Supernova Remnants

Supernova Energy Sources

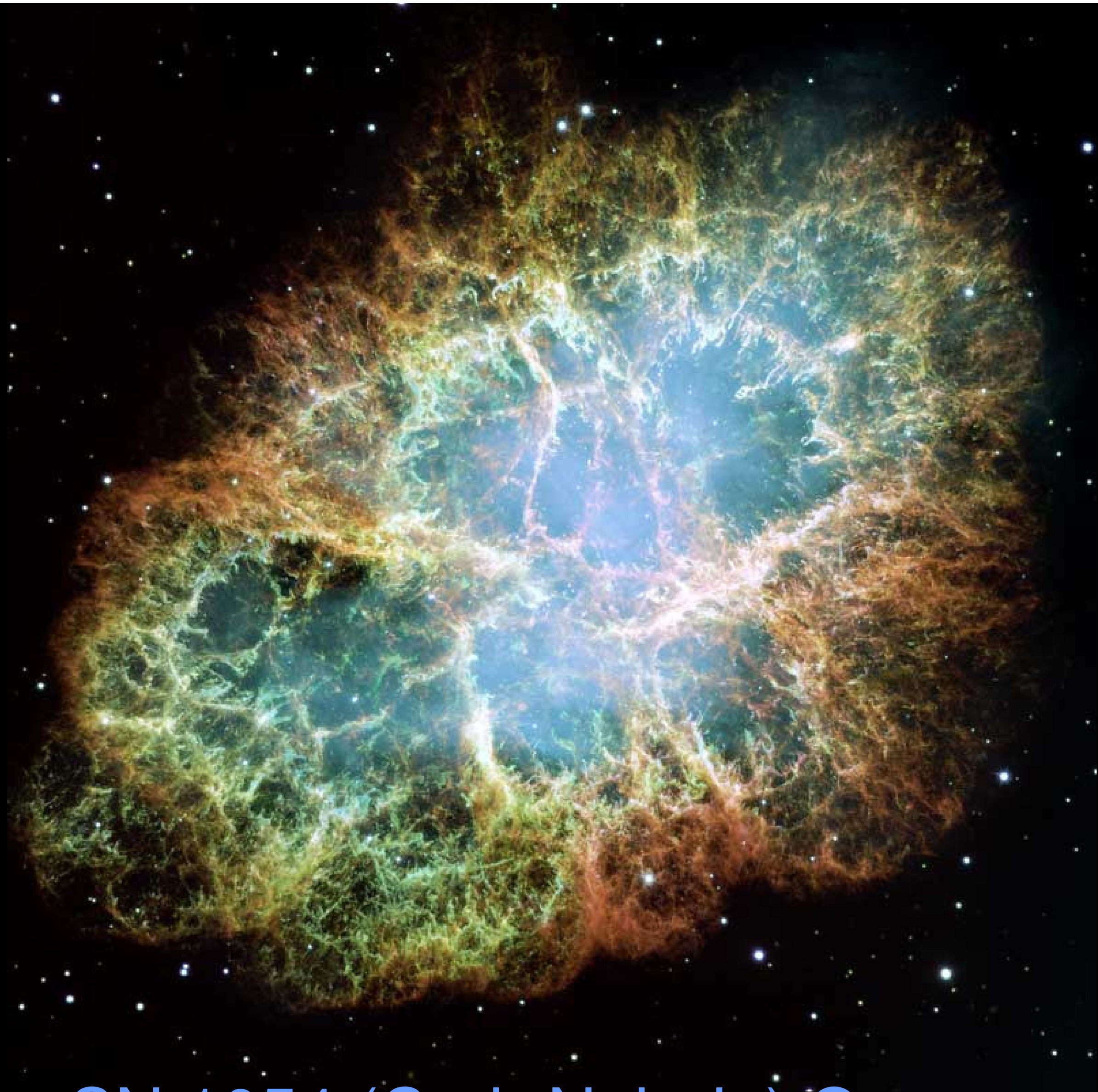
- Core collapse:
  $E \sim GM^2/R \sim 0.1\ Mc^2 \sim 10^{53}$ ergs
  Neutrinos: t ~ 10s
- Radioactivity:
  $0.07\ M_\odot [^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe] \sim 10^{49}$ ergs.
  Light: t ~ 3 months
- Kinetic energy:
  $\sim 10\ M_\odot$, $V_{expansion} \sim 3000$ km/s $\sim 10^{51}$ ergs
  ~ 1% core collapse.
  X-rays: t ~ centuries.

HISTORICAL SUPERNOVAE

Date (AD)	Type	Magnitude at Max	Discovered by	Remnant
1006	I	-10	Chinese/Arabs	SN1006
1054	II	-5	China/Japan	Crab Nebula
1181	II	-1	China/Japan	3C58
1572	I	-4	Tycho Brahe	Tycho
1604	I	-3	Kepler	Kepler
~ 1680	II	5 ?	Flamsteed	Cas A
1987	II	+2.9	Ian Shelton	SN1987A

SN 1006 (Ali Ibn Ridwan)

