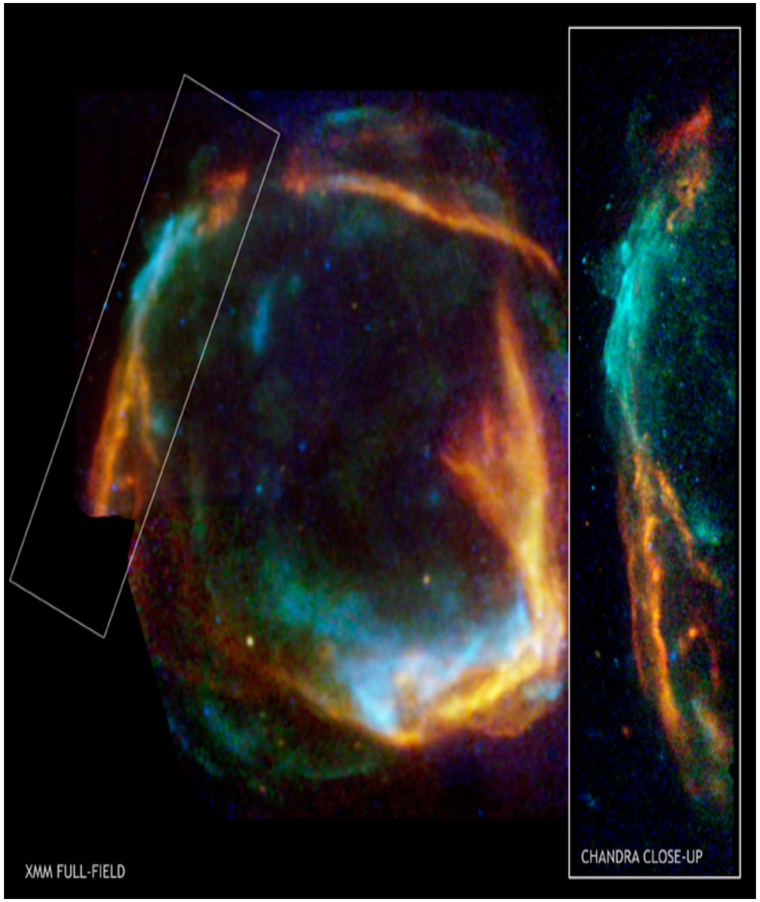
Supernova Remnants

- Shell-type versus Crab-like
- Phases of shell-type SNR

Shell-type SNR



Shell-type SNR:

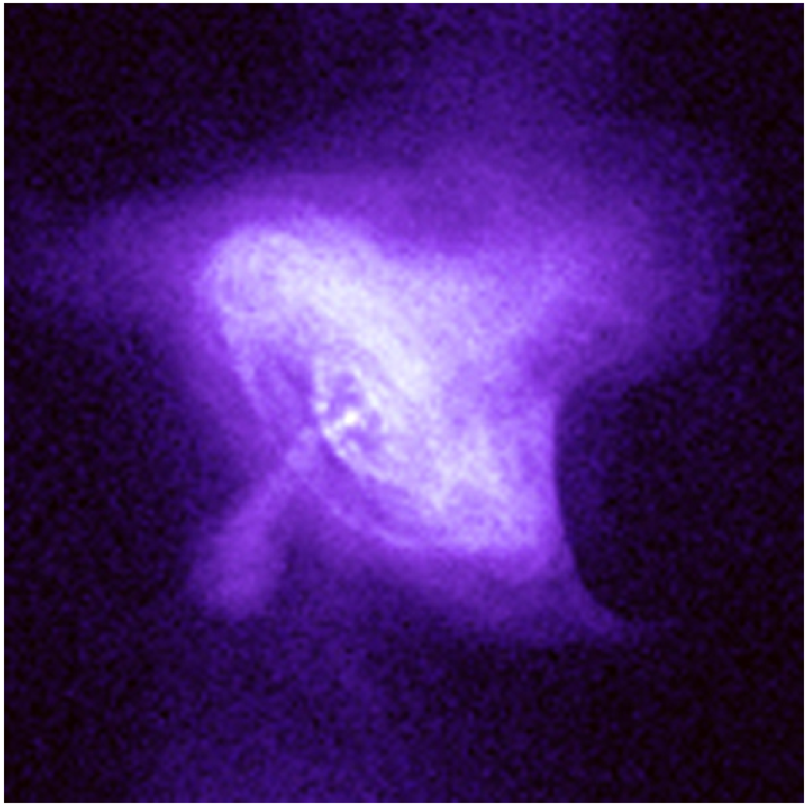
X-ray, radio, and optical emission come from a shell. X-rays are usually thermal, but can have non-thermal components.

