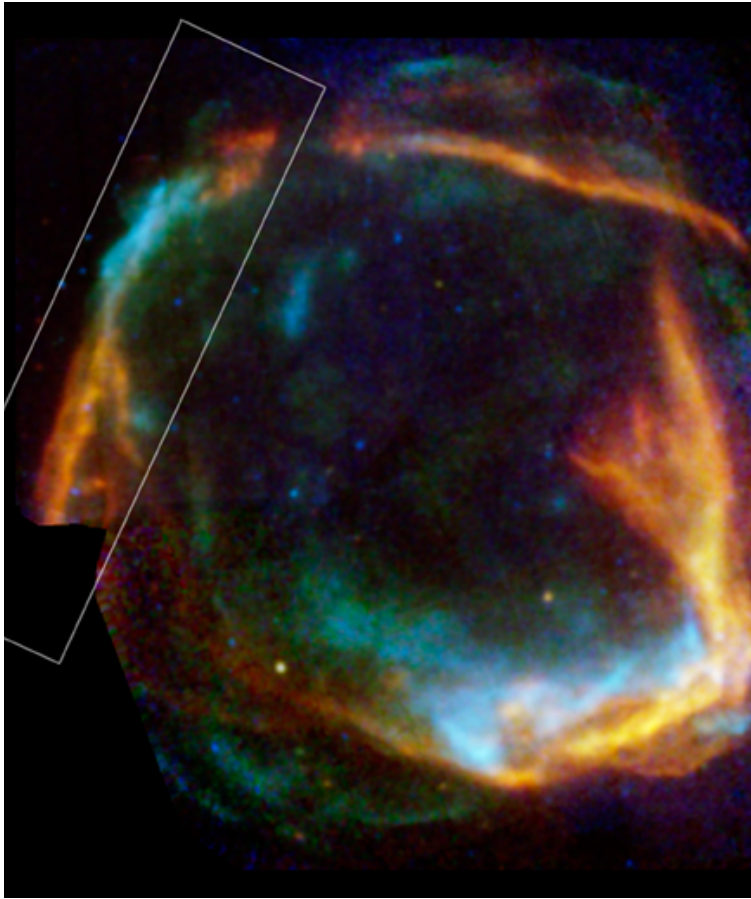


Supernova Remnants

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

Shell-type SNR



RCW 86, SN in 185 AD

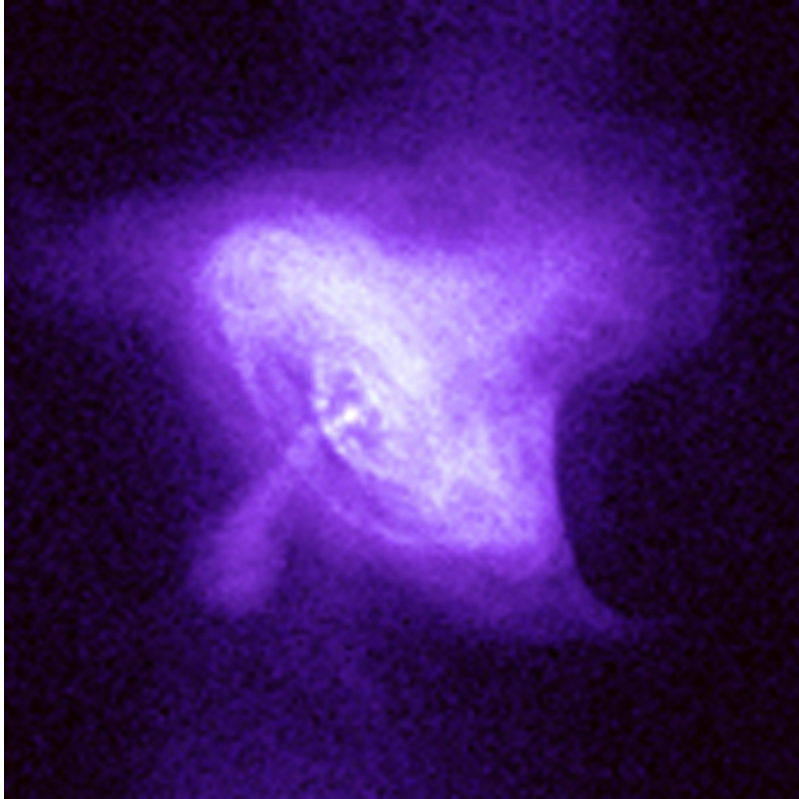
Shell-type SNR:

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.