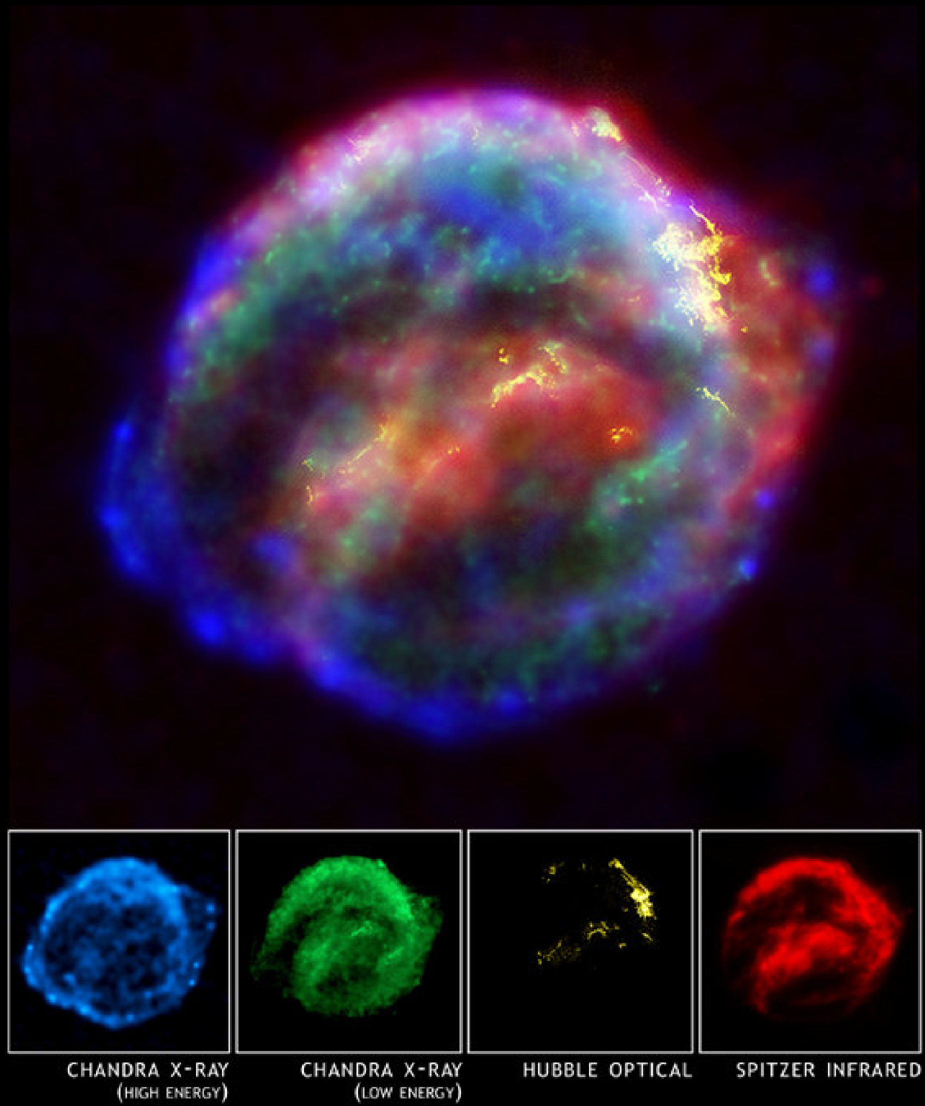
R = 25 l.y., V = 6,500 km s^{-1}



SN 1054 (Crab Nebula) O

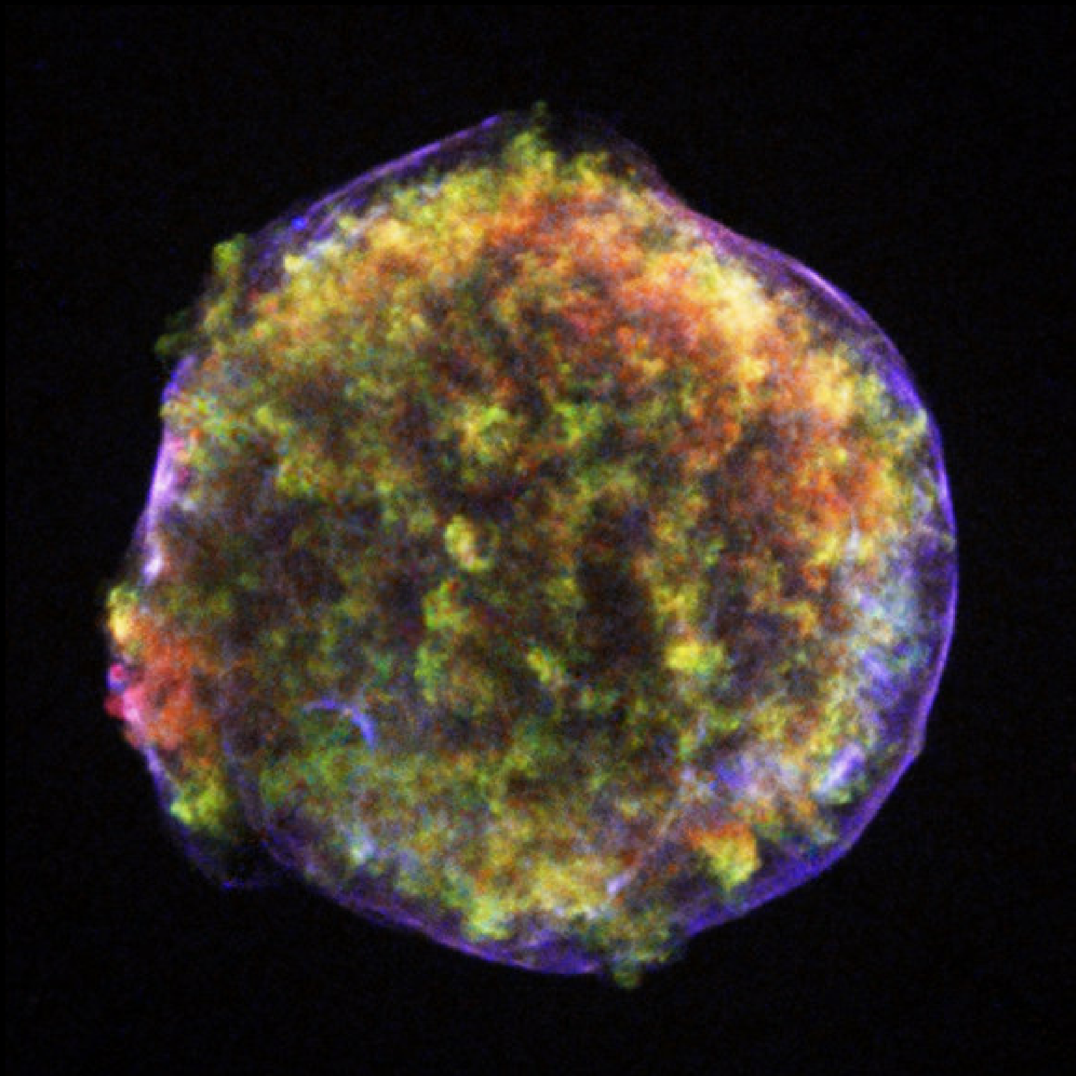
R ~ 5 l.y., V ~ 1,800 km s^{-1}

SN1181 (3C58) X
R ~ 6 l.y.