Shell is expanding.

Power source is inertia left from initial supernova. No current input of energy.

RCW 86, SN in 185 AD

Pulsar Wind Nebulae (Plerions)



Crab, SN in 1054 AD

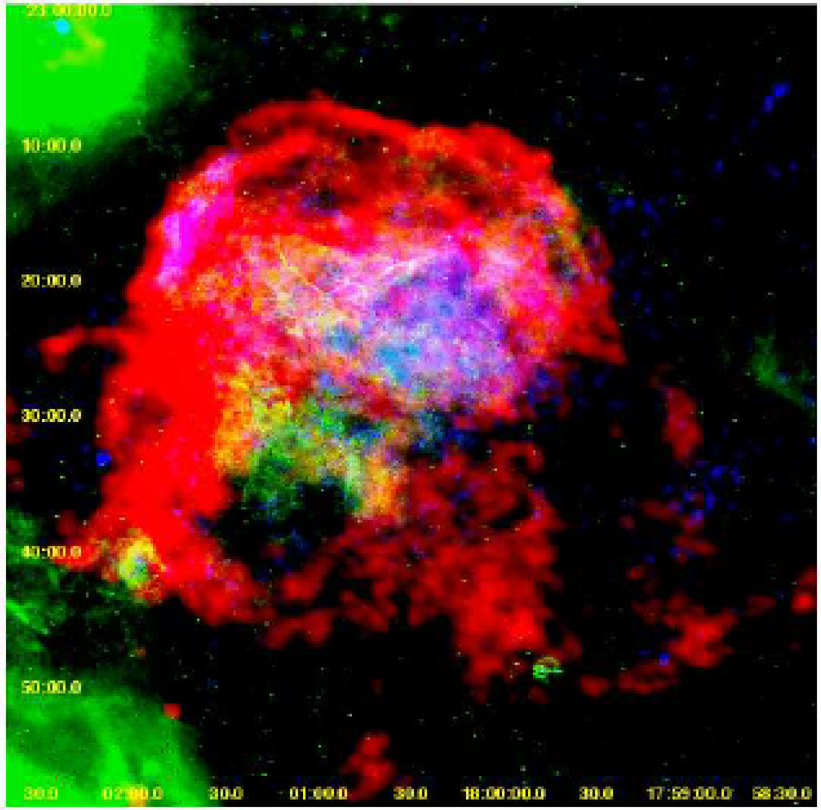
Center filled or Crab-like SNR, or pulsar wind nebulae:

X-ray, radio, and optical emission come from a filled, central region. X-rays are non-thermal.

Motions can be detected internal to the nebula.

Continuously powered by relativistic wind from pulsar at center of nebula.

Mixed Morphology



Plerionic composite: shell-type on the outside, Crab-like at the center.

Thermal composite: Radio shell, center-filled X-ray emission, but X-rays are thermal. Thought to occur in denser ISM than shell-type SNR. X-rays may be due to evaporation of clouds ISM after shock front has passed.

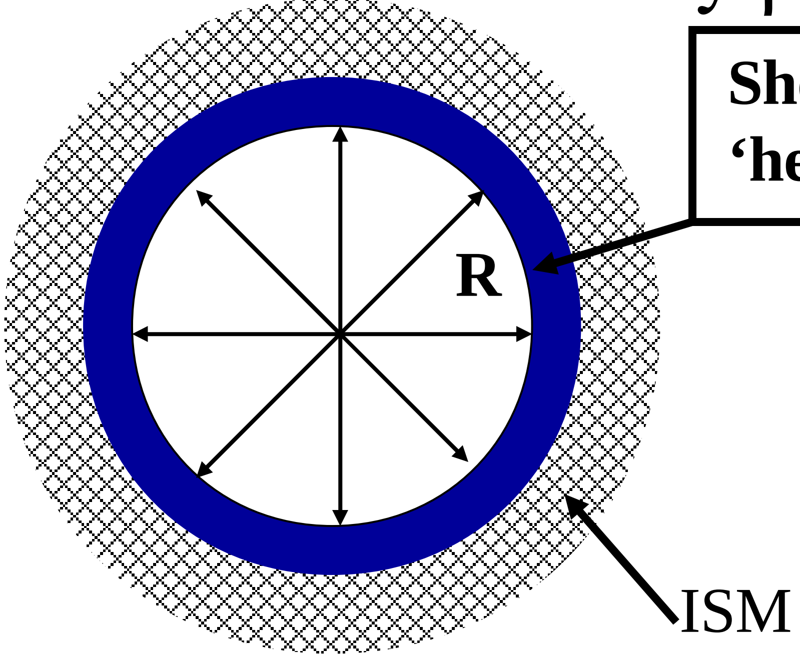
W28: red = radio, green = Hα, blue = X-ray,