Pulsar Wind Nebulae (Plerions)



Crab, SN in 1054 AD

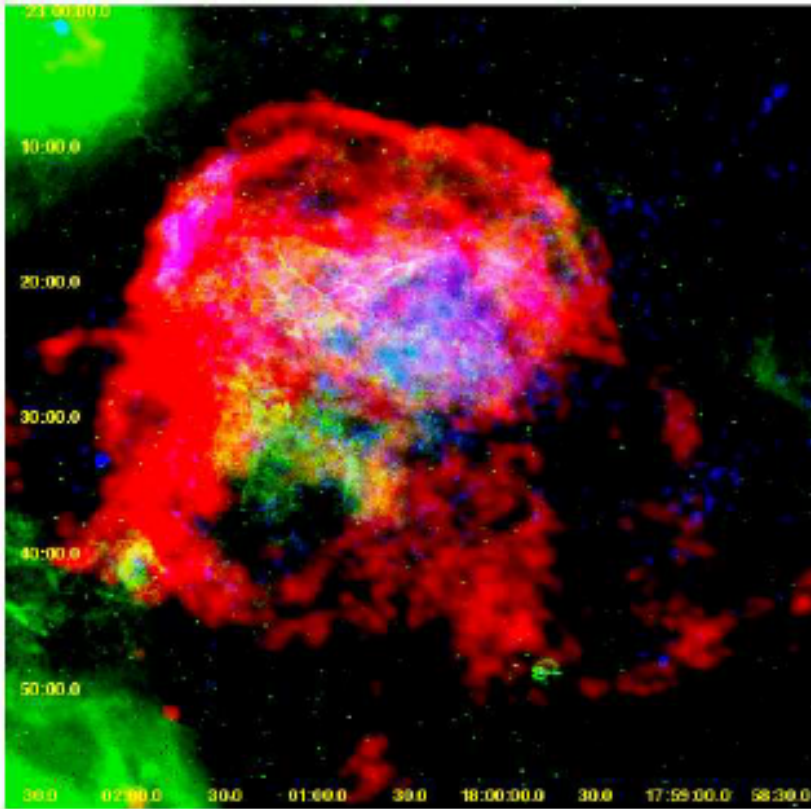
Center filled or Crab-like SNR, or pulsar wind nebulae:

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.