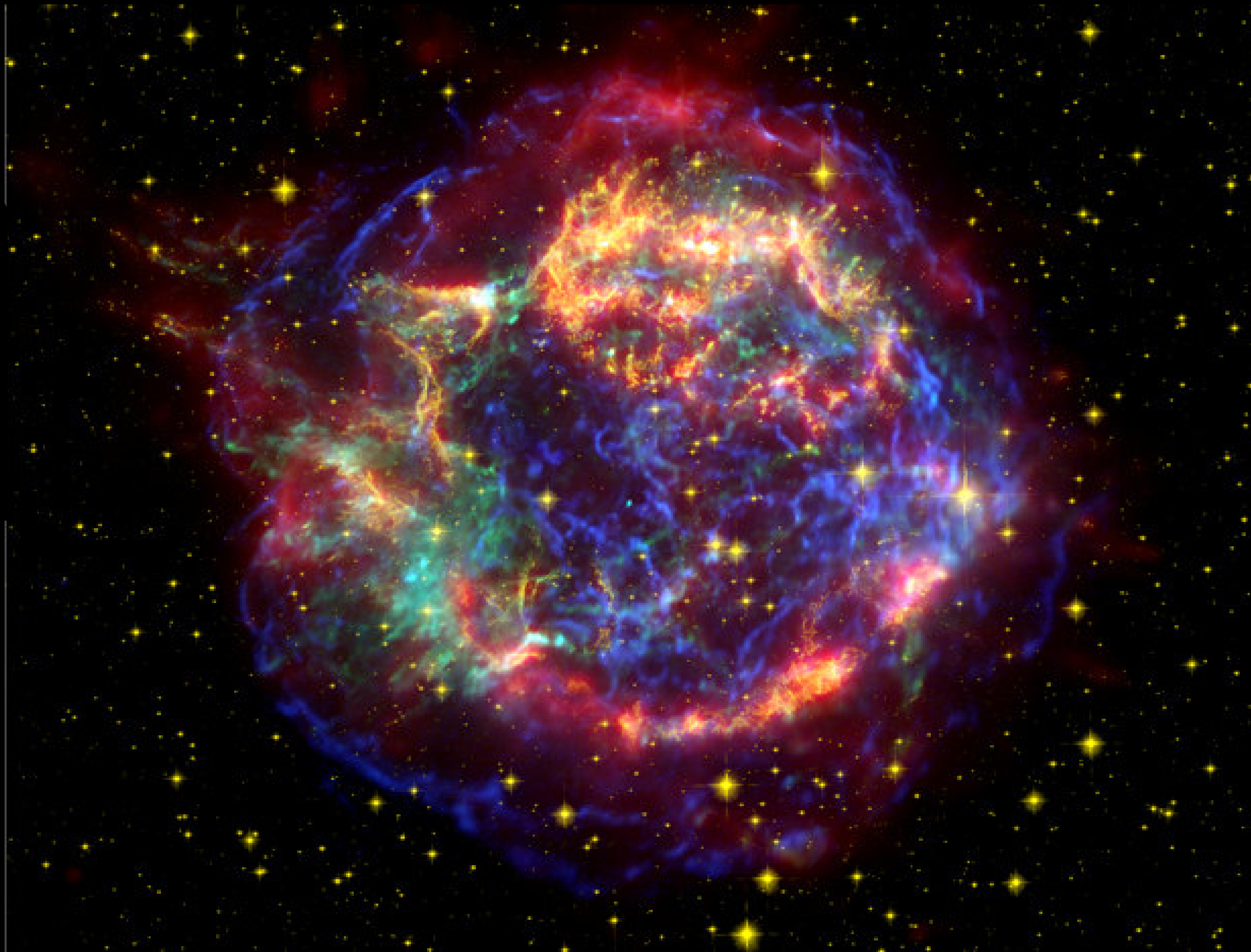


SN 1604 (Kepler)

R ~ 7 l.y., V = 2000 km s^{-1}



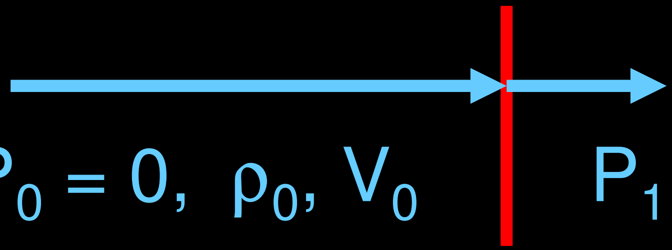
SN 1572 (Tycho), X-ray,
R ~ 5 ly, V ~ 9,000 km s^{-1}



SN1680 (Cas A) X, IR, O

R ~ 5 l.y. V = 6,000 km s^{-1}

Physics of Shocks



$P_0 = 0, \ \rho_0, V_0$ $\qquad$ P_1, ρ_1, V_1

Cold upstream flow $\quad$ Shock front $\quad$ Hot downstream flow

Mass: $\rho_0 V_0 = \rho_1 V_1$

Momentum: $P_0 + \rho_0 V_0^2 = P_1 + \rho_1 V_1^2$

Energy: $[\tfrac{1}{2} \rho_0 V_0^2] V_0 = [U_1 + P_1 + \tfrac{1}{2}\rho_1 V_1^2] V_1; \quad U_1 = 3P_1/2$

