Supernovae and Supernova Remnants

Supernovae
T~ 5000 K characteristic kT of photospheric emission during early period
characteristic emission is optical and infrared
timescale ~ year

Supernova remnants
powered by expansion energy of supernova ejecta,
dissipated as the debris collides with interstellar material generating shocks
T ~ 10^{6-7} characteristic thermal emission is X-rays

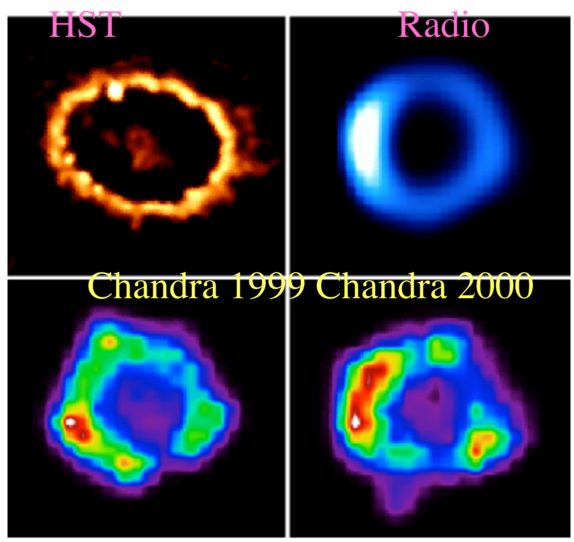
timescale ~100-10,000 years (youngest SN in MW is ~110years old)

In our Galaxy there are~300 identified SNRs

~ 8% detected in the TeV range
~ 10% in the GeV range
~ 30% in optical wavelengths
~ 40% in X-rays
~ 95 % in radio

SuperNova Remnants

- We will distinguish between
  - SN explosions (the actual events and the next few years) and
  - Remnants - what happens over the next few thousand years.



SN 1987A observed in 1999, 2000

SNRs enrich the ISM by dispersing material produced both during the star's life and at the moment of the SN event.

~2 per century for Milky Way (all types)

SNRs are probes both of their progenitor star (and of their pre-supernova life) and of the medium into which they explode (the ISM)

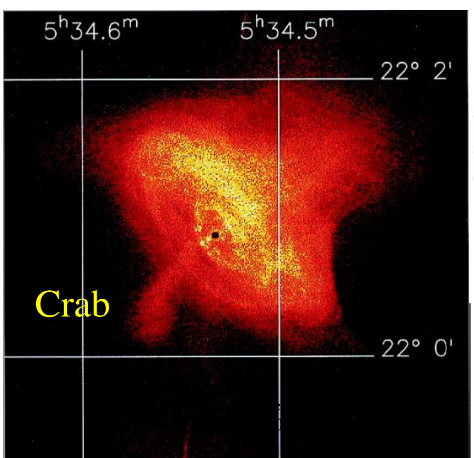
They are also cosmic accelerators (cosmic rays).

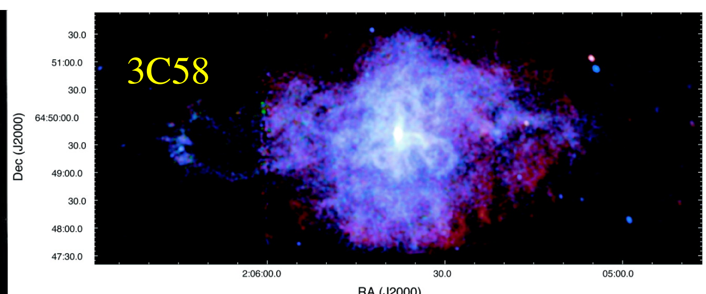
Birth places of neutron stars and stellar mass black holes.

laboratories for study of magnetic fields, shock physics, jets, winds, nuclear physics etc

Sites of ejection of enriched material

- SNR evolution (and their appearance now) depends on many factors:
  - age
  - environment (density)
  - total energy of the explosion
  - progenitor star (mass, type of SN associated..)

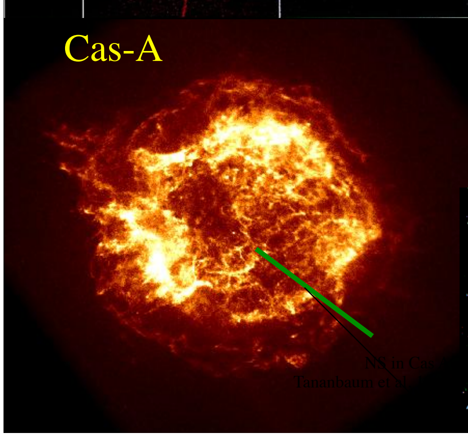


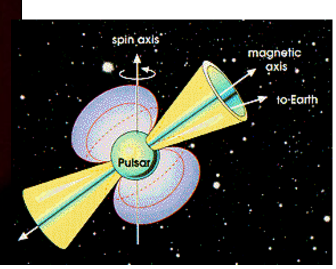


Neutron Stars in SNRs

Pulsars are highly magnetized NS: beacons of light emitted along axis are detected as pulsations