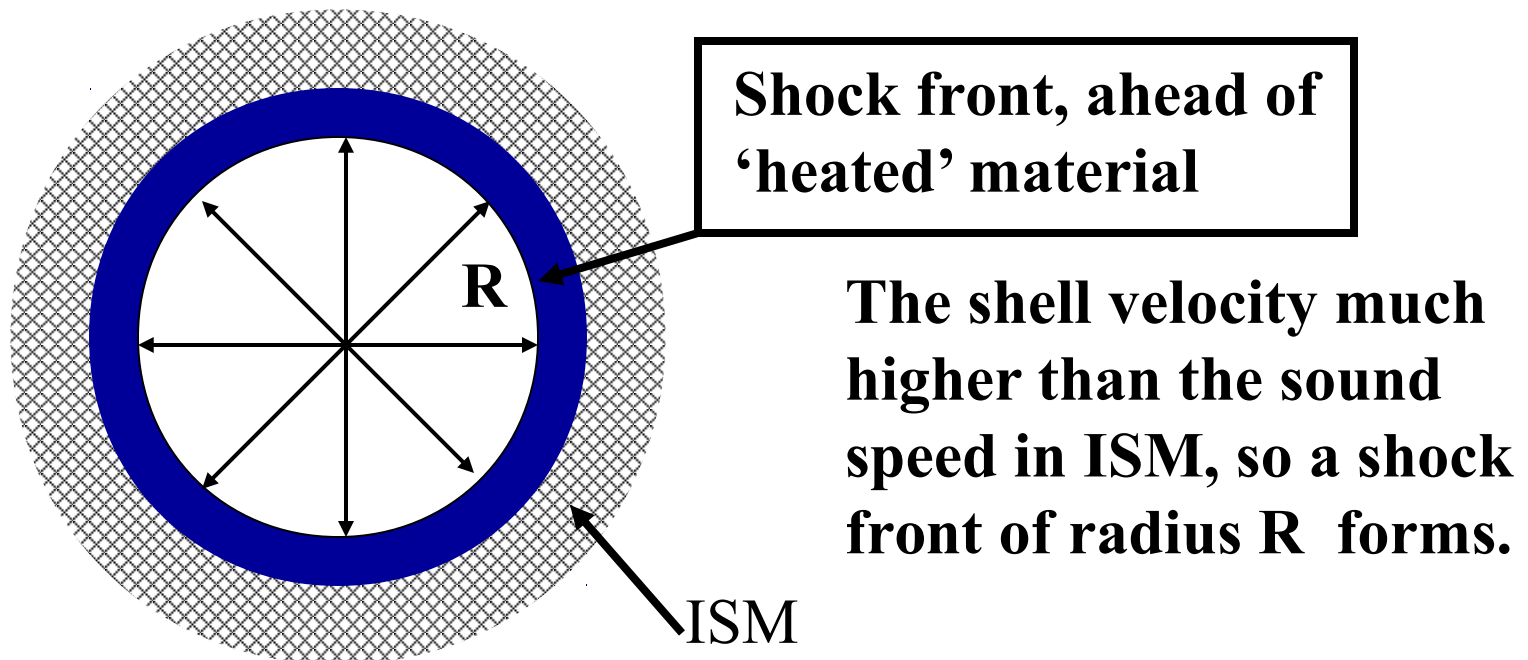
W28: red = radio, green = $H\alpha$,
blue = X-ray,

Phases of Shell-type SNRs

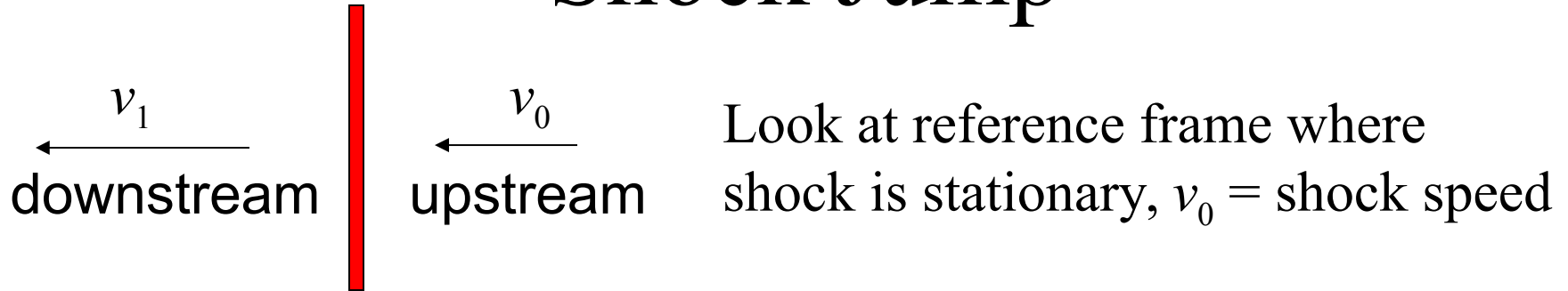
- **Supernova explosion** – ejecta $v \sim 10^4$ km/s
- **Free expansion** - ejecta mass $>$ swept up mass
- **Adiabatic or Sedov** – swept-up mass $>$ eject mass
- **Snow-plow or Cooling** – shock front cools, interior also cools
- **Disappearance** – remnant slows to speed of the random velocities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



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 $c_0 = \text{sqrt}(\gamma P_0 / \rho_0)$ is the sound speed upstream, and find in the limit of large M

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

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 .

