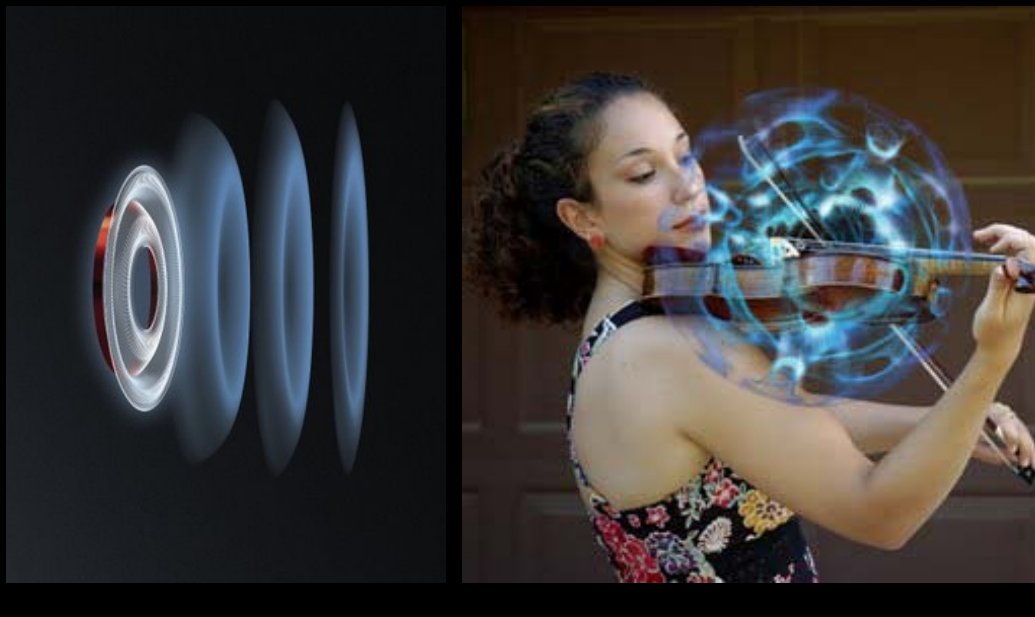
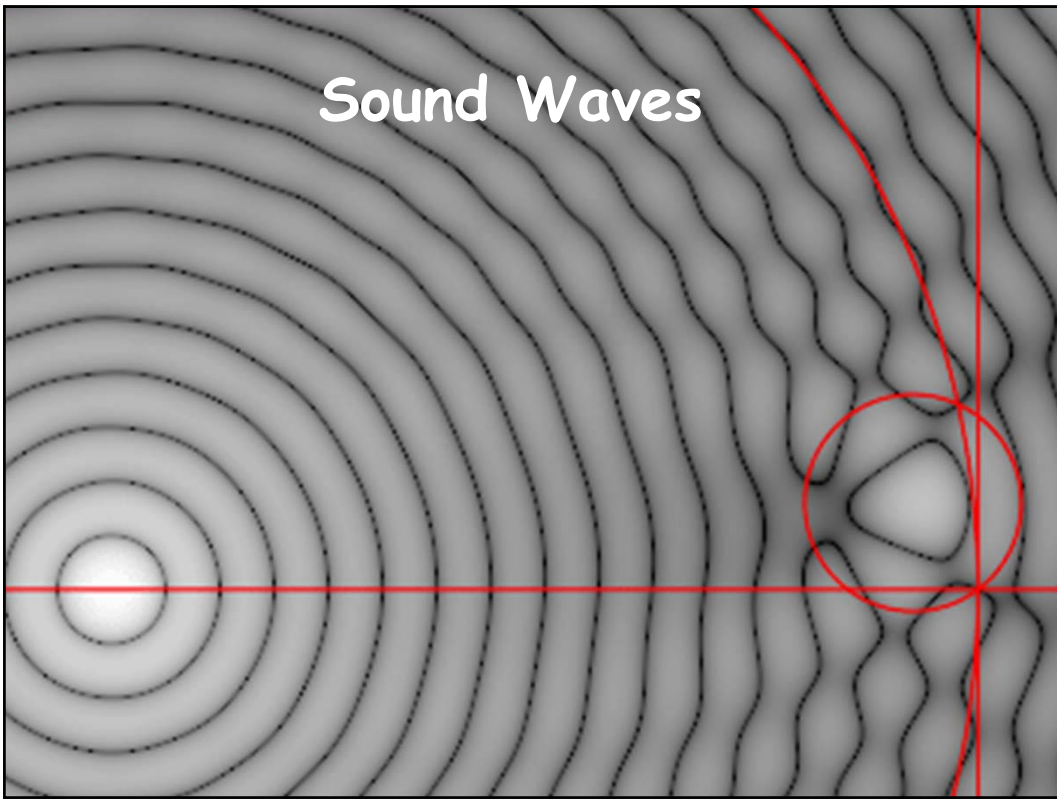