⇨ $V_1 = V_0/4; \ \rho_1 = 4\rho_0;$

⇨ $kT_1 = (3/16) m V_0^2 = 1.2 \text{ keV } [V_0/1000 \text{ km/s}]^2$

The Sedov Solution

-- the earliest and simplest theory for a SNR

Assumptions:

- Energy, E_0, is conserved
- Mass of supernova debris is much less than swept-up mass
- Interstellar gas has uniform density ρ_0

Want to know $R(E_0,\rho_0,t)$

Dimensional analysis: $E_0 \sim MV^2$; $V \sim R/t$; $M \sim \rho_0 R^3$

⇨ $E_0 \sim \rho_0 R^3 (R/t)^2$ ⇨ $R \sim [E_0 t^2/\rho_0]^{1/5}$

Exact solution: $R = 1.15\ [E_0 t^2/\rho_0]^{1/5}$

$R = 6.6$ l.y. $[t/(100\ \mathrm{yr})]^{2/5}\ [E_0/(10^{51}\ \mathrm{ergs})]^{1/5}\ [n_0\ (\mathrm{cm}^{-3})]^{-1/5}$

$V = 2/5(R/t) = 8{,}000\ \mathrm{km\ s}^{-1}\ [t/(100\ \mathrm{yr})]^{-3/5}[E_0/(10^{51}\ \mathrm{ergs})]^{1/5}\ [n_0\ (\mathrm{cm}^{-3})]^{-1/5}$

$kT = 75\ \mathrm{keV}\ [t/(100\ \mathrm{yr})]^{-6/5}\ [E_0/(10^{51}\ \mathrm{ergs})]^{2/5}\ [n_0\ (\mathrm{cm}^{-3})]^{-2/5}$

Too hot for observed SNR: kT will not reach 2 keV until t = 2000 yr

Problems with Sedov Model

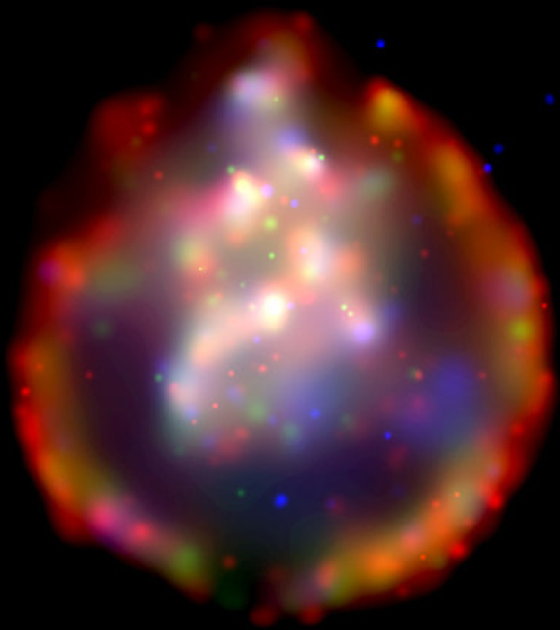
Physics is good, assumptions are bad:

1. Energy is conserved (neglect radiative losses) – probably OK for most young (< 1000 yr) SNRs
2. Neglect mass of debris – no good for R < 20 l.y.
3. Interstellar density is uniform

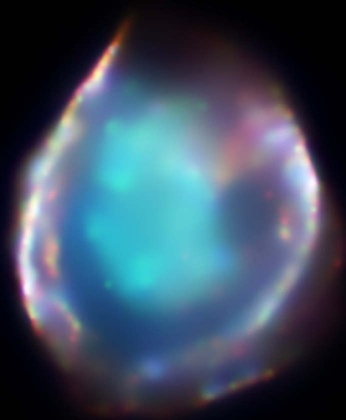
   – maybe OK for thermonuclear SN

   –not good for core collapse SN: massive progenitor stars profoundly modify circumstellar environments