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: $(4\pi/3)\rho R^3 \ll m_0$

- Since momentum is conserved:

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

- As long as swept-up mass \ll 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, $T \propto R^{-3(\gamma-1)}$

- Adiabatic process has $TV^{\gamma-1} = \text{constant}$
where $\gamma = C_p/C_v = \text{ratio of specific heats}$

For ideal gas, $\gamma = (f+2)/f$

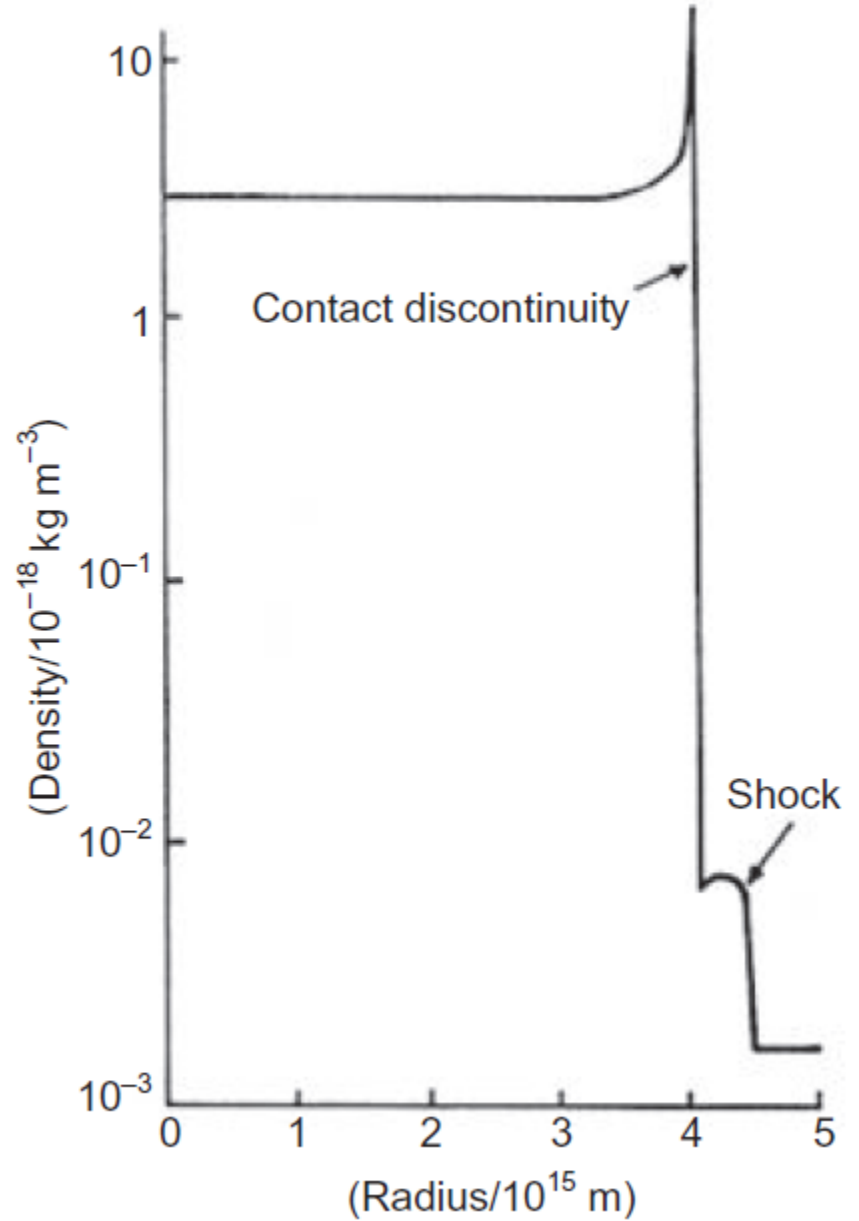
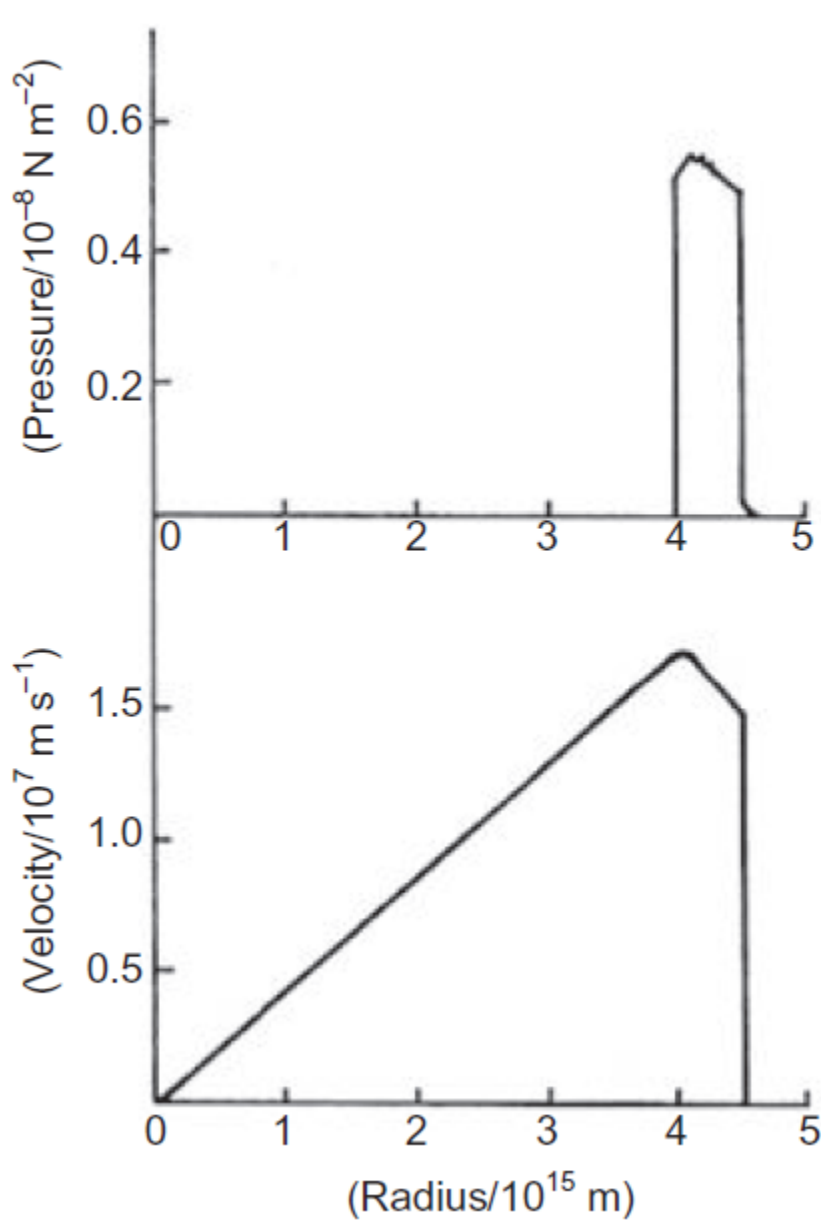
$f = \text{degrees of freedom}$

= 3 for monatomic gas

= 5 for diatomic gas

- Note $V \propto R^3$, so $TV^{\gamma-1} = \text{constant} = TR^{3(\gamma-1)}$
- Hence $T \propto R^{-3(\gamma-1)}$

Free Expansion



Dimensional Analysis

What is the free fall time scale of the Sun?

