnus loop (Hester et al., 1994)
blue: X-ray (ROSAT); red: Hα; Warwick-Green: O III.

Optical filaments due to compressed interstellar clouds.

Phase III: Snow-plough Phase, I

End of Sedov phase when energy cannot be conserved. Shock continues with its intrinsic momentum, “ploughing” through ISM $\Longrightarrow$ snowplough phase or radiative phase.

Major source of energy loss: Radiative cooling. Here: collisional excitation and radiative recombination $\Longrightarrow$ coronal plasma.

During snowplough phase, strong optical line emission, mainly from filaments in rim of SNR with temperature $T \sim 10^4$ K; only weak X-ray emission

Cooling function Λ:

$$n_{\mathrm{H}}^2 \Lambda(T) \approx 10^{-22}\,\mathrm{erg\,cm^3\,s^{-1}}\, n_{\mathrm{H}}^2 T_6^{-1/2} \tag{4.22}$$

cooling timescale:

$$t_{\mathrm{cool}} \approx \frac{nkT}{n^2\Lambda(T)} \sim 4 \times 10^4\,\mathrm{yr}\,\frac{T_6^{3/2}}{n_{\mathrm{H}}} \tag{4.23}$$

But for the Sedov phase:

$$t_{\mathrm{Sedov}} = 3 \times 10^4\,\mathrm{yr}\, T_6^{-5/6} E_{51}^{1/3} n_{\mathrm{H}}^{-1/3} \tag{4.24}$$

Eq. (4.26) follows from solving Eq. (4.20) for t

Phase III: Snow-plough Phase, II

Cooling timescale:

$$t_{\text{cool}} \approx \frac{nkT}{n^2\Lambda(T)} \sim 4 \times 10^4\,\text{yr}\,\frac{T_6^{3/2}}{n_{\text{H}}} \tag{4.25}$$

Sedov time scale:

$$t_{\text{Sedov}} = 3 \times 10^4\,\text{yr}\,T_6^{-5/6}E_{51}^{1/3}n_{\text{H}}^{-1/3} \tag{4.26}$$

Snowplough starts when $t_{\text{cool}} < t_{\text{Sedov}}$,

$$T_6 < E^{1/7}n_{\text{H}}^{2/7} \tag{4.27}$$

Expressing this in terms of the velocity:

$$v \propto \sqrt{T} < 200\,\text{km}\,\text{s}^{-1}\,(E_{51}n_{\text{H}}^2)^{1/14} \tag{4.28}$$

almost independent from E and n.

Phase III: Snow-plough Phase, III

Evolution during snowplough phase dominated by momentum conservation:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\left(\frac{4\pi}{3}\right)\rho r^3 \dot{r}\right) = 0 \tag{4.29}$$

Remember: most mass is already in the shell!

Thus, if snowplough starts at radius r_0 and velocity v_0,

$$\frac{4\pi}{3}\rho r^3 \dot{r} = \frac{4\pi}{3}\rho r_0^3 v_0 \quad\Longleftrightarrow\quad r^3\dot{r} = r_0^3 v_0 \tag{4.30}$$