Phases of Shell-type SNRs

- **Supernova explosion** – ejecta $v \sim 10^4$ km/s
- **Free expansion** - ejecta mass > swept up mass
- **Adiabatic or Sedov** – swept-up mass > eject mass
- **Snow-plow or Cooling** – shock front cools, interior also cools
- **Disappearence** – remnant slows to speed of the random velocities in the surrounding medium, merges with ISM

Shock Formation

At time t=0, mass m_0 of gas is ejected with velocity v_0 and total kinetic energy E_0. This interacts with surrounding interstellar material with density ρ_0 and low T.



Shock front, ahead of 'heated' material

The shell velocity much higher than the sound speed in ISM, so a shock front of radius R forms.

Free Expansion

- Shell of swept-up material in front of shock does not represent a significant increase in mass of the system.
- ISM mass previously within the swept-up sphere of radius R is still small compared to the ejecta mass: $(4\pi/3)\rho R^3 << m_0$

- Since momentum is conserved:

$$m_0 v_0 = (m_0 + (4\pi/3)\rho_0 R^3)v$$

- As long as swept-up mass << ejecta mass, the velocity of the shock front remains constant and $R_s(t) \sim v_0 t$
- The temperature decreases due to adiabatic expansion, $T \propto R^{-3(\gamma-1)}$

Sedov Phase

Dynamics can be described by location of shock front versus time. We look for a self similar solution, in which the dynamics can be reduced to one variable = Rt^{λ}

Note that dynamics are determined by initial energy of explosion, E, and density of ISM, ρ_0.

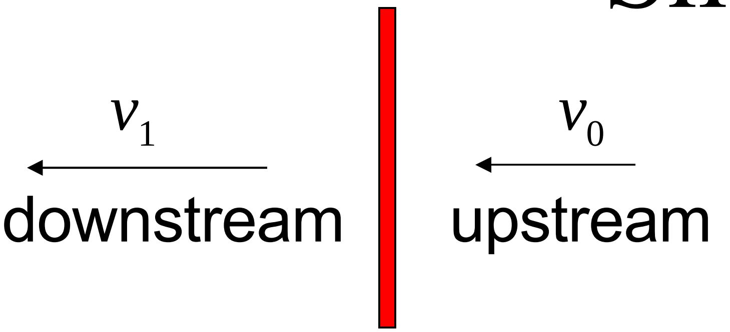
Consider quantity E/ρ_0. It has units of (length)^5(time)$^{-2}$.

Therefore, $(E/\rho_0)(t^2/R^5)$ is a dimensionless quantity which describes the dynamics of the expansion.

The solution requires $\mathrm{R(t)} = \mathrm{k}(E/\rho_0)^{1/5}\, t^{2/5}$ and $v(t) = 2R/5t$

This solution describes the expansion of SNR pretty well.

Shock Jump



v_1

downstream

v_0

upstream

Look at reference frame where shock is stationary, v_0 = shock speed

Mass flux: $\rho_1 v_1 = \rho_0 v_0$ Momentum flux: $P_1 + \rho_1 v_1^2 = P_0 + \rho_0 v_0^2$

Energy flux: $\frac{1}{2}\rho_1 v_1^3 + P v_1 \gamma/(\gamma-1) = \frac{1}{2}\rho_0 v_0^3 + P v_0 \gamma/(\gamma-1)$

Where ρ is density, P is pressure, γ is the adiabatic index.