Inputs:

- Mass = $M = 2 \times 10^{33}$ g
- Radius = $r = 7 \times 10^{10}$ cm
- $G = 6.7 \times 10^{-8}$ erg cm g⁻² = 6.7×10^{-8} cm³ s⁻² g⁻¹.

Output is time = t with units of seconds,

$$T = M^a r^b G^c$$

find a, b, c to make units work.

Sedov Phase

Have an explosion with energy, E , that goes off in the ISM of density, ρ_0 . These are the only two variables in the problem.

Dynamics can be described by location of shock front versus time. Look for a solution, $R = E^a \rho_0^b t^c$.

Have students work out solution.

Sedov Phase

Have an explosion with energy, E , that goes off in the ISM of density, ρ_0 . These are the only two variables in the problem.

Dynamics can be described by location of shock front versus time. From dimensional analysis,

$$R = E^{1/5} \rho_0^{-1/5} t^{2/5} = (E/\rho_0)^{1/5} t^{2/5}$$

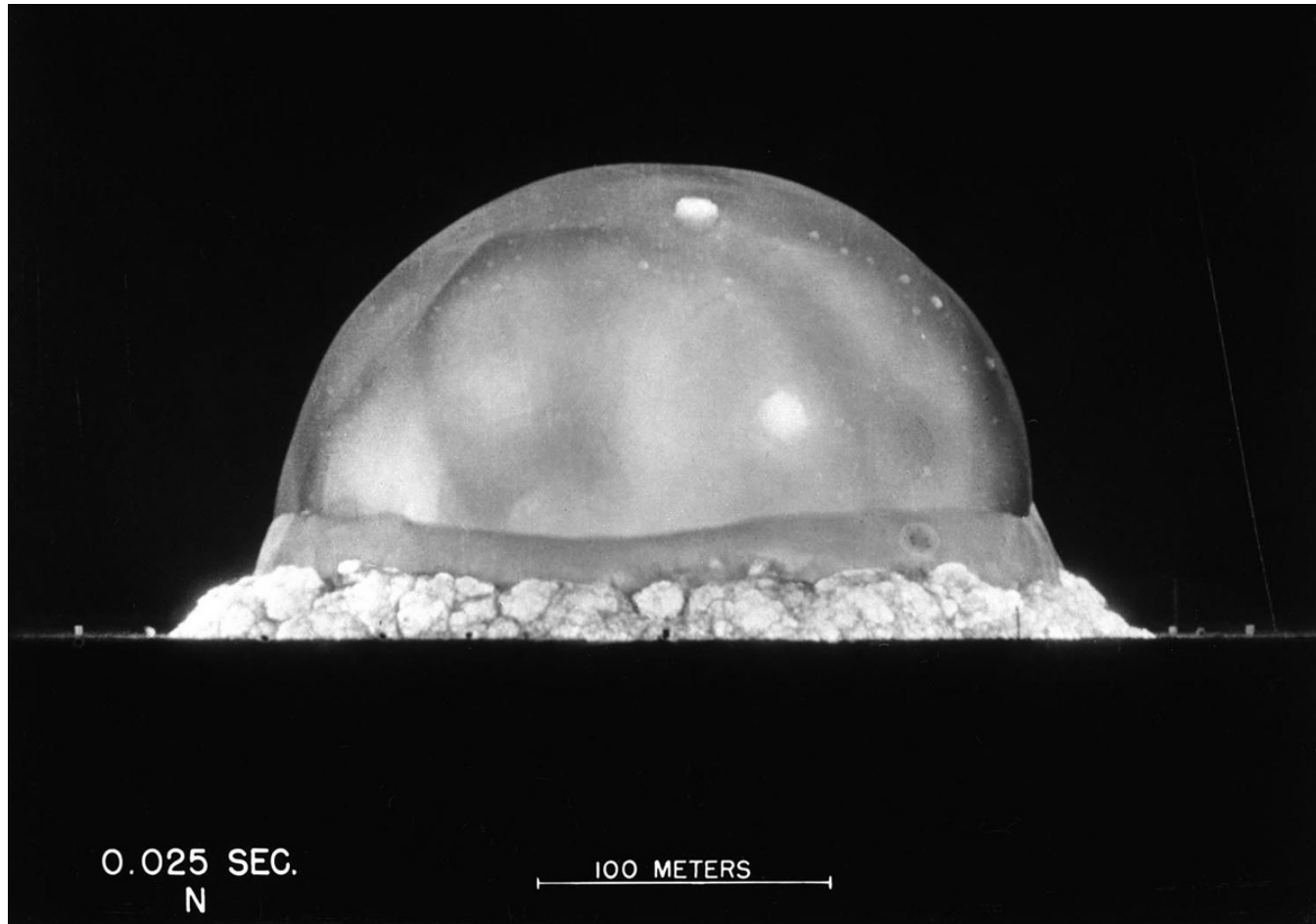
Another way to think about this is that E/ρ_0 has units of $(\text{length})^5(\text{time})^{-2}$. Therefore, $(E/\rho_0)(t^2/R^5)$ is a dimensionless quantity which describes the dynamics of the expansion.