Two large SNRs in LMC where Sedov model might be OK

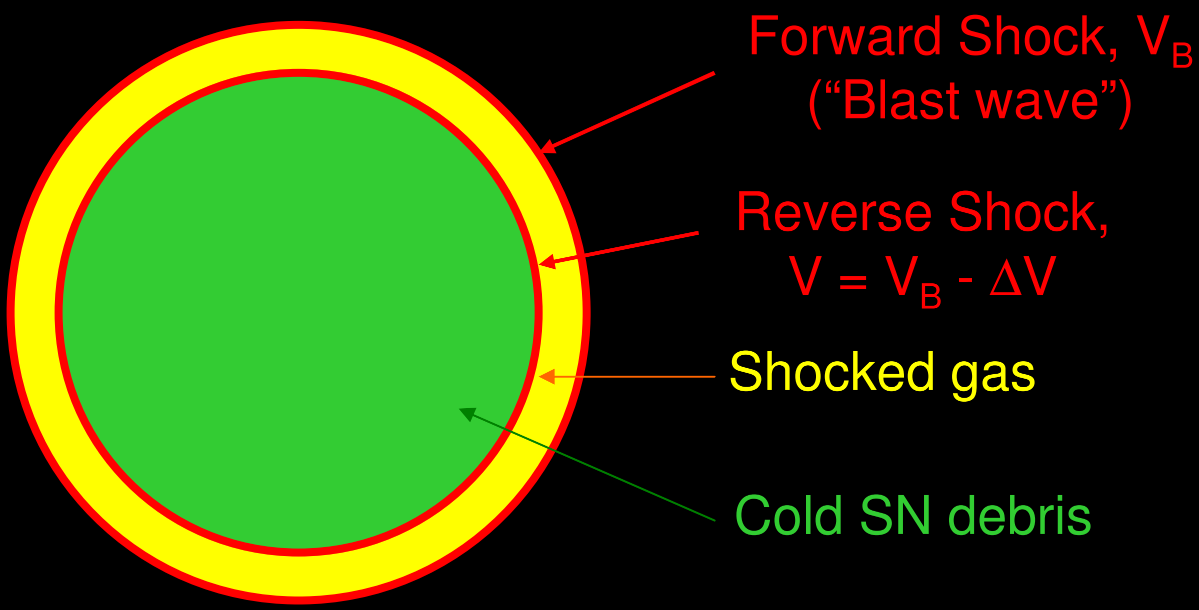


SNR 0103-72.06: X-ray
O, Ne core
R = 80 LY, t = 10,000 yr



DEM 71: X-ray:
Fe, Si core, R ~ 35 l.y.

Emission from SN debris: Reverse Shock



Uniform debris model: $\rho_d = M_d/[(4/3)\pi R^3] = (3M_d/4\pi)[Vt]^{-3}$
$P = \rho_0 V^2 = \rho_d \Delta V^2 \Rightarrow \Delta V \sim V_B[t/t_1]^{3/2}$; t_1: $\rho_0 = \rho_d(t_1)$, or
$R_{SNR} \sim 14$ l.y. $[M/10M_{SUN}]^{1/3} n_0^{-1/3}$

When $t = t_1$, swept-up interstellar mass = debris mass, reverse shock moves inward rapidly
Generally, X-rays dominated by shocked SN debris

Problems with Sedov Model

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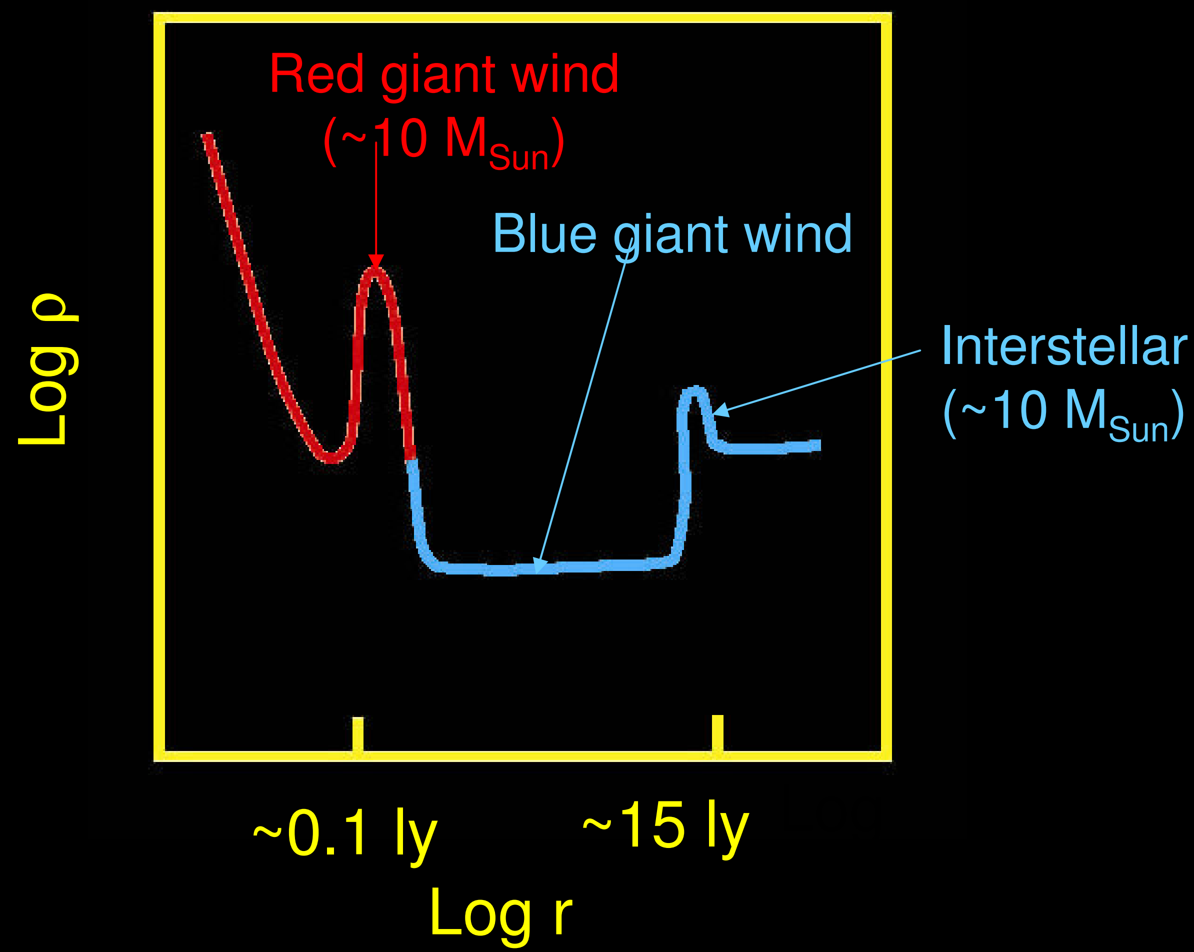
2. Neglect mass of debris – no good for R < 20 l.y.
3. Interstellar density is uniform