Infer energy loss rate, B field from pulsation characteristics



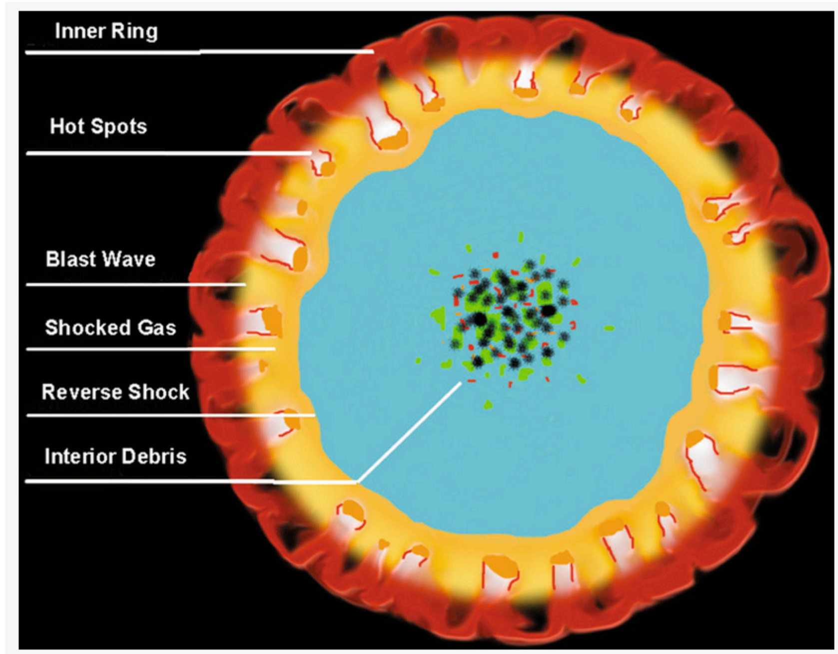


Relativistic wind is seen as a nebula around pulsar

Thermal (blackbody) emission can also emitted from the surface of the NS

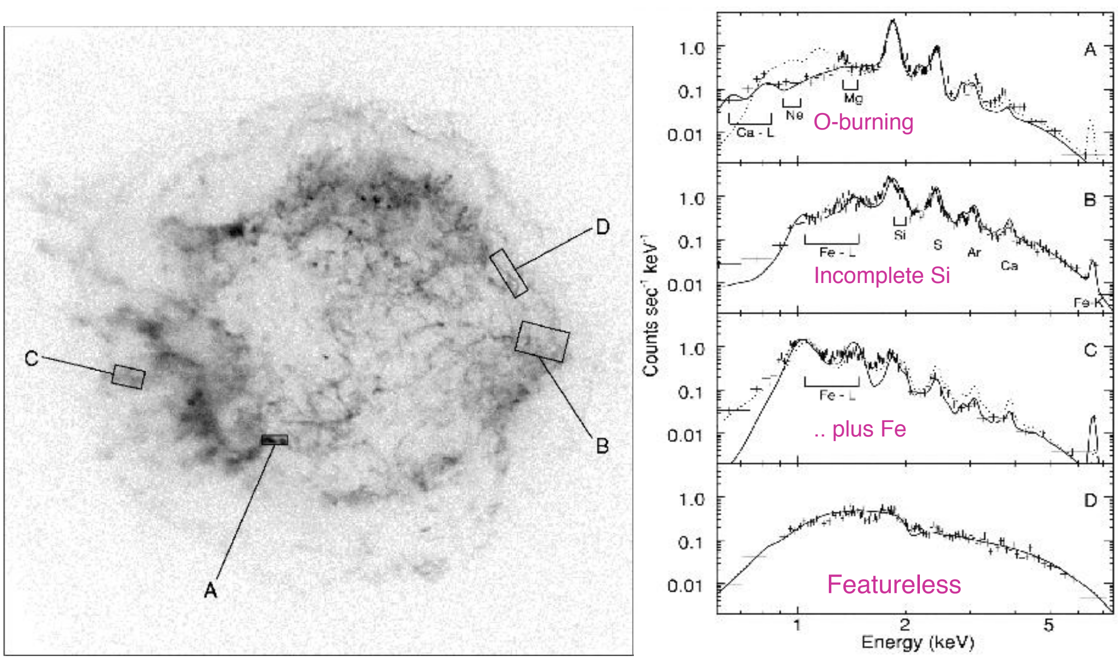
The Young SNR

The nucleosynthesis products in the interior debris are confined mostly within a sphere expanding with velocity ~ 2000 km s^{-1}



The blue-yellow interface represents the reverse shock , while the yellow annulus represents the X-ray-emitting gas, bounded on the outside by the blast wave . The white fingers represent protrusions of relatively dense gas.

Cassiopeia A: Observations of Explosive Nucleosynthesis Spectral/Spatial Decomposition



(Hughes et al. 2000 ApJ, 518, L109)

Notice inhomogeneity of element distribution

Origin of the Elements- repeat

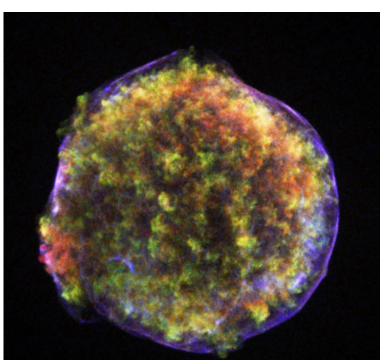
C burning produces O, Ne, Mg, etc $T \sim 2 \times 10^{9}$ K

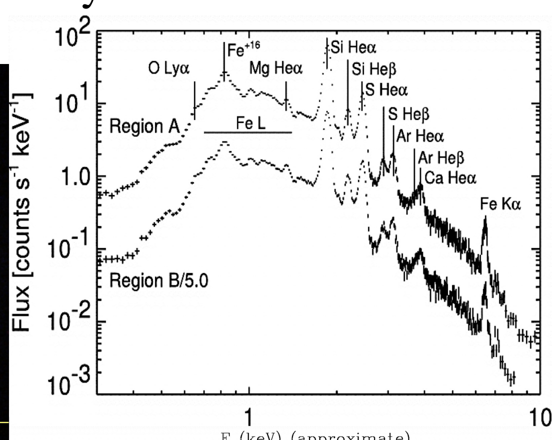
Ne burning produces O, Mg, etc $T \sim 2.3 \times 10^{9}$ K

O burning produces Si, S, Ar, Ca, etc $T \sim 3.5 \times 10^{9}$ K

Si burning produces Fe, Si, S, Ca, etc $T \sim 5 \times 10^{9}$ K

Nucleosynthesis Products in SNRs

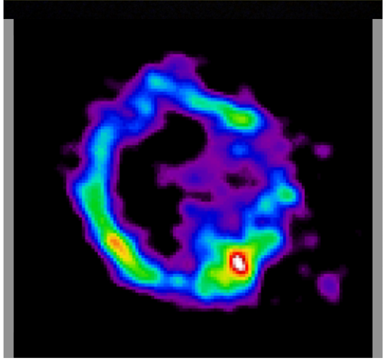


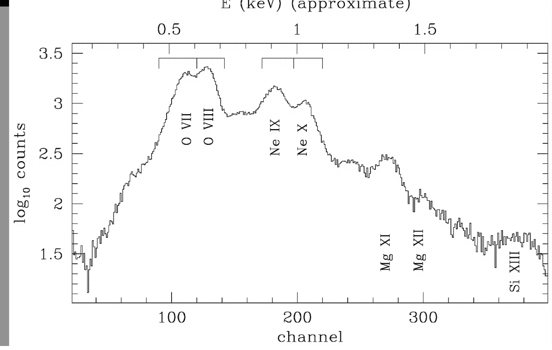


Tycho's SNR

Type Ia
White dwarf + companion

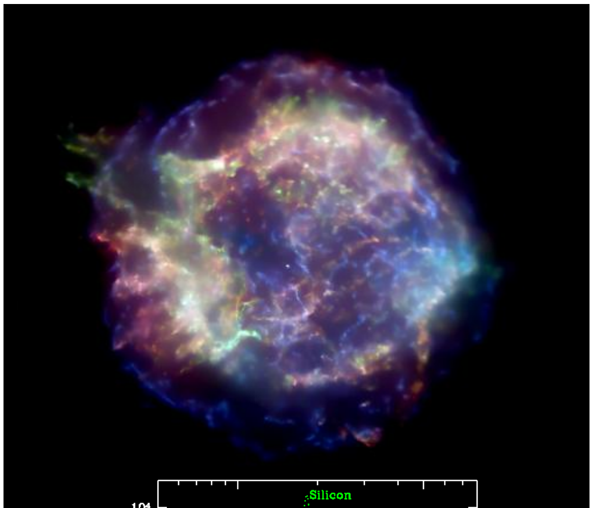
Si, S, Ar, Ca
Expect lots of Fe: most not yet shocked

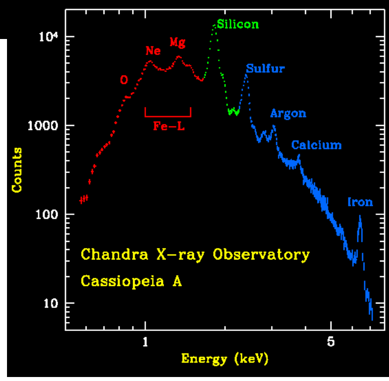




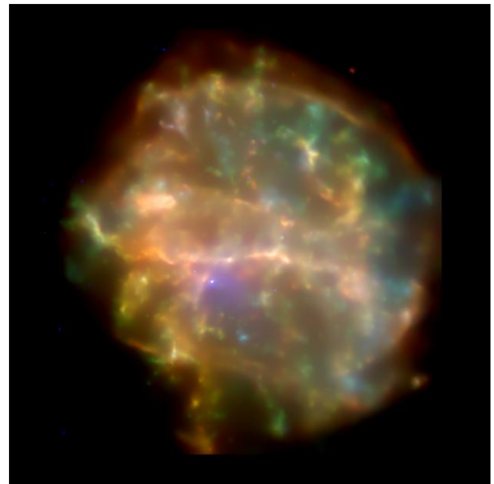
E0102-72

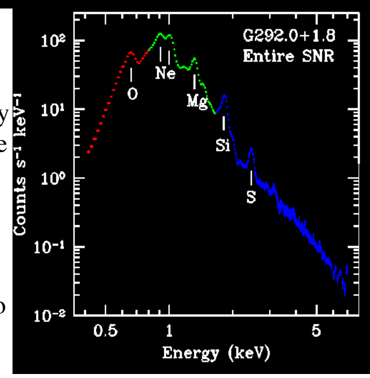
Core-collapse
$\sim 25\ M_{sun}$
mostly O, Ne, Mg