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

This solution describes the expansion of SNR pretty well.

Sedov Phase

Can you estimate the energy of this atomic bomb explosion from the photograph?



Sedov Solution

In Sedov solution, find for downstream material:

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

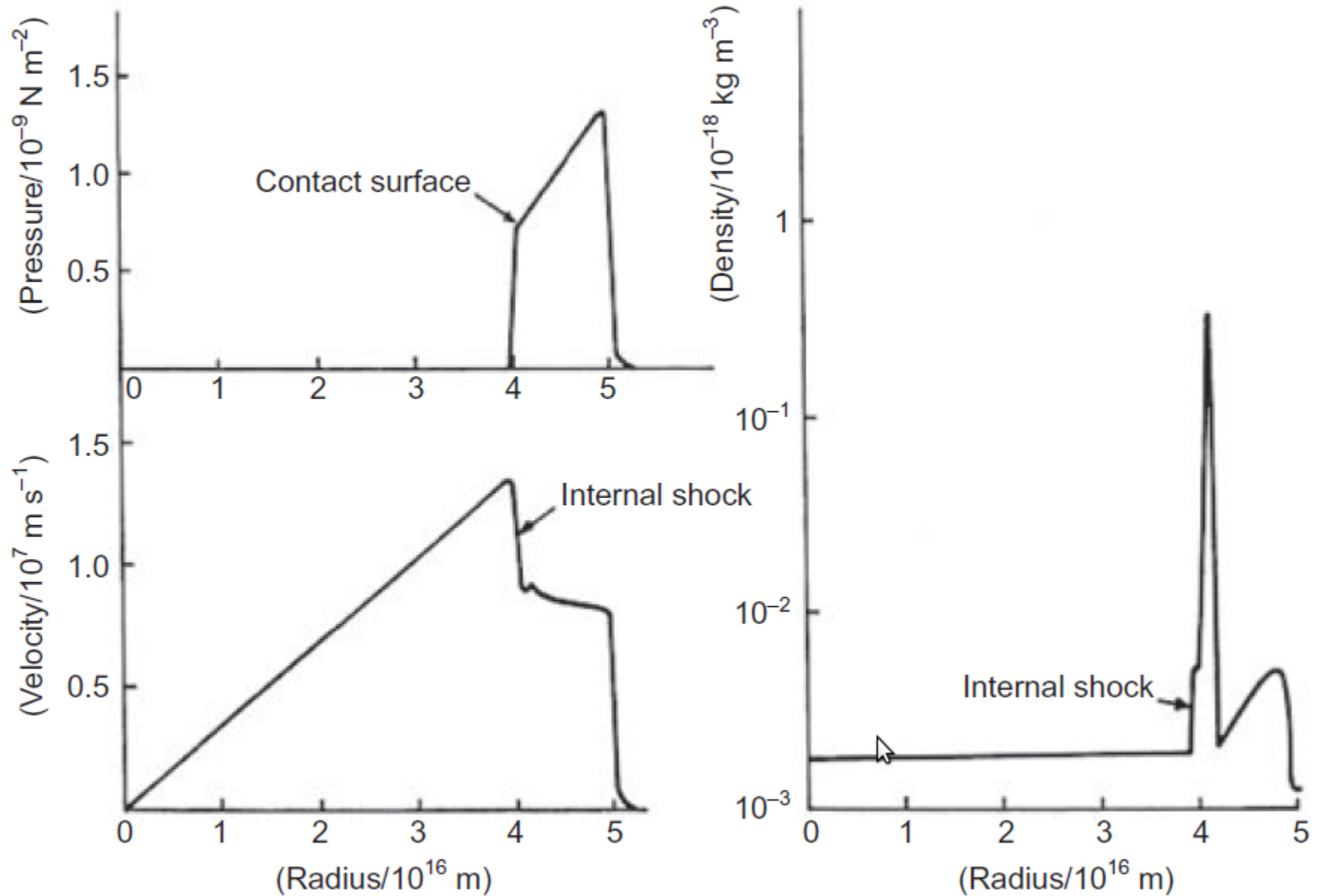
temperature = $(3m/16k) v^2$ where m is the mean mass per particle downstream (including electrons) and k is Boltzmann's constant.