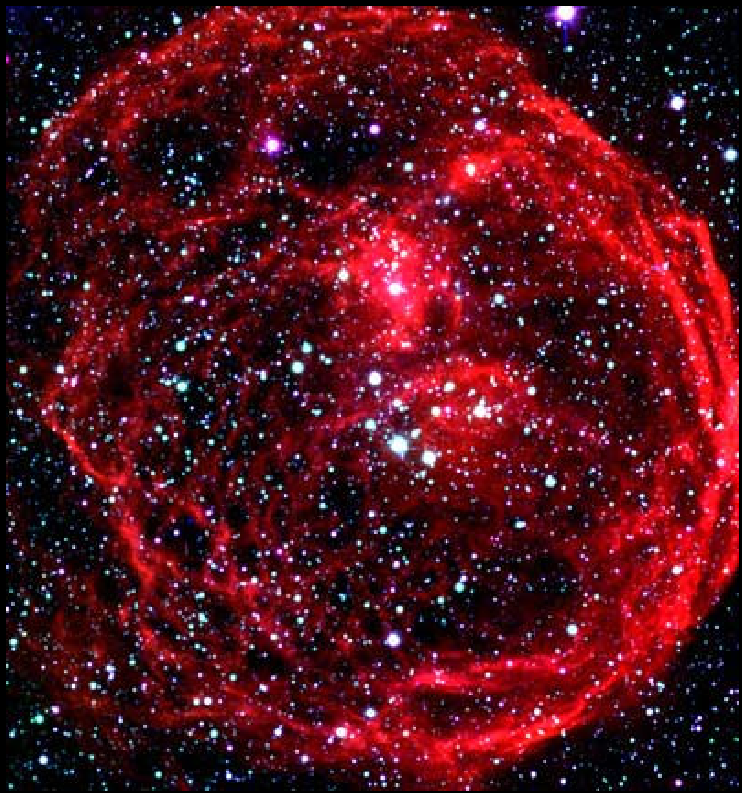
   – maybe OK for thermonuclear SN,

   – but not good for core collapse SN: massive progenitor stars profoundly modify circumstellar environments

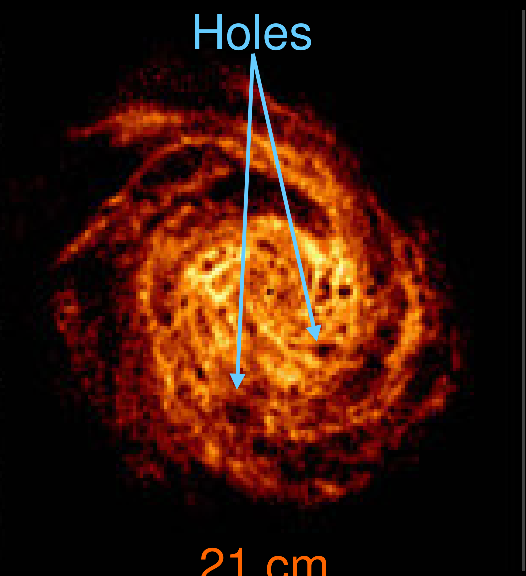
Massive progenitors and circumstellar gas



Superbubble: caused by multiple supernovae from a star cluster

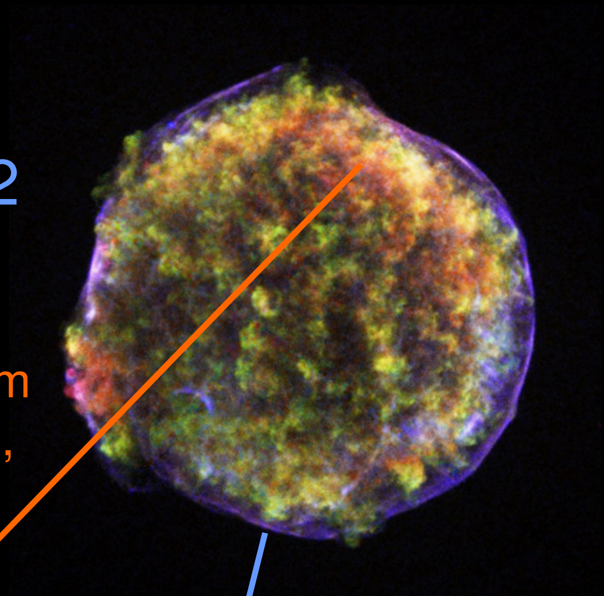


Henize 70: R = 150 l.y.,
V ~ 40 km s^{-1} ⇨ t ~ 10^6 yr.