# Sound Waves

## Sound Waves:





# Sound Waves

direction of propagation →

A

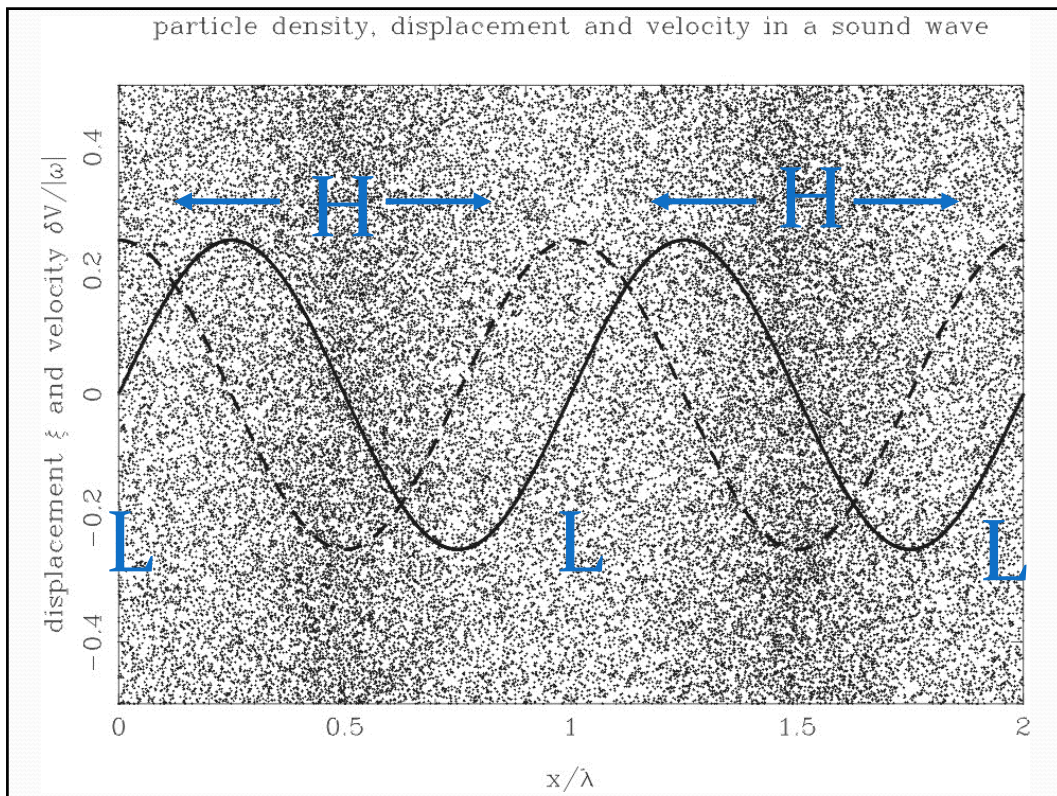
B

compression  