- Type Ia produce mainly Fe -- low O/Fe ratio.
- Type II produces: mainly O -- high O/Fe ratio



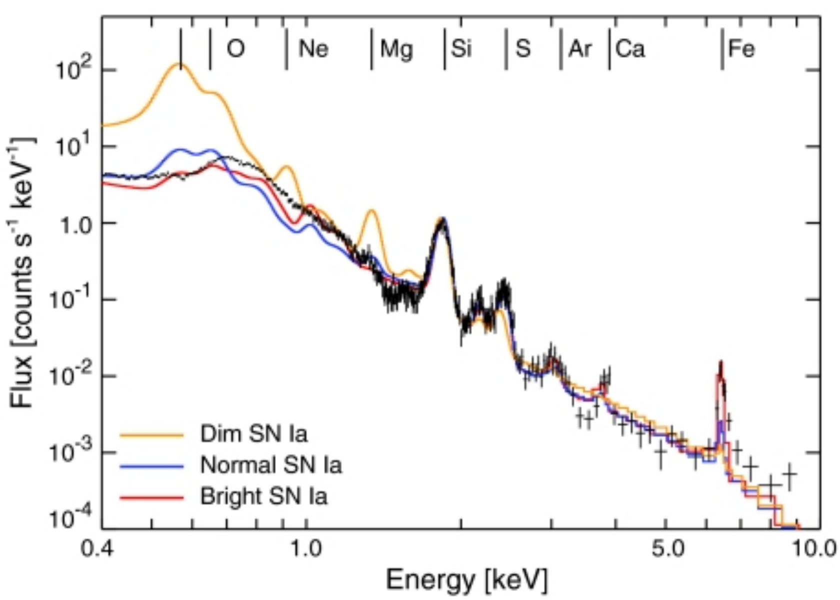


Comparison of Yields From Different Type Ia Models with X-ray Spectral data

Measurement of chemical abundance pattern in SNR allows determination of SN physics

C. Badenes

Proc Natl Acad Sci U S A. 2010 107(16): 7141–7146.



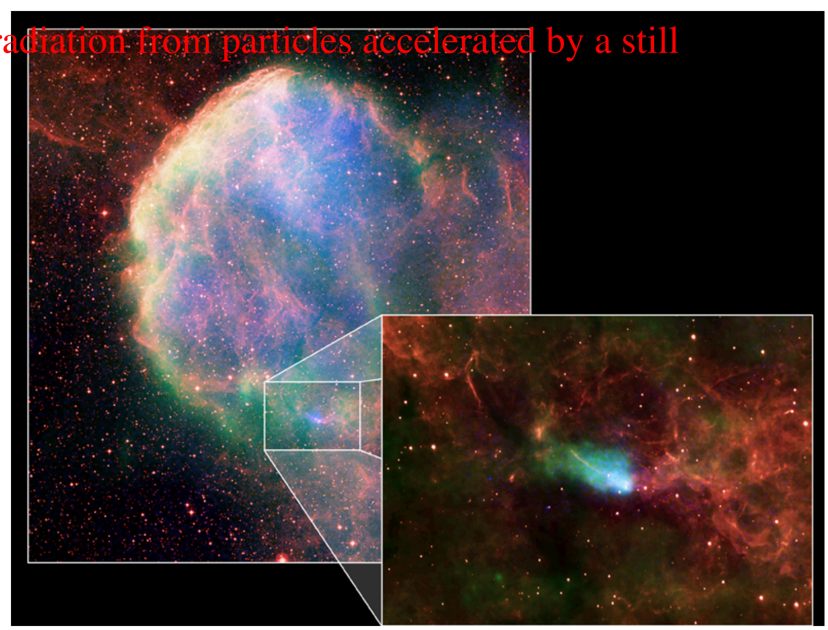
SNR Types

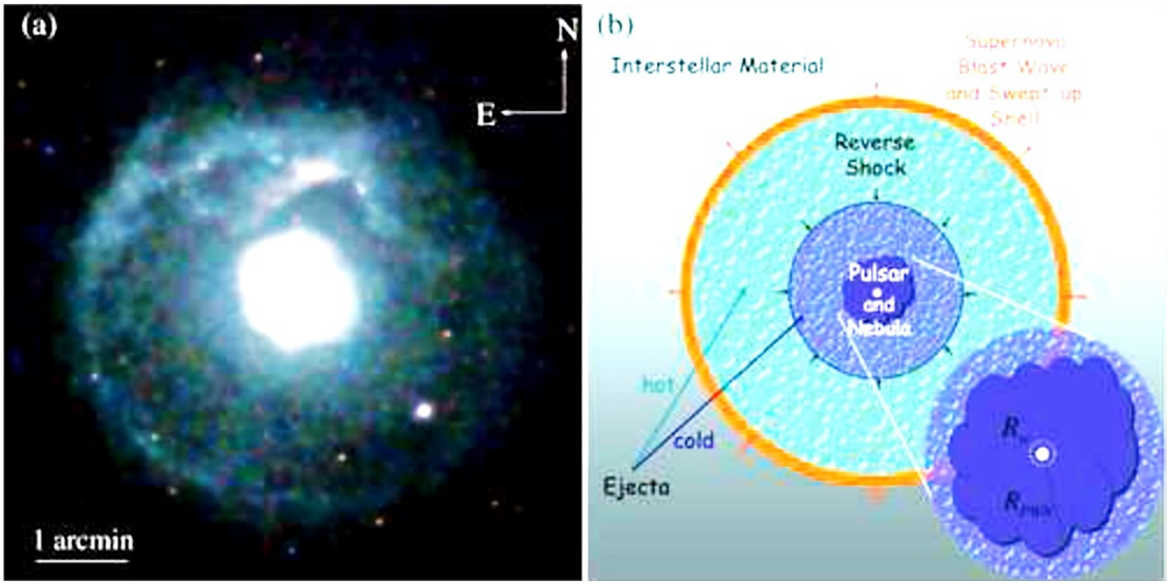
A Rogues gallery

- Shell-like – thermal
  - Young objects whose global X-ray emission is dominated by emission from ejecta
    - Cas A, Tycho
  - Old objects dominated by thermal emission at the primary shock
    - Cygnus Loop, PKS1209-52
- Shell-like – non-thermal
  - Young SNRs dominated by non-thermal emission, often bright VHE gamma ray sources
    - RX1730-3946, Vela Jr, G1.9+0.3, SN1006
- Pulsar wind nebulae
  - Centrally peaked emission from non-thermal radiation due to electrons powered by a rapidly rotating neutron star
    - Crab Nebula, 3C 58
- Composite- sum of thermal+non-thermal