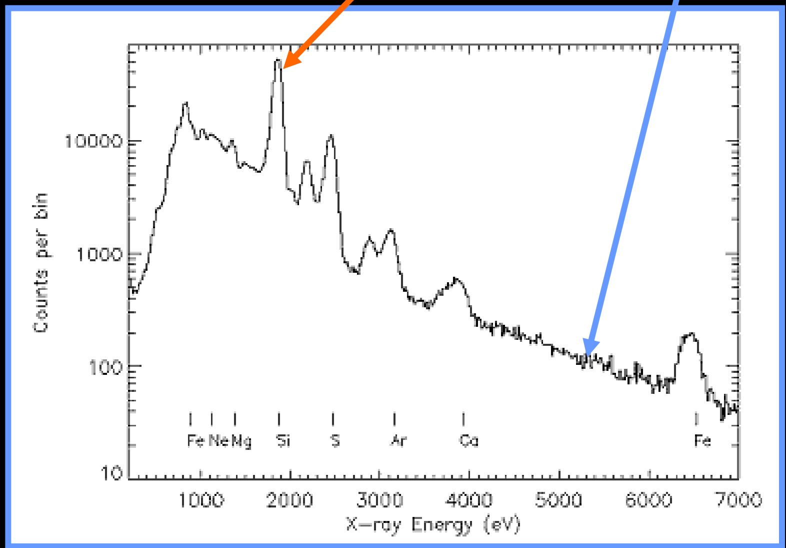
Radiation from SNRs

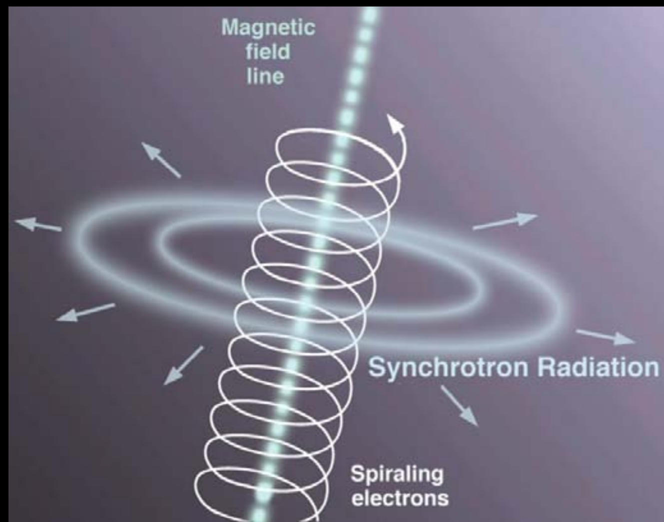
SN1572



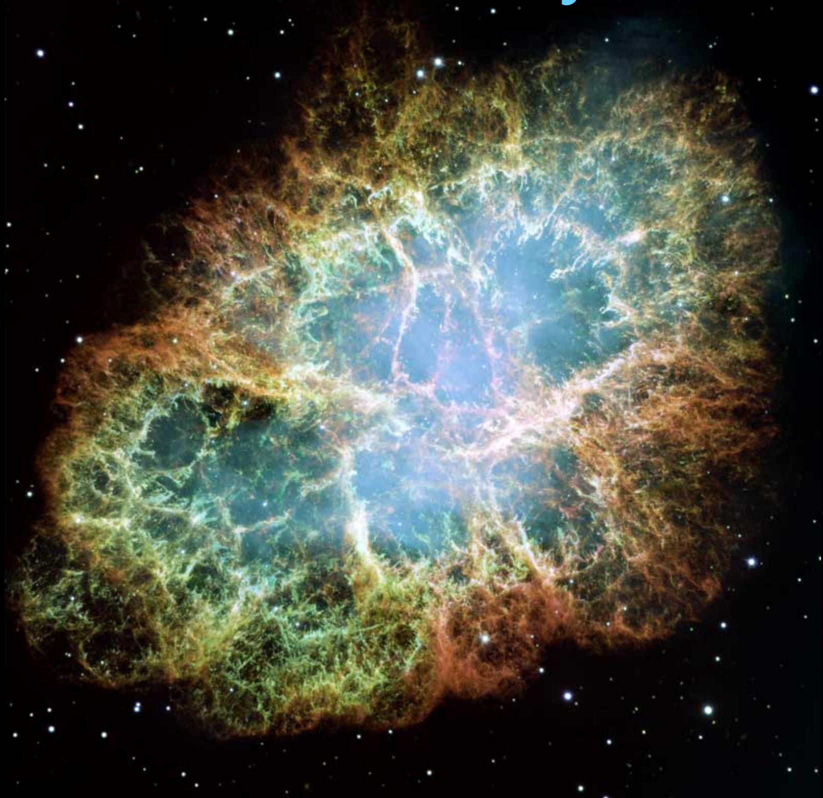
X-ray line emission from shock heated gas e.g.,
$e + Si^{+12} \rightarrow e + Si^{+12*}$

Synchrotron emission from Relativistic electrons accelerated by repeated crossing of reverse shock





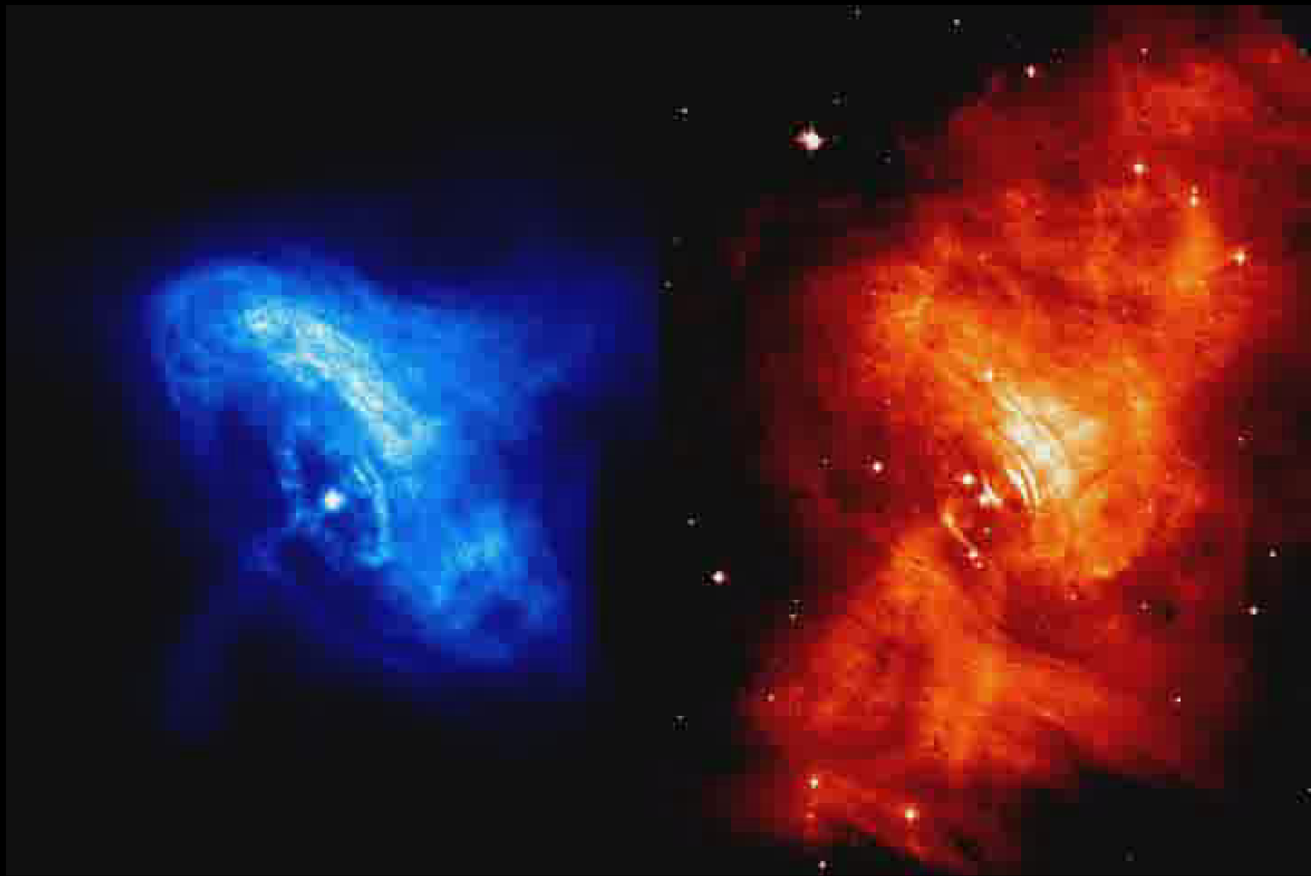
Crab Nebula: relativistic electrons accelerated by neutron star magnetic field