rarefaction

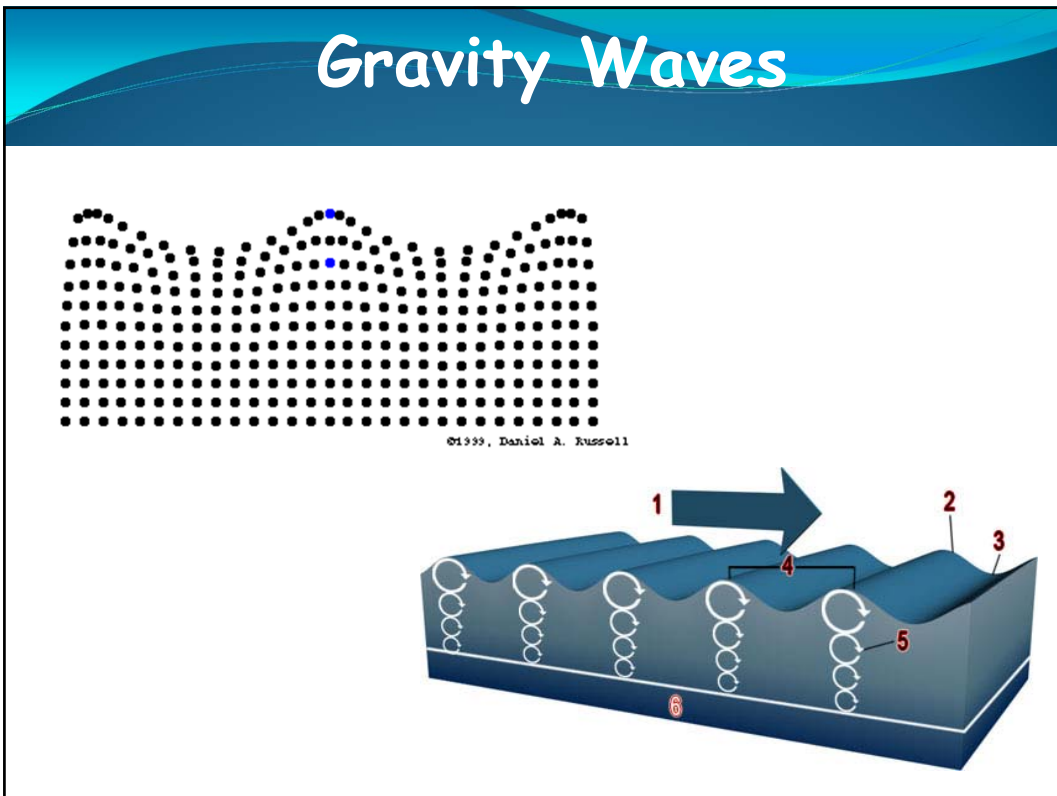
C

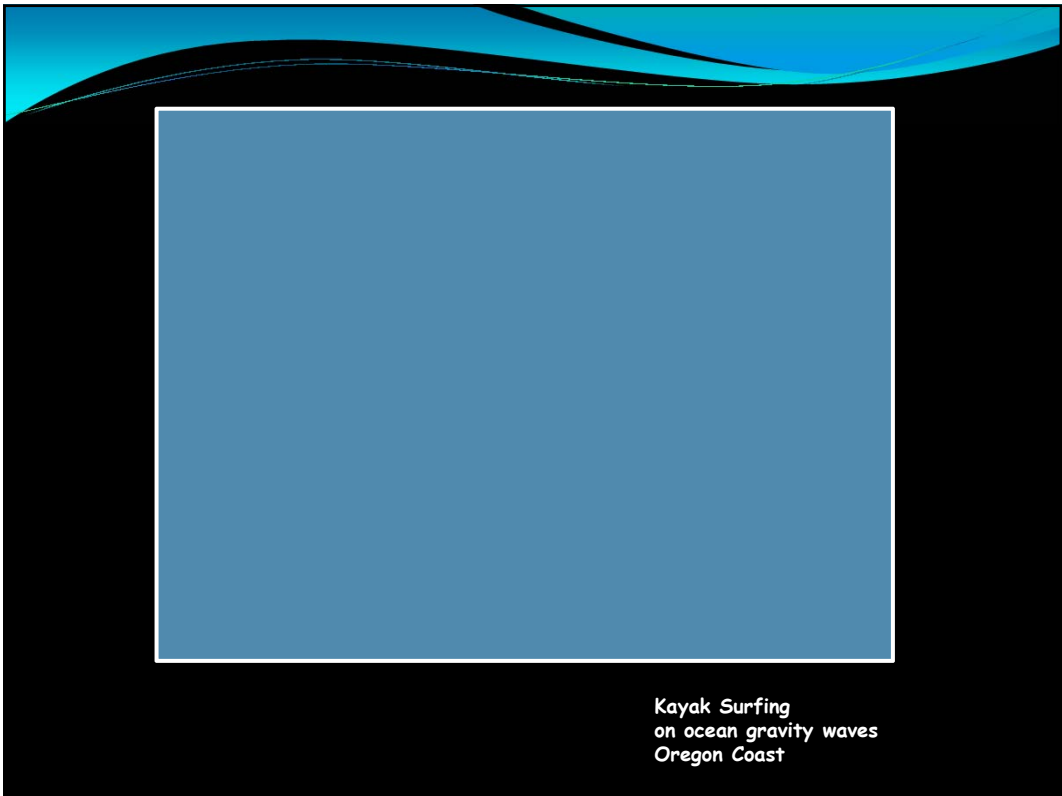
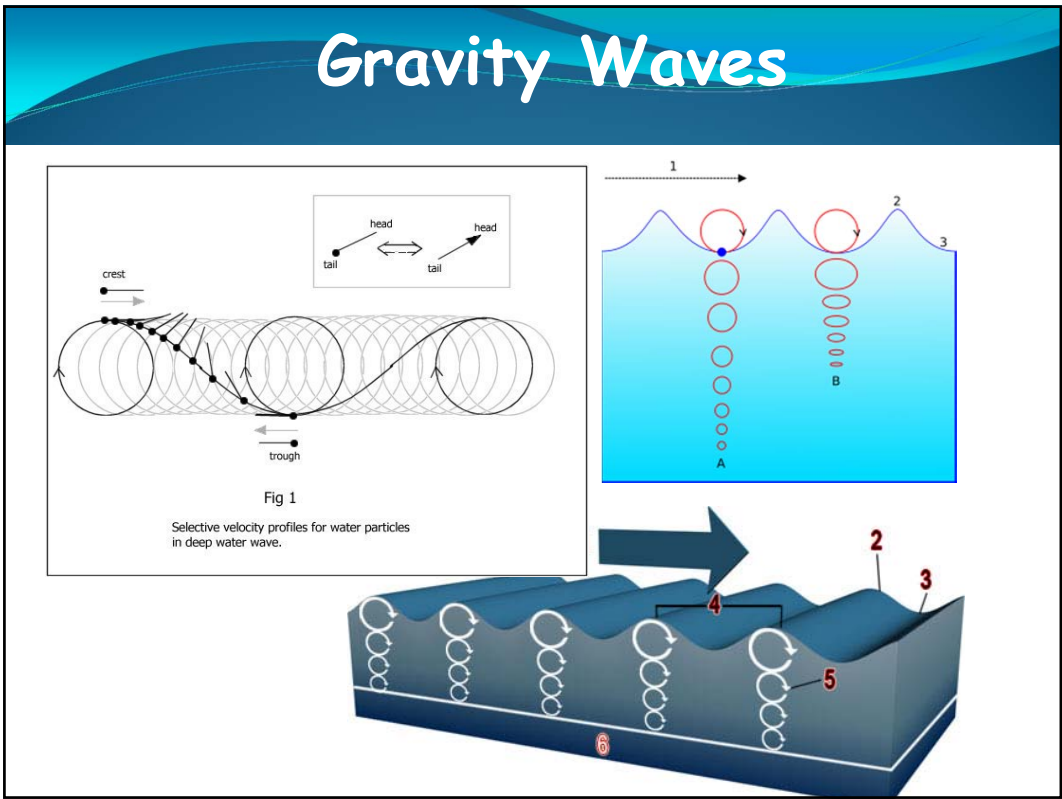
λ      A