Combining Bremmstrahlung and Synchrotron Radiation- Composite SNR

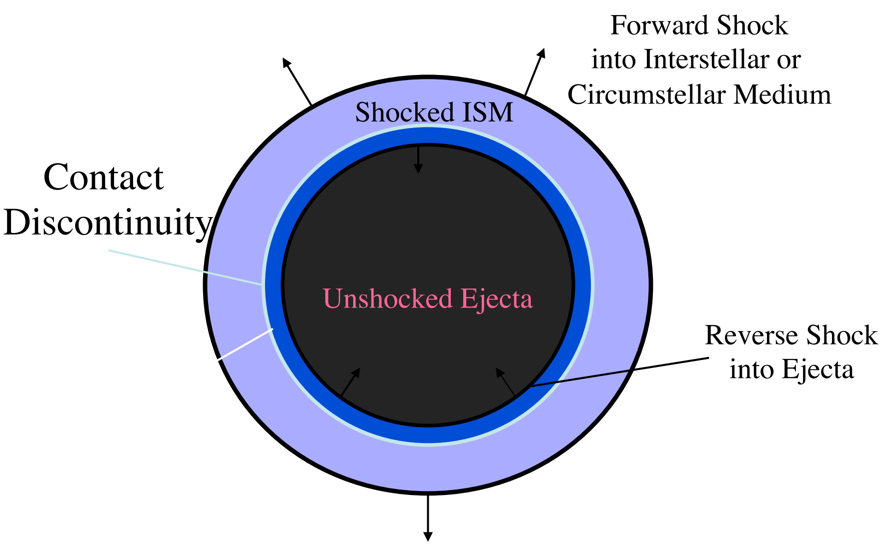
- In some supernova remnants one sees both processes at work
  - Bremmstrahlung from electrons that are shock heated by the SN blast wave +line emission
  - Synchrotron radiation from particles accelerated by a still active pulsar





- Composite SNR G21.5- 0.9 (Matheson & Safi-Harb 2005).

Supernova Remnant Cartoon



Forward shock moves supersonically into interstellar/ circumstellar medium
Reverse shock propagates into ejecta, starting from outside

Schematic Structure of Young SNR

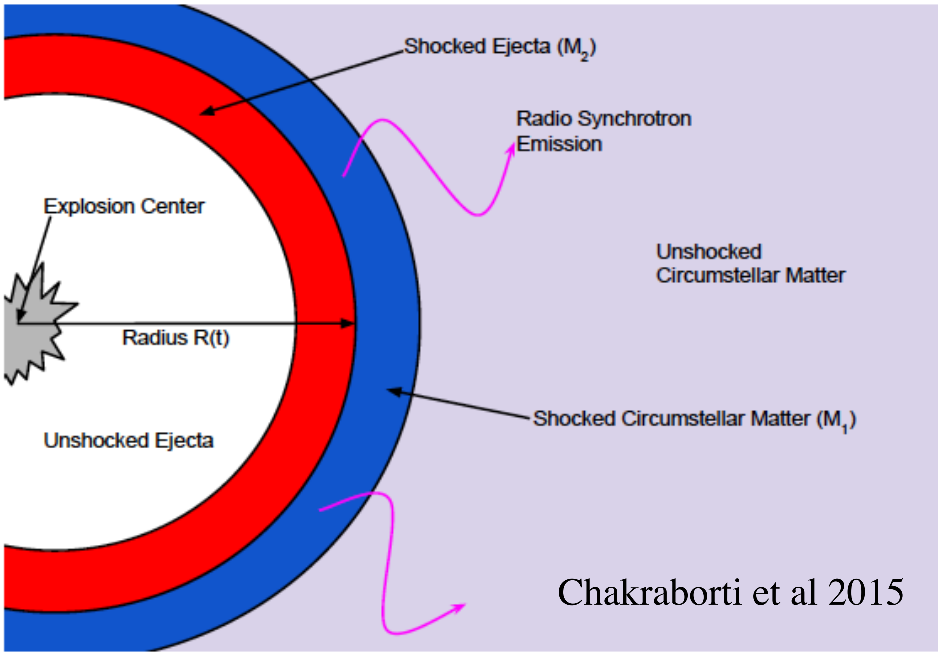


FIG. 1.— Schematic representation of the model used to predict the size and flux density evolution of young supernova remnants.

Summary of SNR Expansion Phases

I. $m_o >> M_{ISM}$: free expansion

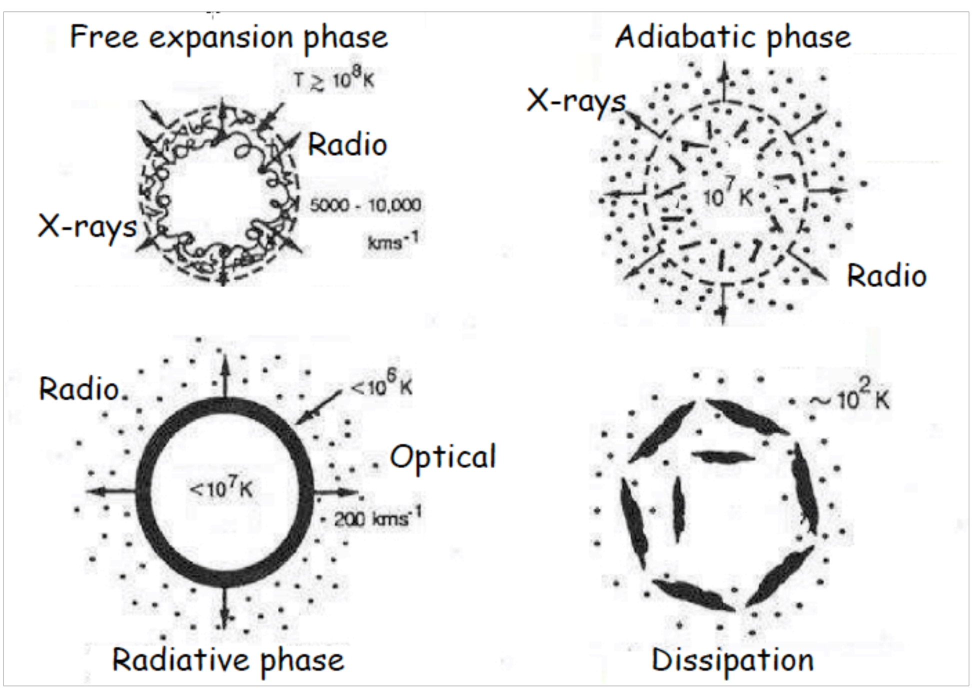
II. $m_o < M_{ISM}$ - shock heated gas adiabatic due to high temperature: Sedov phase (adiabatic)

III. $m_o << M_{ISM}$ - gas cools radiatively at constant momentum

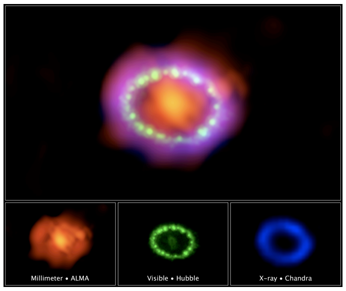
3 phases in SNR's life.