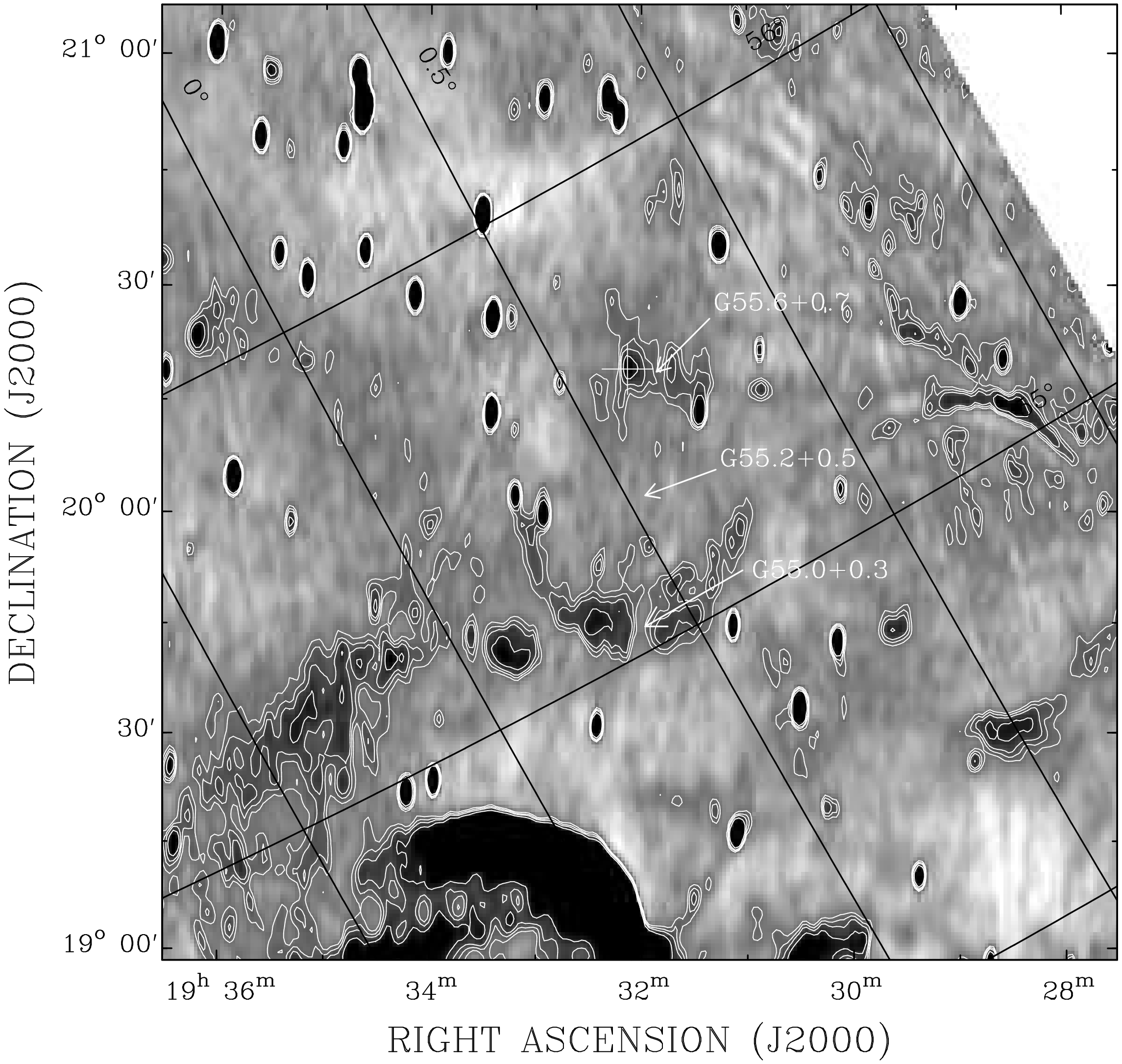
Separation of variables gives

$$r(t) = r_0\left(1 + \frac{4v_0}{r_0}(t - t_0)\right)^{1/4} \propto t^{1/4} \tag{4.31}$$

with $v_0 \sim 200\,\mathrm{km\,s^{-1}}$,

$$v \sim 200\,\mathrm{km\,s^{-1}}\left(\frac{t}{3\times 10^4\,\mathrm{yr}}\right)^{-3/4} \tag{4.32}$$

Phase IV: Merging Phase



Radio map of G55.0+0.3 (1.4 GHz, age $\sim 10^6$ years; Matthews et al., 1998)

Once speed drops to sound velocity of ISM,

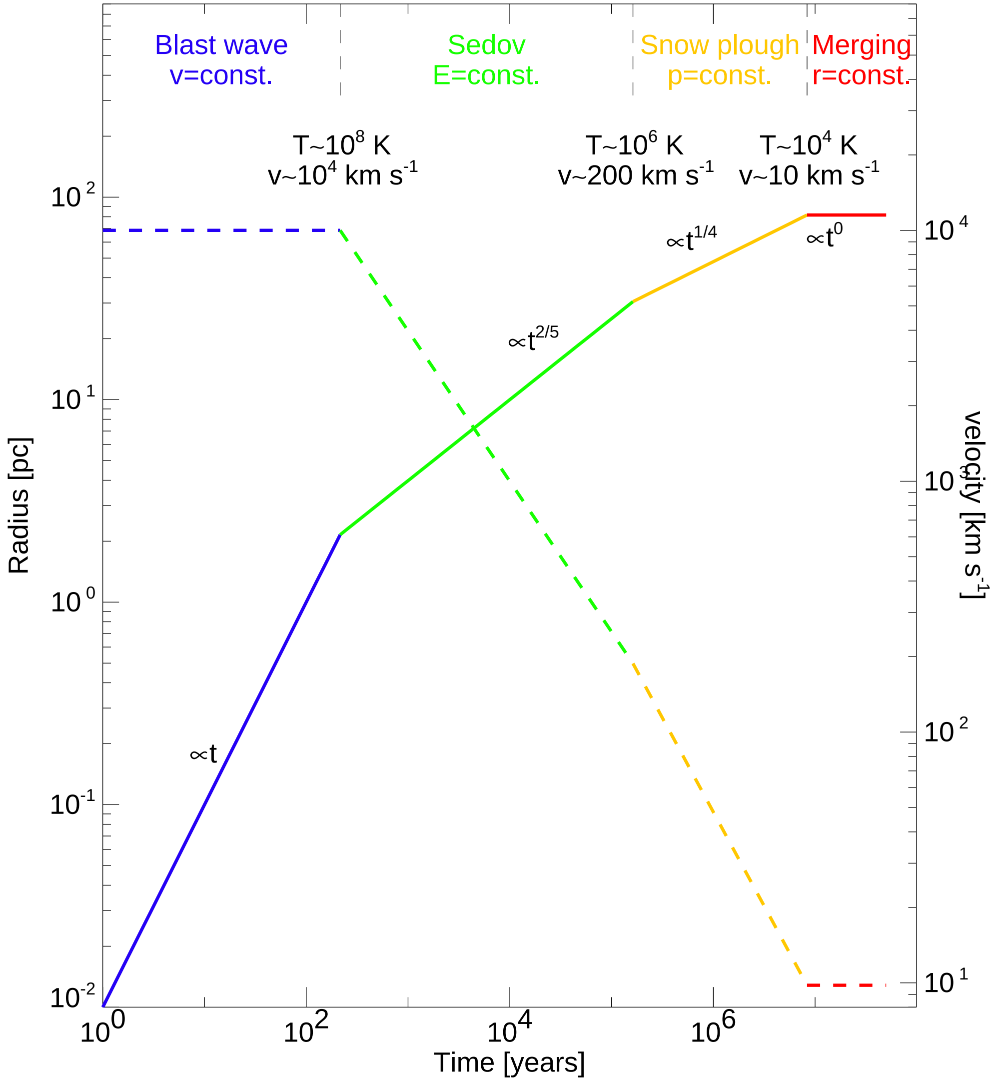
$$c_{s,\mathrm{ISM}} \sim 10\ldots100\,\mathrm{km\,s^{-1}} \qquad (4.33)$$

supernova remnant starts to dissolve

$\Longrightarrow$ Merging Phase

Elements produced during supernova mix into ISM (“chemical enrichment”).

Summary



after Padmanabhan (2002, Fig. 4.6)

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