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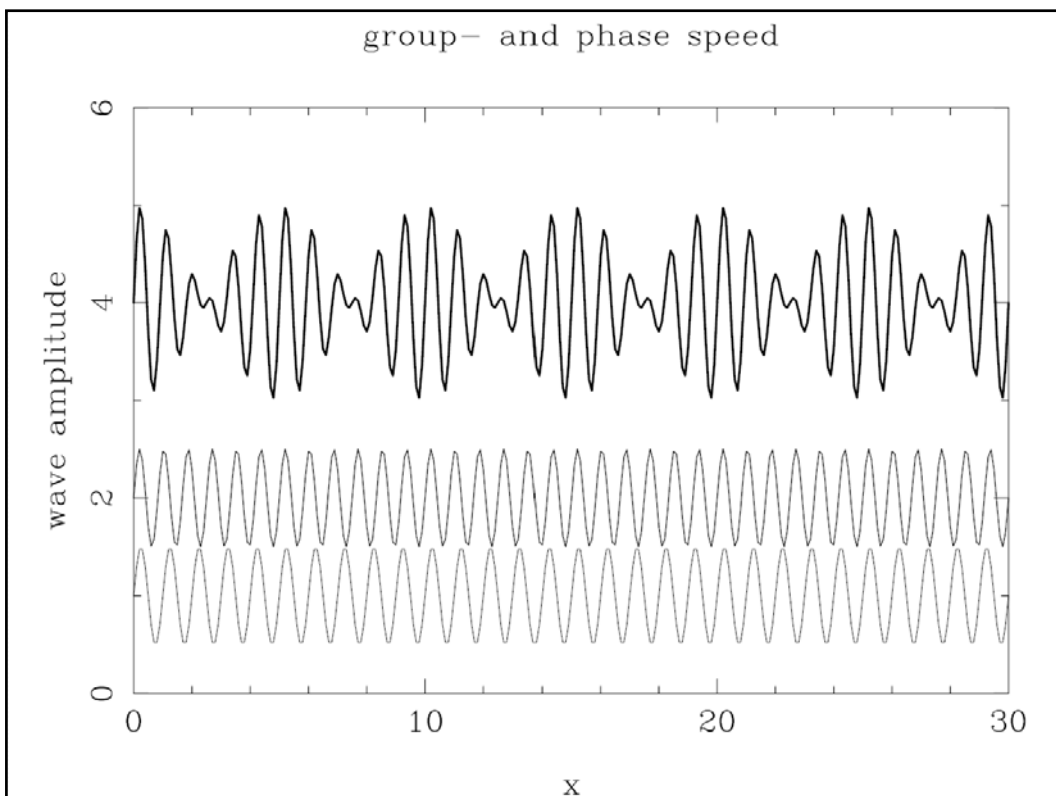
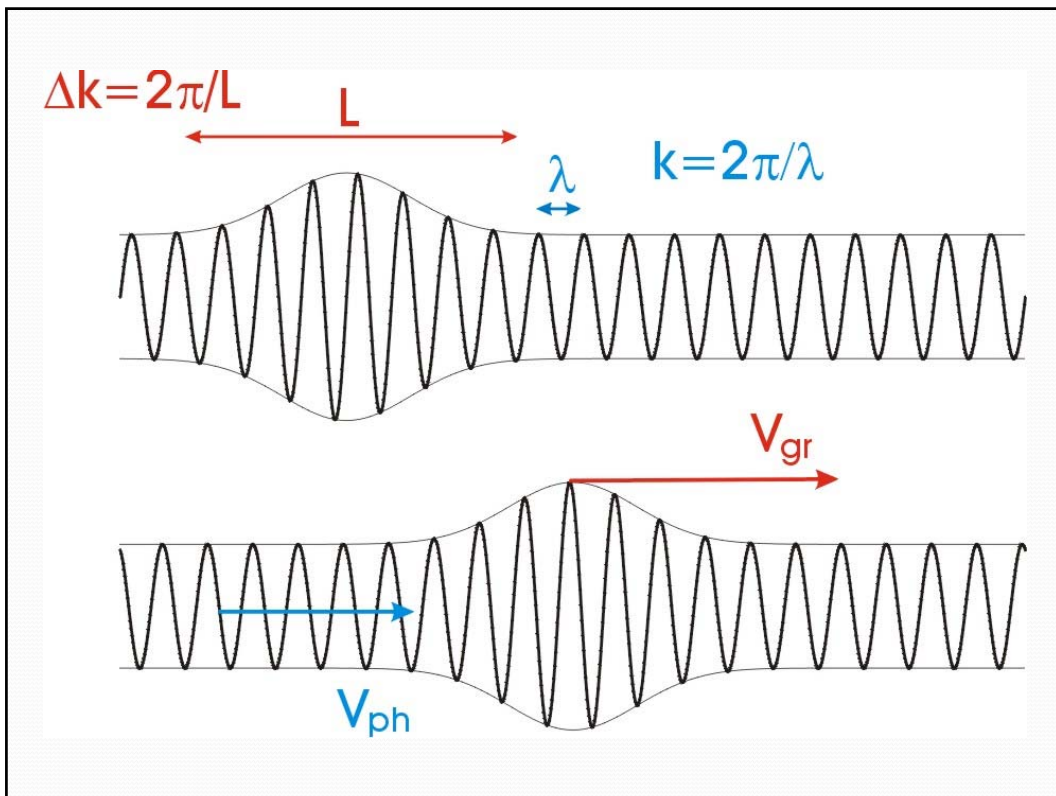