- Free expansion (less than 200-300 years) depending on local medium
- Adiabatic or "Taylor-Sedov" phase (about 20,000 years)
- Radiative or Snow-plow phase (up to 500,000 years)

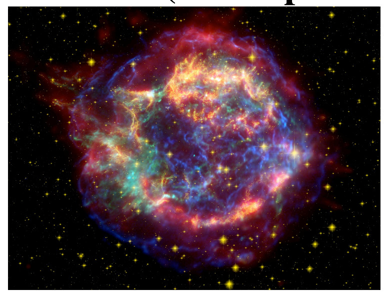
and then … Merge with the ISM



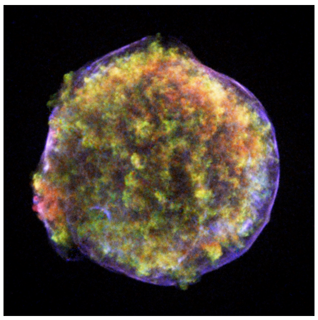
Phase I (SN 1987A)



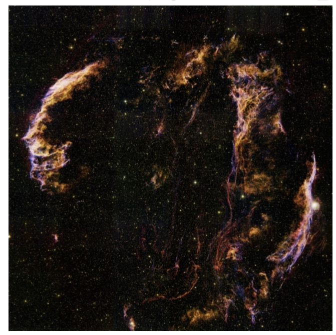
Phase I/II (Cassiopeia A)



Phase II (Tycho, SN 1572)



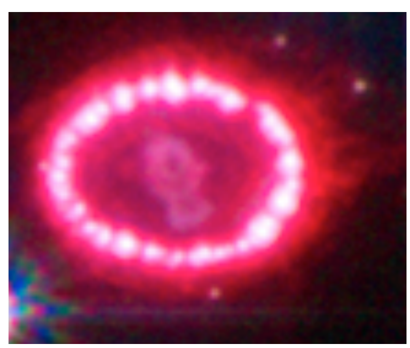
Phase III (Cygnus Loop)



Free expansion phase

- Independent of the nature of the SN explosion
- No deceleration
- Evolution only depends on E_o the initial energy.
- Velocity of ejected shell ~ 10^4 km s^{-1}
- Mass swept-up small until $M_{SN} \sim M_{eje} \sim 1\ M_\odot$

===> $R_s = 250$ yrs $M_{eje}^{5/6}\, n^{-1/3}\, E_{51}^{-1/2}$



1987A HST in 2010

E_{51} is KE in units of 10^{51}

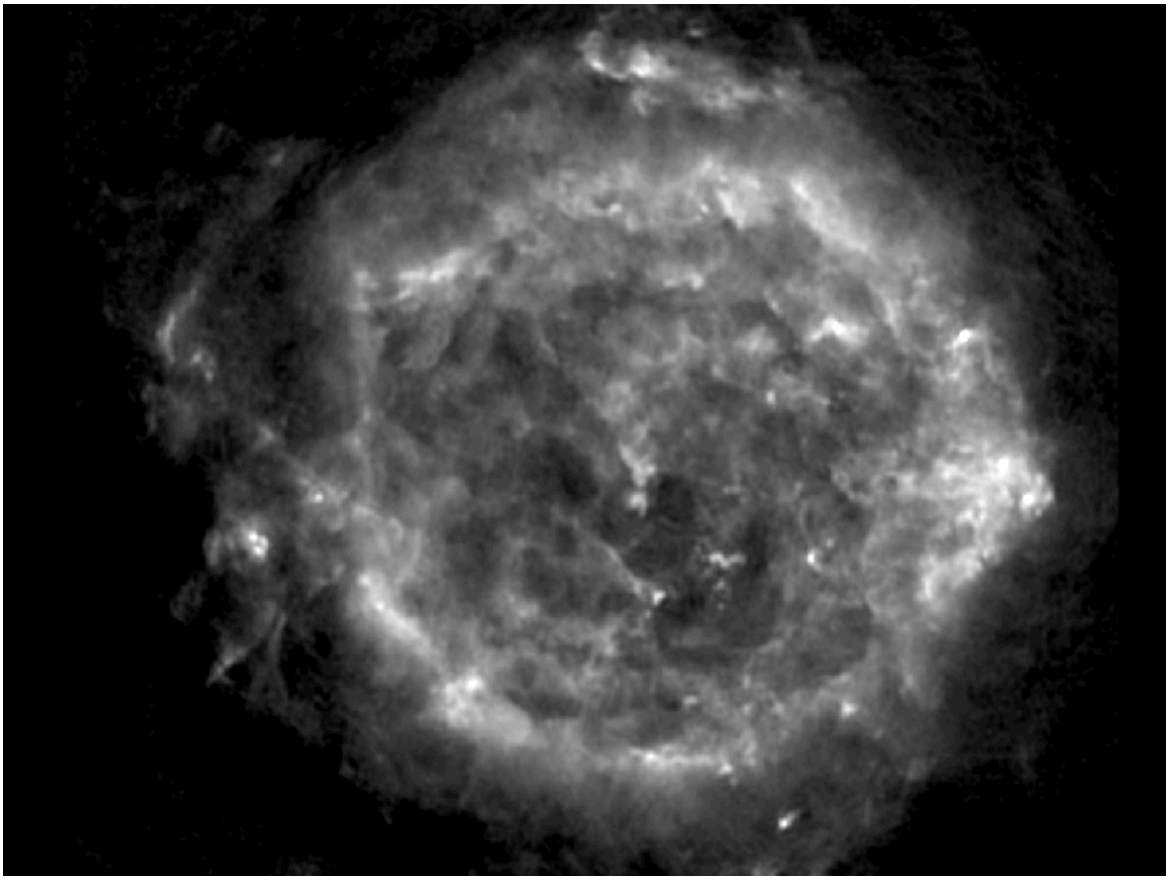
M_{ejc}- is ejecta mass in solar masses

n is number density of gas

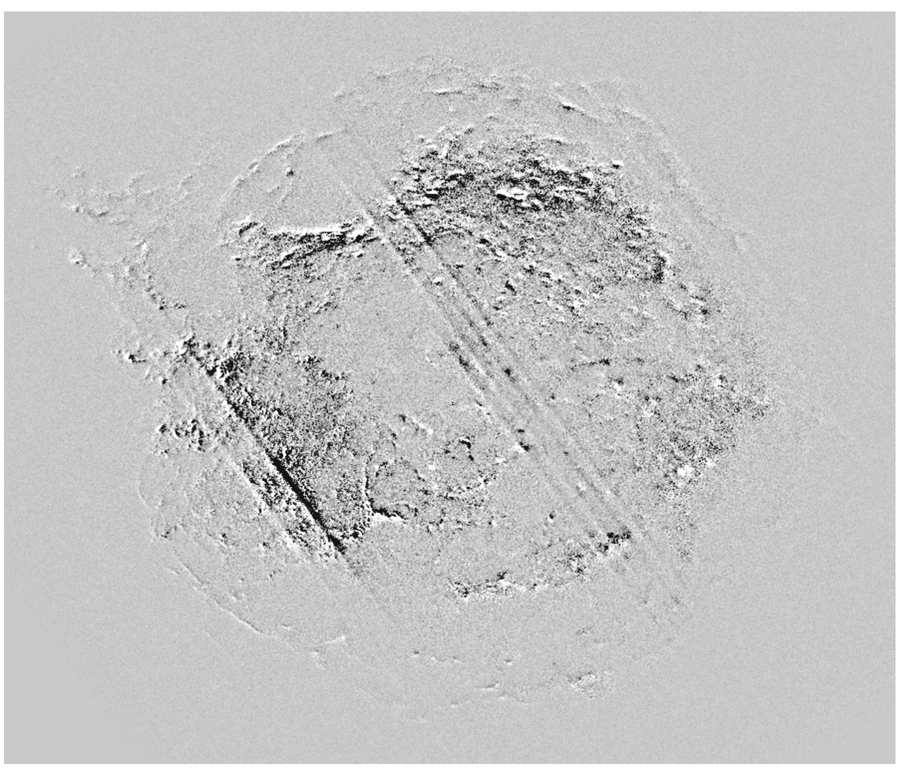
https://www.nasa.gov/feature/goddard/2017/the-dawn-of-a-new-era-for-supernova-1987a