Temperature $\sim (10 \text{ K})v^2$ 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.

Also have internal shock that propagates back into the SNR.

Sedov Phase

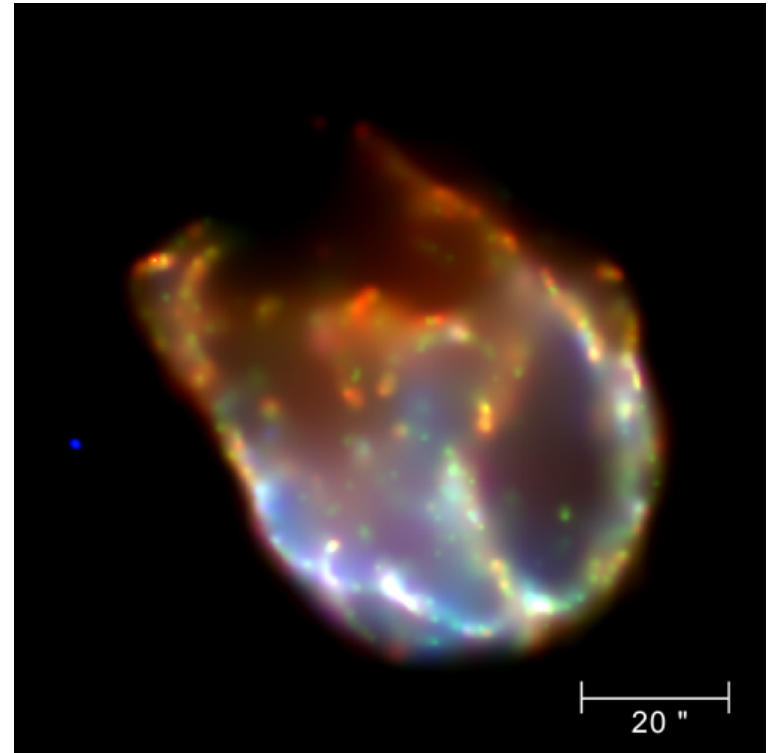


N132D in the LMC

Shock speed $\sim 2,000$ 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

$$(4\pi/3)R^3\rho_0v = \text{constant.}$$

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

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
- **Disappearance** – Up to millions of years