# Gravity Waves

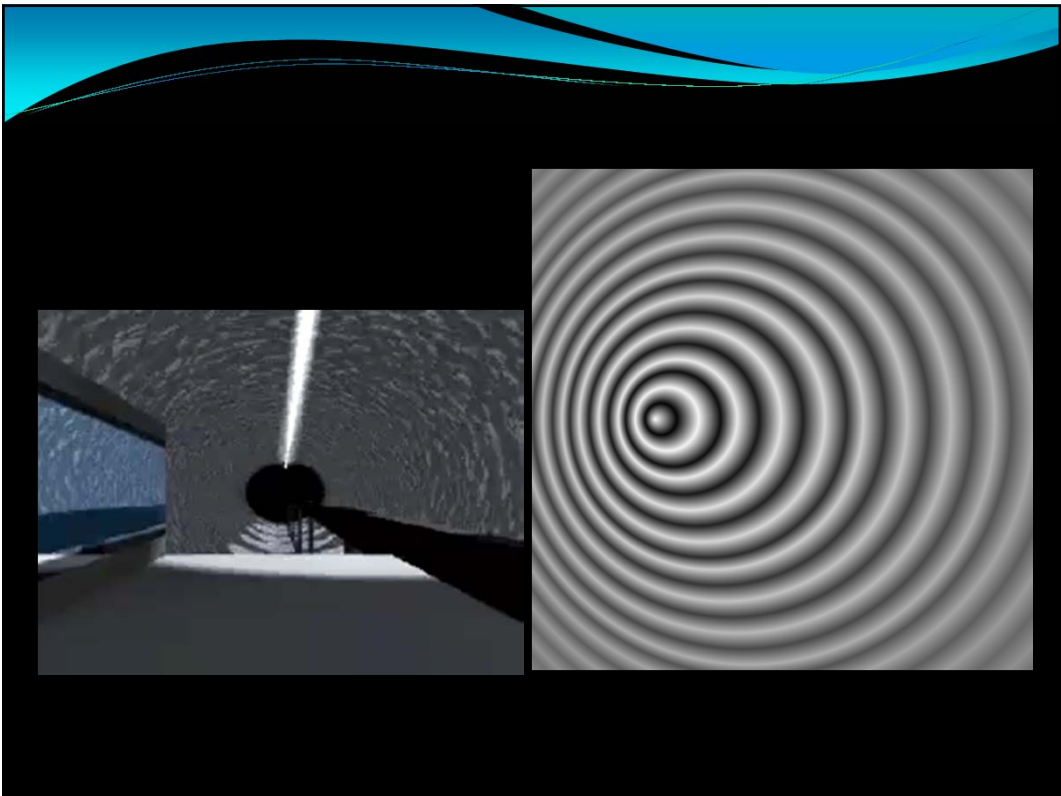






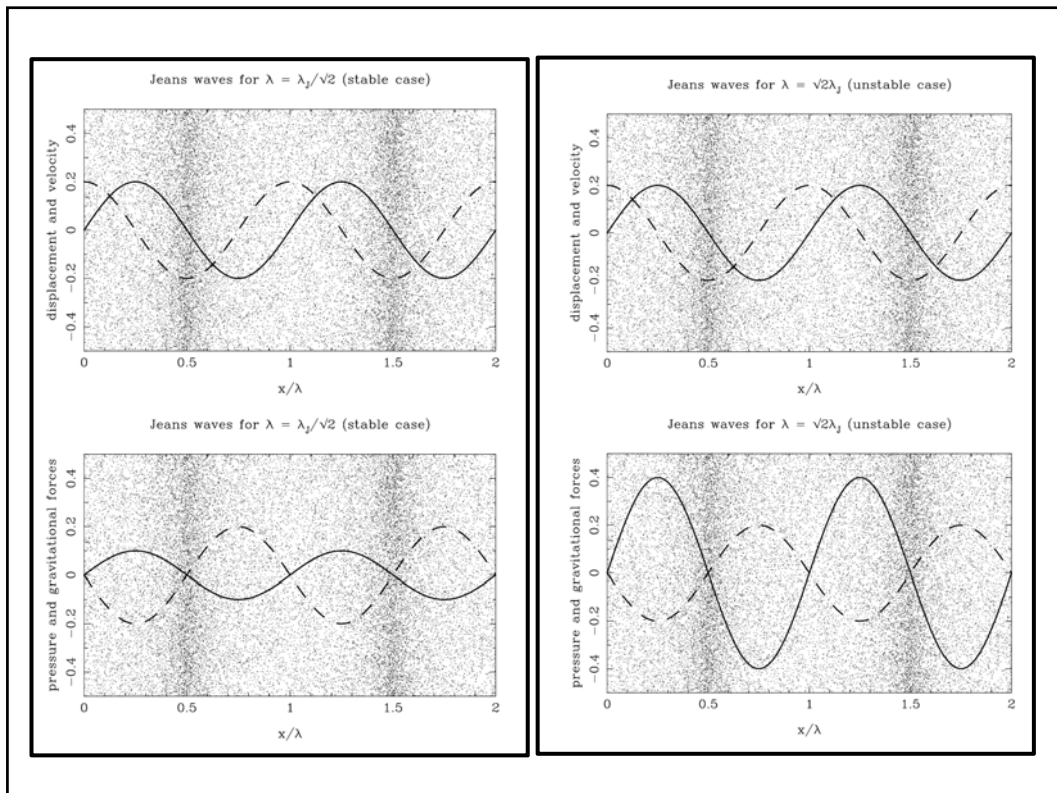


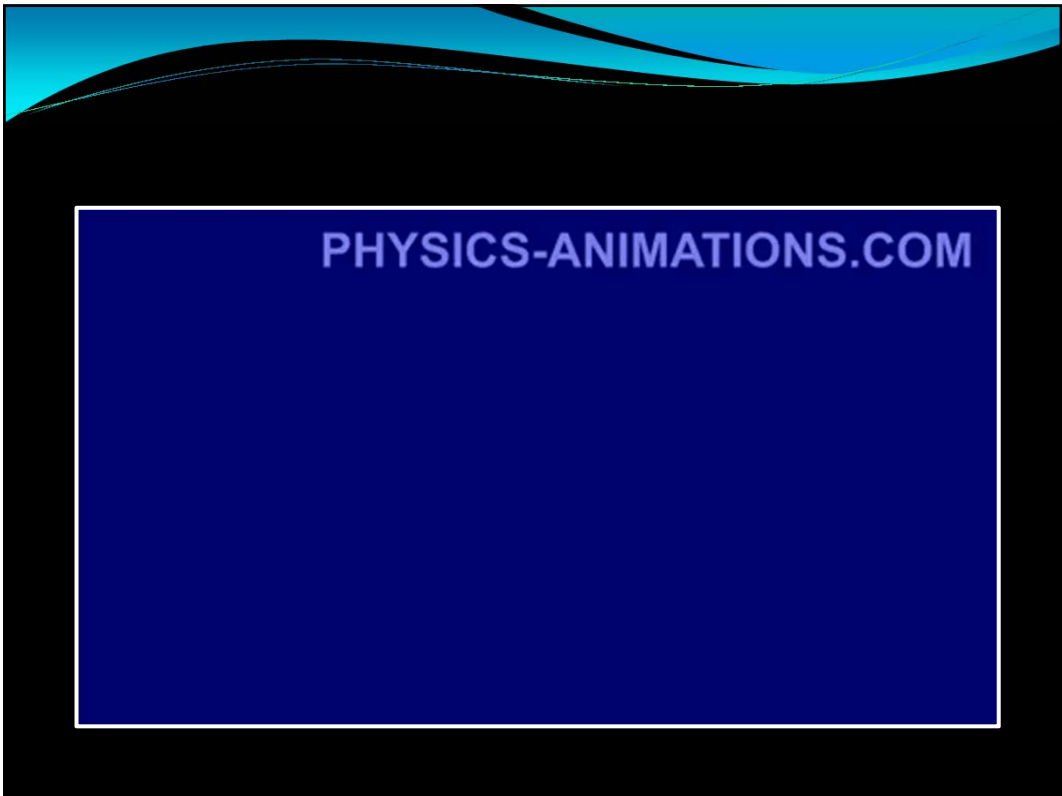
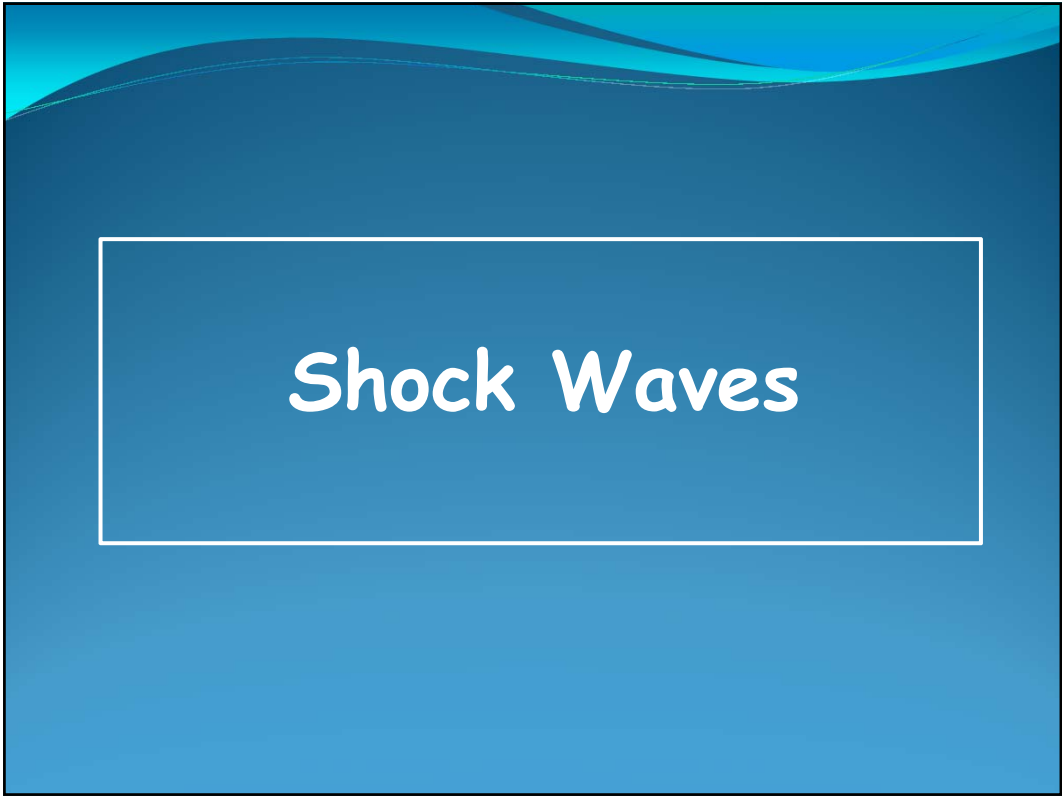
# Doppler Effect