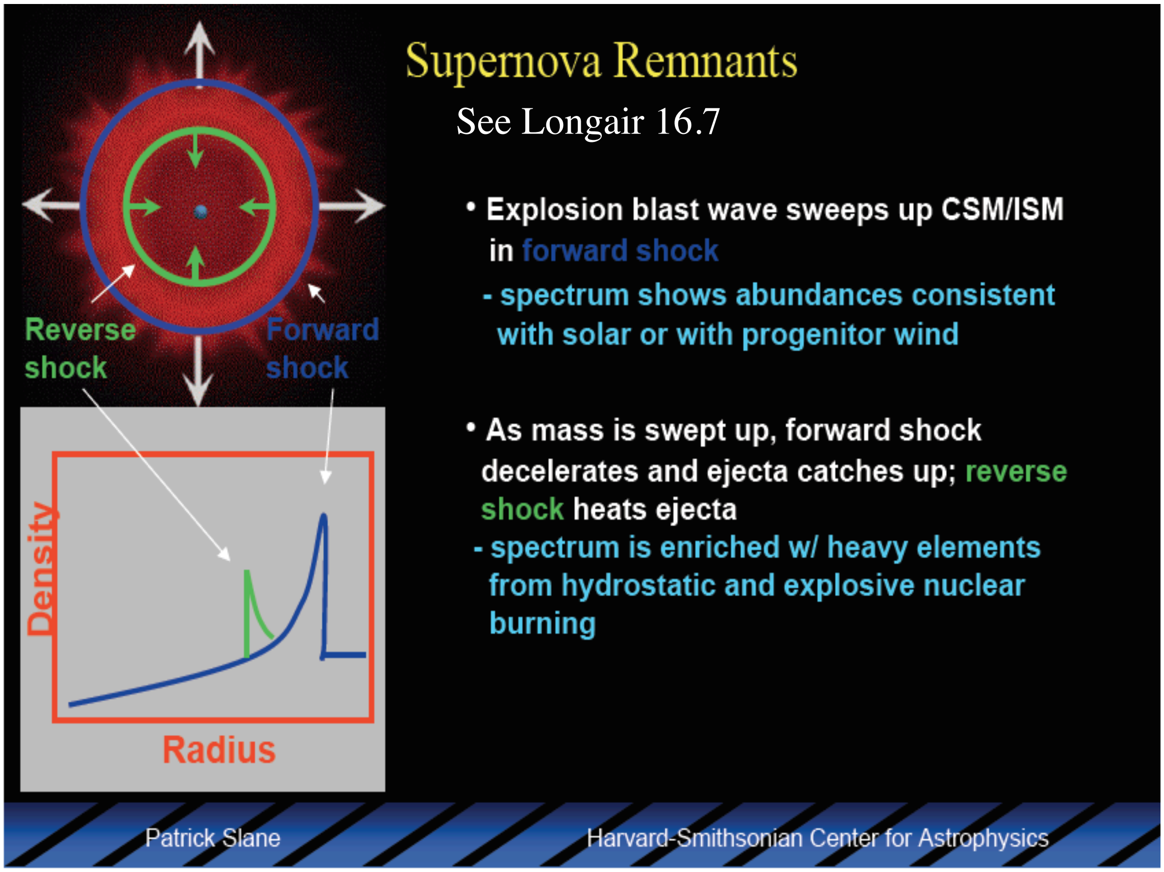
https://public.nrao.edu/news/2017-alma-dust-sn1987a/#PRimage4

SNR next enters its Adiabatic Phase



Cas-A Difference of X-ray Images Taken 2 Years Apart Delaney e al 2005





Supernova Remnants

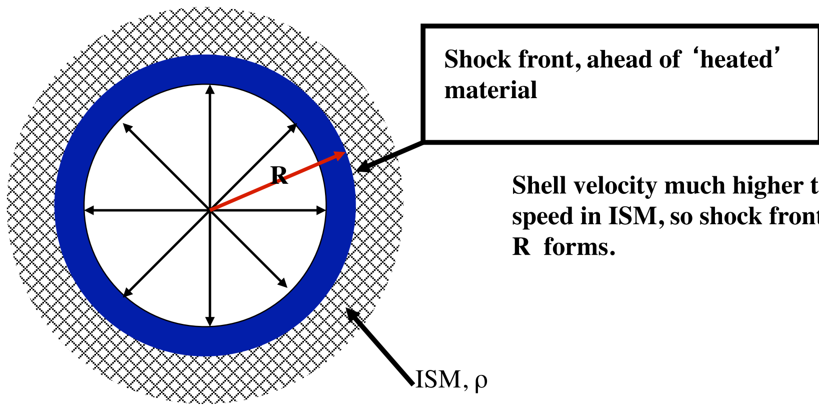
Development of SNR is characterized in phases – *values are averages* for "end of phase"

Phase	I	II	III
Mass swept up ($M_\odot$)	0.2	180	3600
Velocity (km/s)	3000	200	10
Radius (pc)	0.9	11	30
Time (yrs)	90	22,000	100,000

Phase IV represents disappearance of remnant

Shock Expansion

- At time t=0, mass m_0 of gas is ejected with velocity v_0 and total energy E_0 .
- This interacts with surrounding interstellar material with density ρ and low temperature.



Shell velocity much higher than sound speed in ISM, so shock front of radius R forms.

0

- System radiates (dE/dt) E_0 ~$10^{48\text{-}52}$ergs

SNR Development - Phase I- Free Expansion Adapted from L. Culhane

- Shell of swept-up material in front of shock does not represent a significant increase in mass of the system.
- **<u>ISM mass</u>** within sphere radius R is still **<u>small</u>**.

$$m_0 >> \frac{4\pi}{3}\rho_0 R^3(t) \qquad \textbf{(1)}$$

ρ_0= ISM density, R(t)=shock size as a function of time

- Since momentum is conserved:

$$m_0 v_0 = (m_0 + \frac{4\pi}{3} \rho_0 R^3(t)).v(t) \quad \textbf{(2)}$$

initial mass swept up mass

- Applying condition (1) to expression (2) shows that the velocity of the shock front remains constant, thus :

$v(t) \sim v_0$

$R(t) \sim v_0\, t$

Adapted from L. Culhane

Scaling Laws in Free Expansion Phase

$$r = \left(\frac{3}{4\,\pi}\,\frac{M_{ej}}{n_{ism}\,\mu\,m_H}\right)^{\frac{1}{3}} = 1.9\,pc\,\left(\frac{M_{ej}(M_\odot)}{n_{ism}}\right)^{\frac{1}{3}}$$

$$t = 200\,yrs\,\left(\frac{M_{ej}(M_\odot)}{n_{ism}}\right)^{\frac{1}{3}}\frac{1}{v_s(10{,}000\,km\,s^{-1})}$$

K. Long

- Forward shock into the ISM- is a 'contact discontinuity'- outside of this the ISM does not yet 'know' about the SN blast wave

- Reverse shock- information about the interaction with the ISM travels backwards into the SN ejecta
- Shell like remnants
- **Shell velocity much higher than sound speed in ISM, so shock front of radius R forms.**

Sedov-Taylor phase

This solution is the limit when the swept-up mass exceeds the SN ejecta mass -the SNR retains only vestiges of the initial ejecta mass and its distribution.