Introduce the Mach number $M = v_0/c_0$ where $c_0 = \mathrm{sqrt}(\gamma P_0/\rho_0)$ is the sound speed upstream, and find in the limit of large M

$\rho_1/\rho_0 = (\gamma+1)/(\gamma-1)$ and $T_1/T_0 = 2\gamma(\gamma-1)M^2/(\gamma+1)^2$

For $\gamma = 5/3$, find $\rho_1/\rho_0 = 4$ and $T_1/T_0 = (5/16)M^2$

Get large increase in temperature for large M.

Sedov Solution

In Sedov solution, find for downstream material:

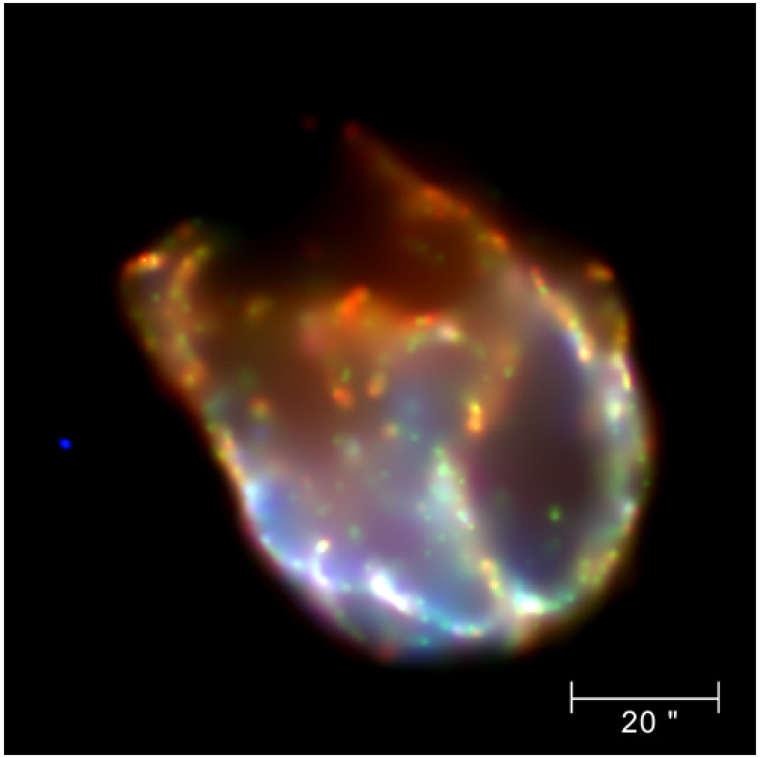
pressure = (3/4) $\rho_0 v^2$

temperature = $(3m/16k)\, v^2$ where m is the mean mass per particle downstream (including electrons) and k is Boltzmann’s constant.

Temperature ~ (10 K)v^2 for v in km/s,

For $v \sim 1000$ km/s, have $T \sim 10^7$ K which means gas is heated to X-ray producing temperatures.

N132D in the LMC



Shock speed ~ 2,000 km/s.

Gas is heated by shock to X-ray emitting temperatures.

Although gas glows in X-rays, the loss of energy due to radiation is relatively unimportant to the dynamics of the expansion, i.e. cooling time is longer than age of SNR.

Radiative Cooling

- Eventually, the shock slows down, gas is heated less. Define end of adiabatic phase as when half of energy has been radiated away. Typically, shock speed is then about 200 km/s (with dependence on initial energy and ISM density). Most material swept-up into dense, cool shell. Residual hot gas in interior emits weak X-rays.
- Matter behind shock cools quickly, pressure is no longer important, shell moves with constant momentum $(4\pi/3)R^3\rho_0 v$ = constant.

$$R = R_{rad}\left(\frac{8}{5}\frac{t}{t_{rad}} - \frac{3}{5}\right)^{1/4}$$

Disappearance

- When shock velocity drop to ~20 km/s, the expansion becomes subsonic and the SNR merges with the ISM.
- However, the SNR leaves magnetic fields and cosmic rays which can still persist with observable imprints for millions of years.

Phases of Shell-type SNRs

- **Supernova explosion** – Fast
- **Free expansion** - Hundreds of years
- **Adiabatic or Sedov** – 10,000-20,000 years
- **Snow-plow or Cooling** – Few 100,000 years
- **Disappearence** – Up to millions of years