# Jeans Instability





# Shocks

1. Shocks are **sudden** transitions in flow properties such as density, velocity and pressure;
2. In shocks the kinetic energy of the flow is converted into **heat**, (pressure);
3. Shocks are **inevitable** if sound waves propagate over long distances;
4. Shocks always occur when a flow hits an obstacle **supersonically**
5. In shocks, the flow speed along the shock normal changes from **supersonic** to **subsonic**

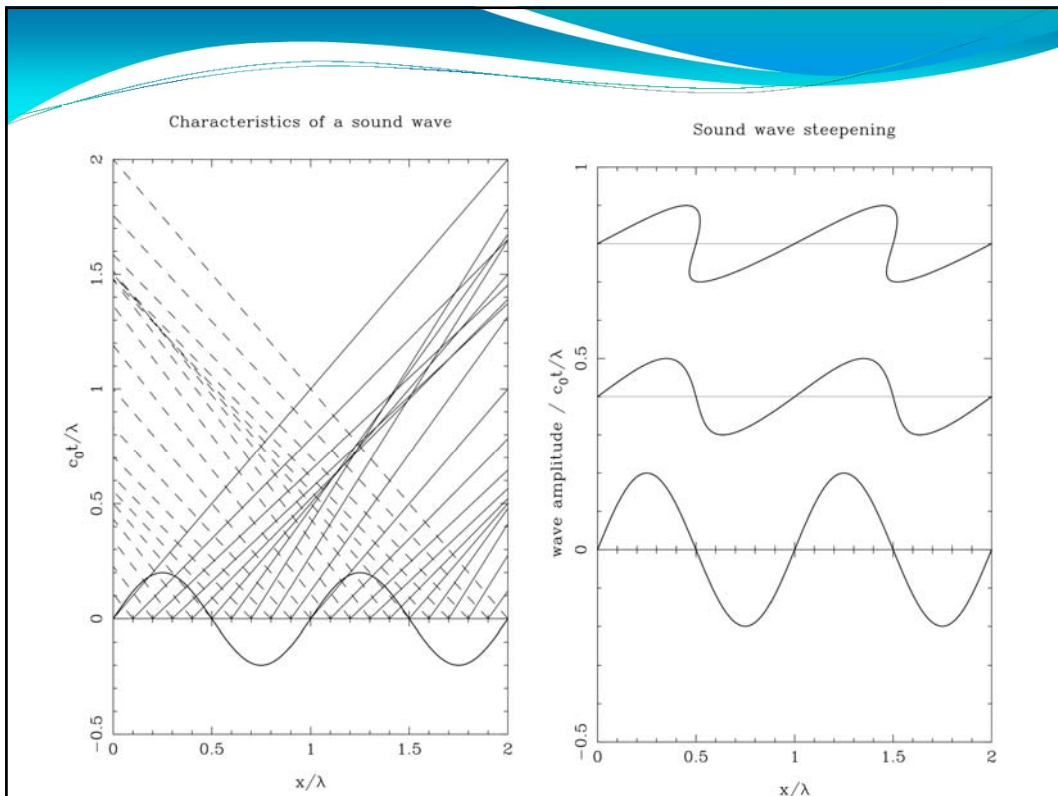
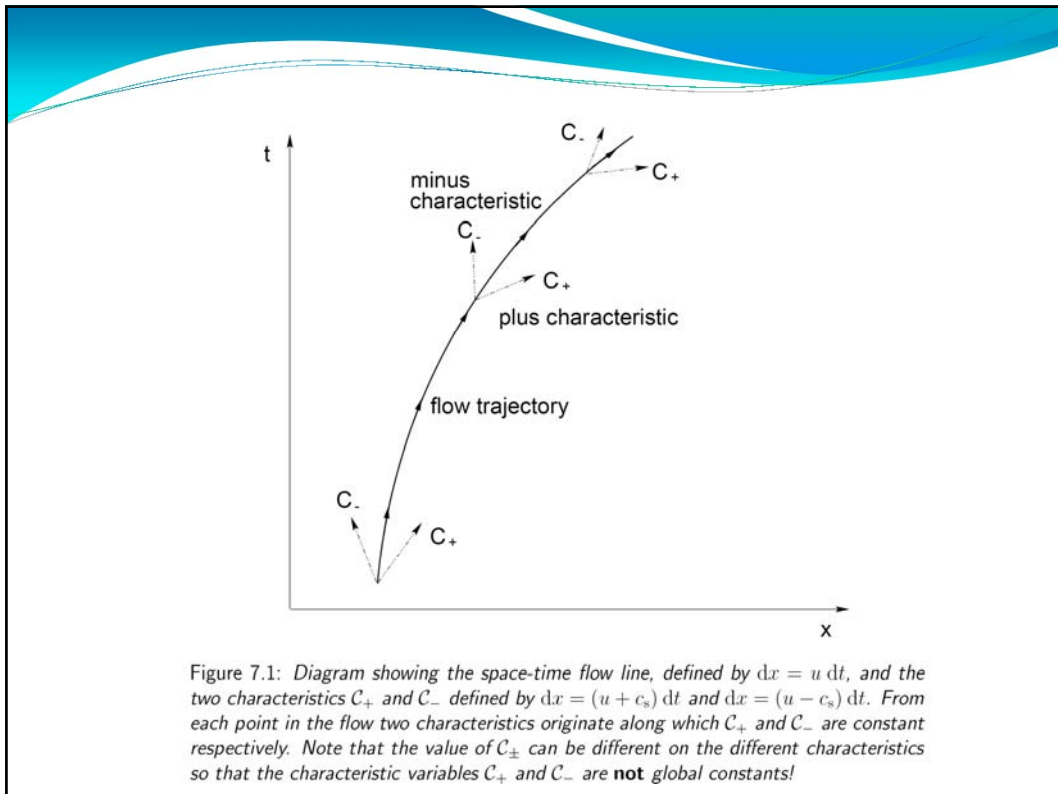
Shock must form