The key word here is SELF SIMILAR *(solutions can be scaled from solutions elsewhere)*

==> $P(r,t)=P_s(r_s)f(r.r_s)$
$r_s=A(E_0/\rho_0)t^{2/5}$;
$v_s=dr/dt=(2/5)A(E_0/\rho_0)^{1/5}t^{-3/5}$

In the Sedov-Taylor model the thermal emission comes from a thin shell behind the blast wave. As the shock expends the pressure drops between the shock wave and the material ejected.

Phase II - adiabatic expansion-

Adapted from L. Culhane

Radiative losses are unimportant in this phase - no exchange of heat with surroundings.

Large amount of ISM swept-up:

$$m_0 << \frac{4\pi}{3}\rho_0 R^3(t) \quad \textbf{(3)}$$

Thus conservation of momentum becomes :

$$m_0 v_0 = \frac{4\pi}{3}\rho_0 R^3(t)v(t)$$ since m_o is small

$$= \frac{4\pi}{3}\rho_0 R^3(t)\frac{dR(t)}{dt} \quad \textbf{(4)}$$

Integrating:

$$m_0 v_0 t = \frac{\pi}{3}\rho_0 R^4(t) \quad \textbf{(5)}$$

R(t) = 4v(t)t

v(t) = R(t)/4t

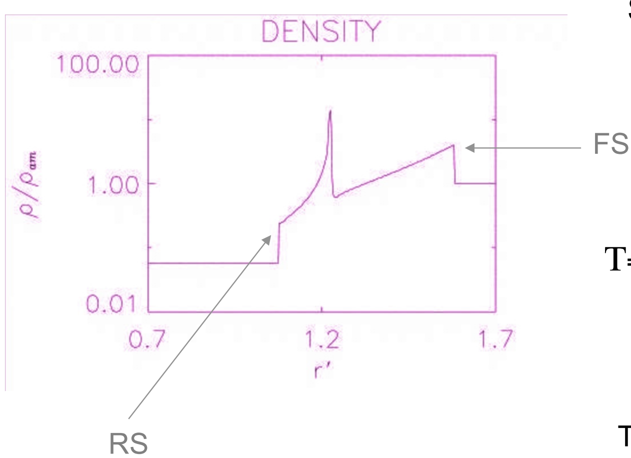
Sedov-Taylor Phase Parameters in Useful Units

- K. Long

$$r_s \sim 5.2 \left(\frac{E_{51}}{n_h}\right)^{\frac{1}{5}} (t_{kyr})^{\frac{2}{5}}\, pc$$

$$v_s \sim 2000 \left(\frac{E_{51}}{n_h}\right)^{\frac{1}{5}} (t_{kyr})^{-\frac{3}{5}}\, km/s$$

$$T_s \sim 5.7\, x\, 10^7 \left(\frac{E_{51}}{n_n}\right)^{\frac{2}{5}} (t_{kyr})^{-\frac{6}{5}} K = 4.9 \left(\frac{E_{51}}{n_h}\right)^{\frac{2}{5}} (t_{kyr})^{-\frac{6}{5}}\, keV$$



Shocks compress and heat gas

Mass, momentum, energy conservation give relations (for γ=5/3)

$\rho = 4\rho_0$

$V = 3/4\, v_{shock}$

$T=1.1\ m/m_H\ (v/1000\ km/s)^2$ keV

X-rays are the characteristic emission

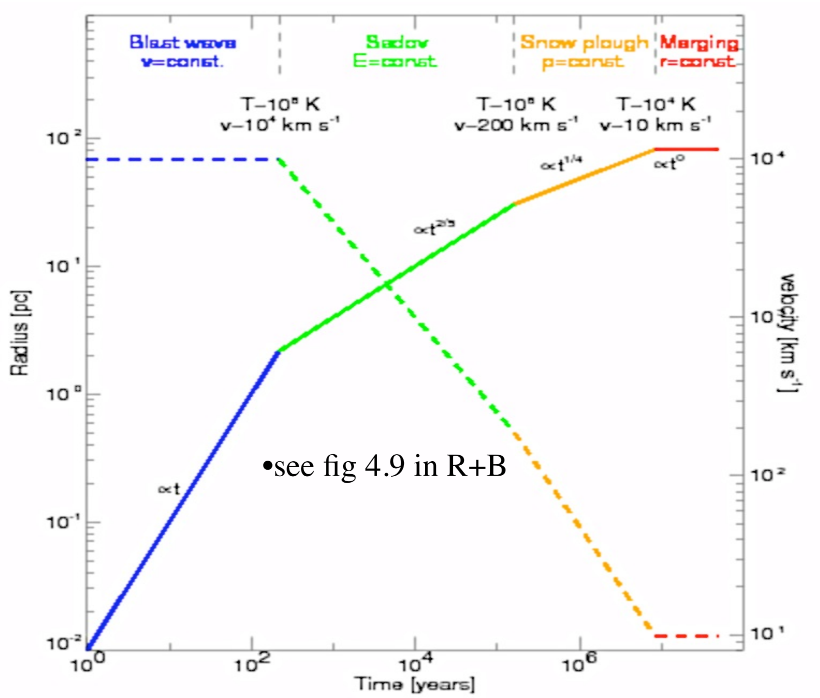
These relations change if significant energy is diverted to accelerating cosmic rays

The shock is "collisionless" because its size scale is much smaller than the mean-free-path for collisions (heating at the shock occurs by plasma processes) coupled through the structure of turbulence in shocks and acceleration

Collisions do mediate ionizations and excitations in the shocked gas

The 4 Phases in the Life of a SNR

- 4 limits
  1) blast wave, velocity=const
  2)Sedov: Energy =const
  3) Snow plough momentum= constant
  4)no longer expands, merges with ISM

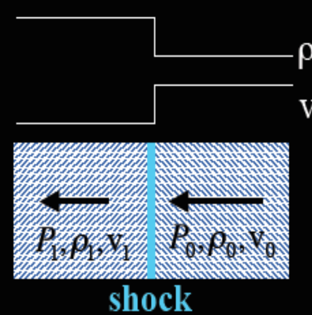


•see fig 4.9 in R+B

:, Fig. 4.6)

Shocks in SNRs

- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with γ=5/3)



$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k} m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

$$v_{ps} = \frac{3v_s}{4}$$

X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g. cosmic rays), the temperature will be lower than this

Patrick Slane Harvard-Smithsonian Center for Astrophysics

Summary

- Free Expansion Phase

the ejecta expands freely into the interstellar medium.

The expanding envelope compresses the ISM, creates a shock wave because of its high velocity, and sweeps up the ISM.

During this initial phase, the mass of gas swept up is <<mass of the ejecta and the expansion of the envelope is not affected by the outer interstellar gas and it keeps its initial speed and energy.

Summary

- Adiabatic Expansion Phase

When mass of gas swept up > mass of ejecta the kinetic energy of the original exploded envelope is transferred to the swept up gas, and the swept up gas is heated up by the shock wave roughly independent of the physics of the explosion.

The radiative losses from the swept up gas are low (energy is conserved)

The evolution during this phase is determined by the energy of explosion E_0, the density of interstellar gas, and the elapsed time from the explosion t.