Optical
(H, O, Synch)

X-ray, Optical, Radio

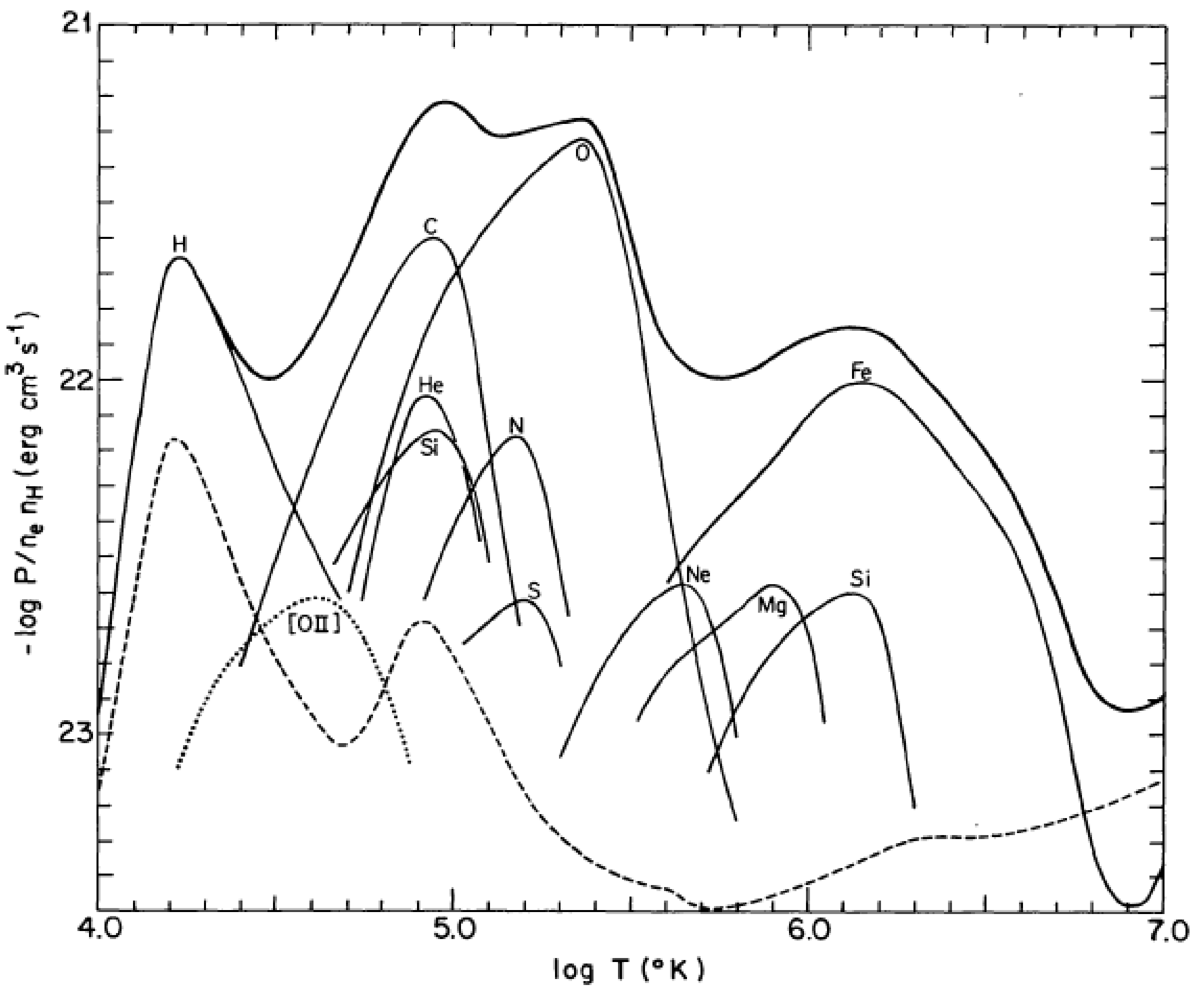
Crab Nebula Movie



X-ray　　　　Optical

Major Unsolved Problems of Supernova Remnants

- Shock acceleration: what fraction of energy goes into accelerating relativistic electrons and generating magnetic fields?
- Neutron star: why are some (like Crab Nebula) very active electromagnetically, while others (like Cas A) very inactive?
- Element distribution: what instabilities determine the very complex distribution of elements in supernova remnants?


21
22
23
4.0
5.0
6.0
7.0
- log P/n_e n_H (erg cm^3 s^-1)
log T (°K)
H
C
O
He
Si
N
S
[OII]
Ne
Mg
Si
Fe