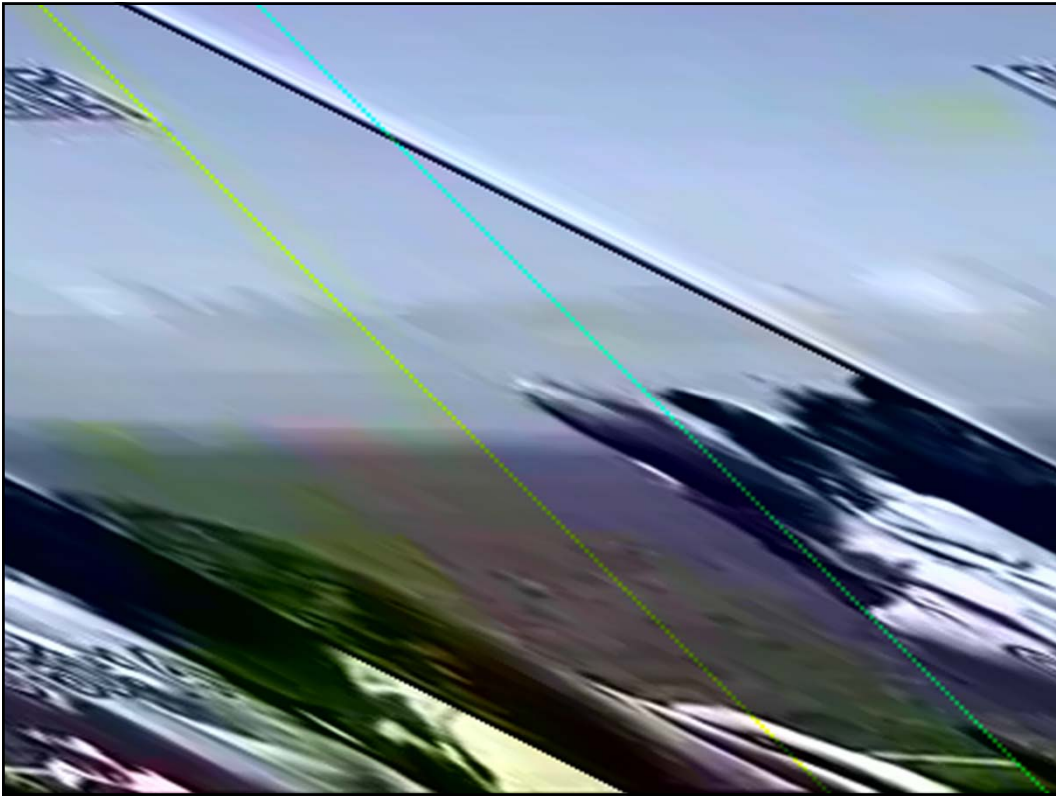
## Wave Breaking

High-pressure/density regions move faster

$$u = \frac{2c_{s0}}{\gamma - 1} \left[ \left( \frac{\rho}{\rho_0} \right)^{(\gamma-1)/2} - 1 \right]$$