Self similar solution relating the density, pressure, and temperature of the gas, and the expansion velocity (Sedov-Taylor)

Phase III - Rapid Cooling

- SNR cooled, => no high pressure to drive it forward.
- Shock front is coasting

$$\frac{4}{3}\pi R^3 \rho_0 v \text{ = constant}$$

- Most material swept-up into dense, cool shell.
- Residual hot gas in interior emits weak X-rays.

End of Snowplough Phase- Draine sec 39.1.4

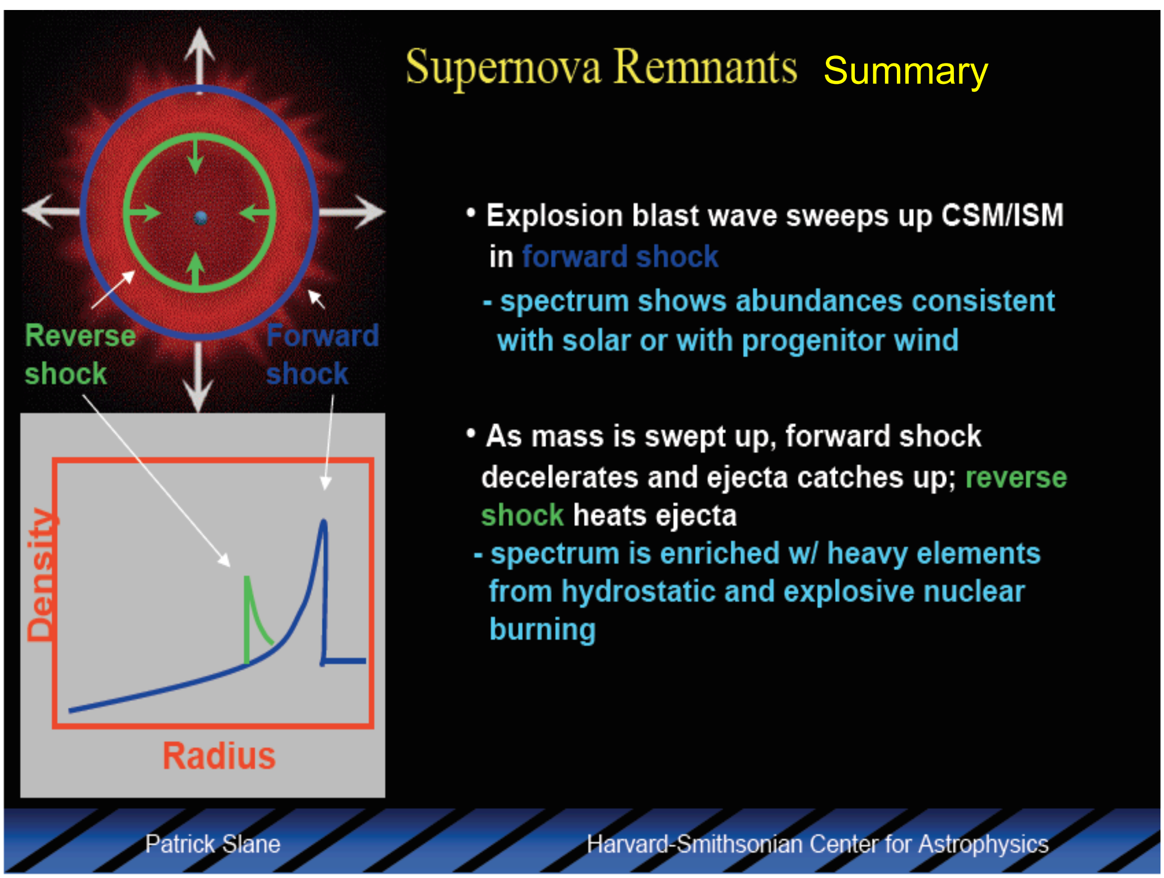
- The strong shock gradually slows (radiative losses and accumulation of 'snowplowed' material)
- Shock compression declines until $v_{shock} \sim c_s$ (sound speed); no more shock
- Using this criteria the 'fade away' time
- $t_{fade} \sim ((R_{rad}/t_{rad})/c_s)^{7/5}\ t_{rad}$
- $t_{fade} \sim 1.9 \times 10^6$ yrs $E_{51}^{0.32}\ n^{-0.37}(c_s/10\text{km/sec})^{-7/5}$; $c_s = 0.3\text{km/sec}(T/10\text{k})^{1/2}$
- $R_{fade} \sim 0.06\text{kpc}\ E_{51}^{0.32}\ n^{-0.37}(c_s/10\text{km/sec})^{-2/5}$

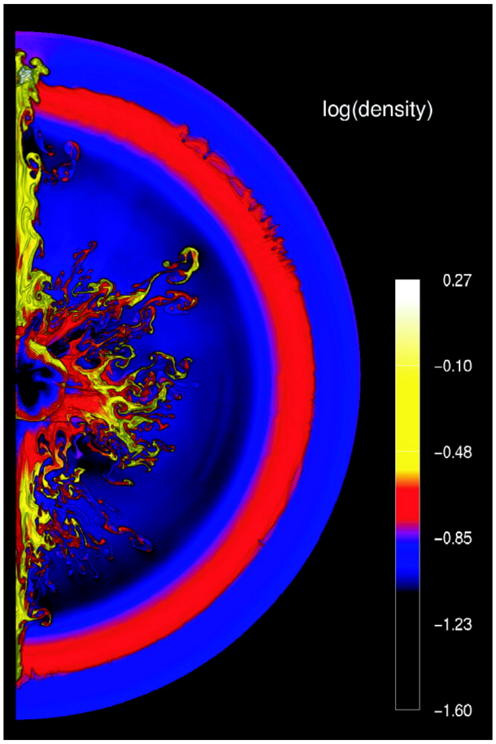
Snowplough Scaling Relations

- Notice the SNR is very big and very old !
- Nearest example is the Cygnus Loop

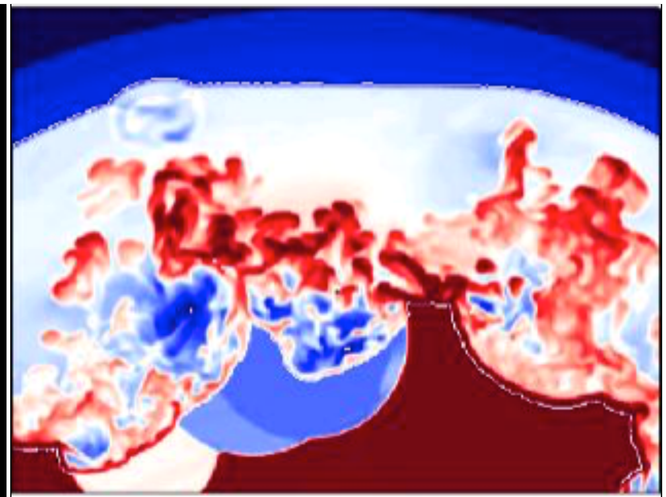
$$r_{rad} = 25\,pc\,\left(\frac{E_{51}}{n_h}\right)^{\frac{1}{5}}$$

$$t_{rad} = 47\,kyr\,\left(\frac{E_{51}}{n_h}\right)^{\frac{1}{3}}$$





Kifonidis et al. 2000



Fe bubbles Blondin et al. 2001

Instabilities

irregular shock boundaries
mixing between ejecta layers
mixing between ejecta and ISM

What it really looks like