$$\approx c_{s0} \left( \frac{\Delta\rho}{\rho} \right)$$

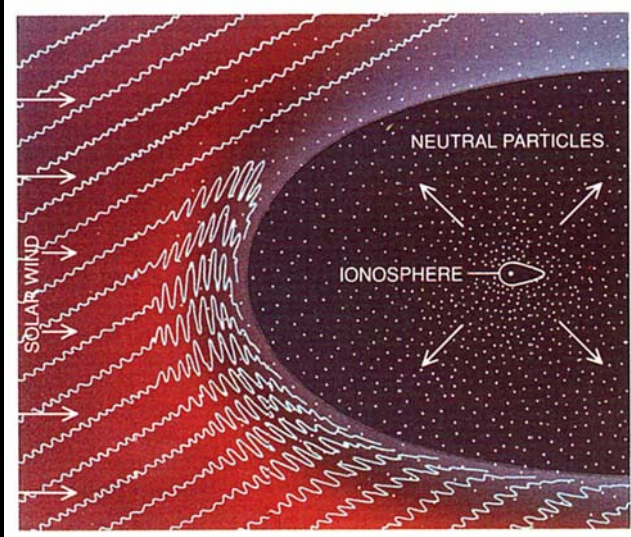




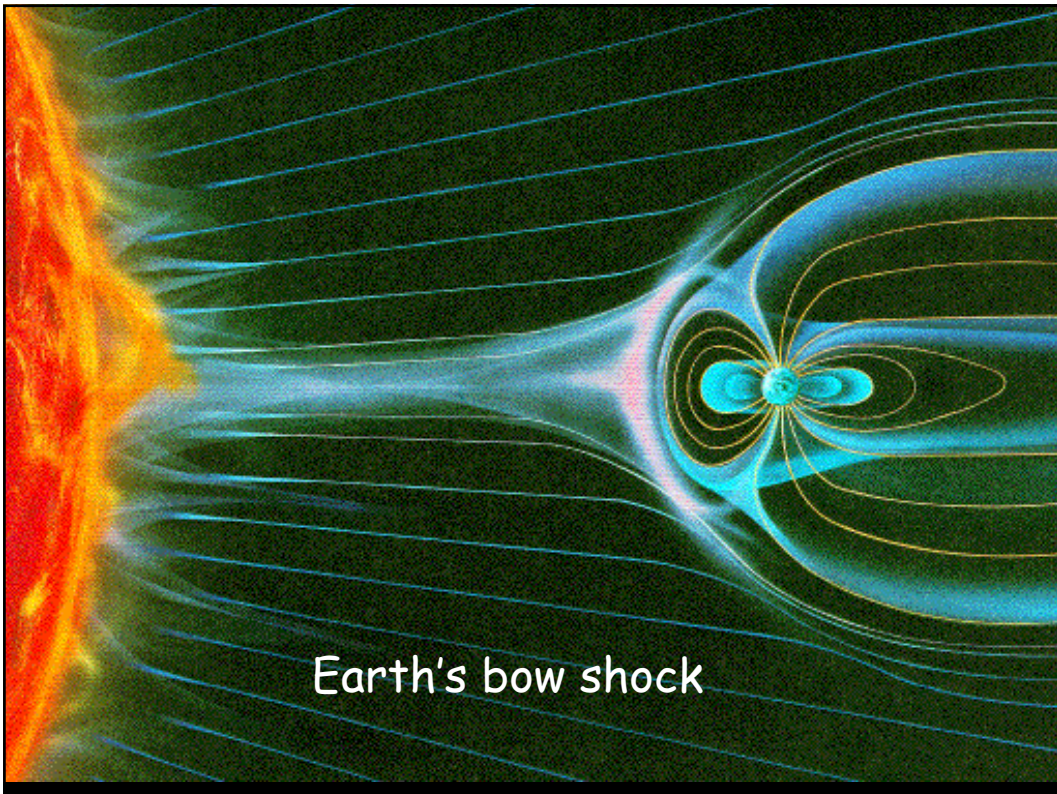
## Chelyabinsk Meteorite (Feb. 2013): Sonic Boom



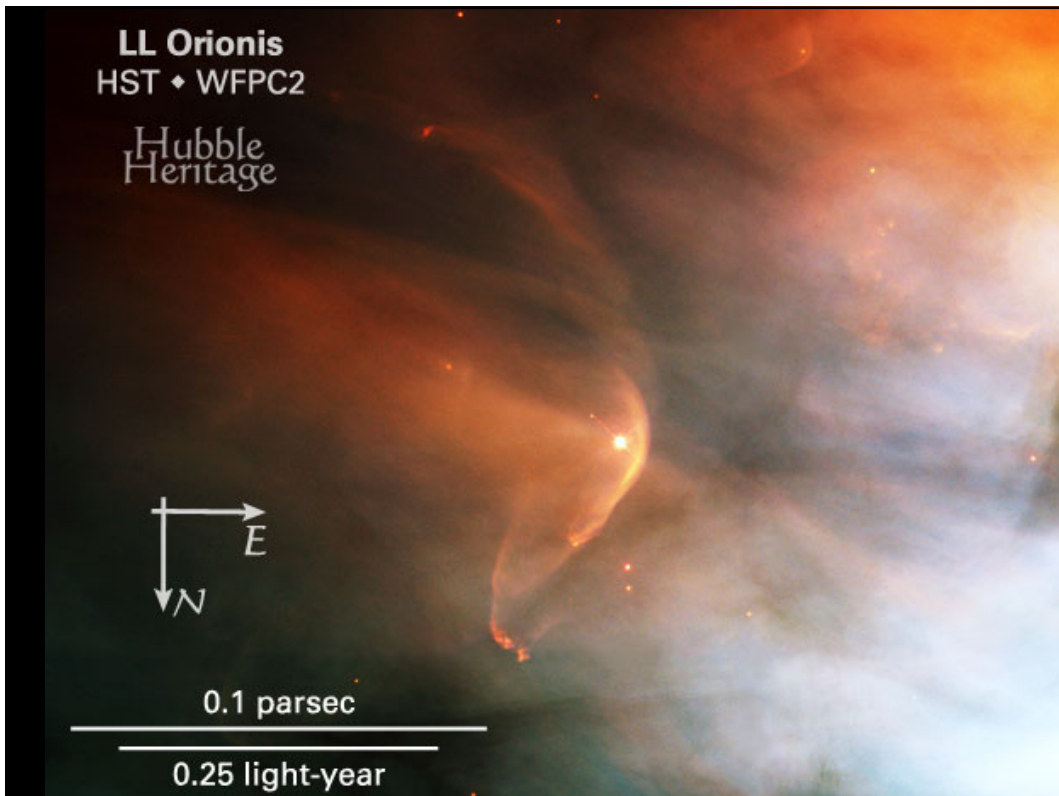
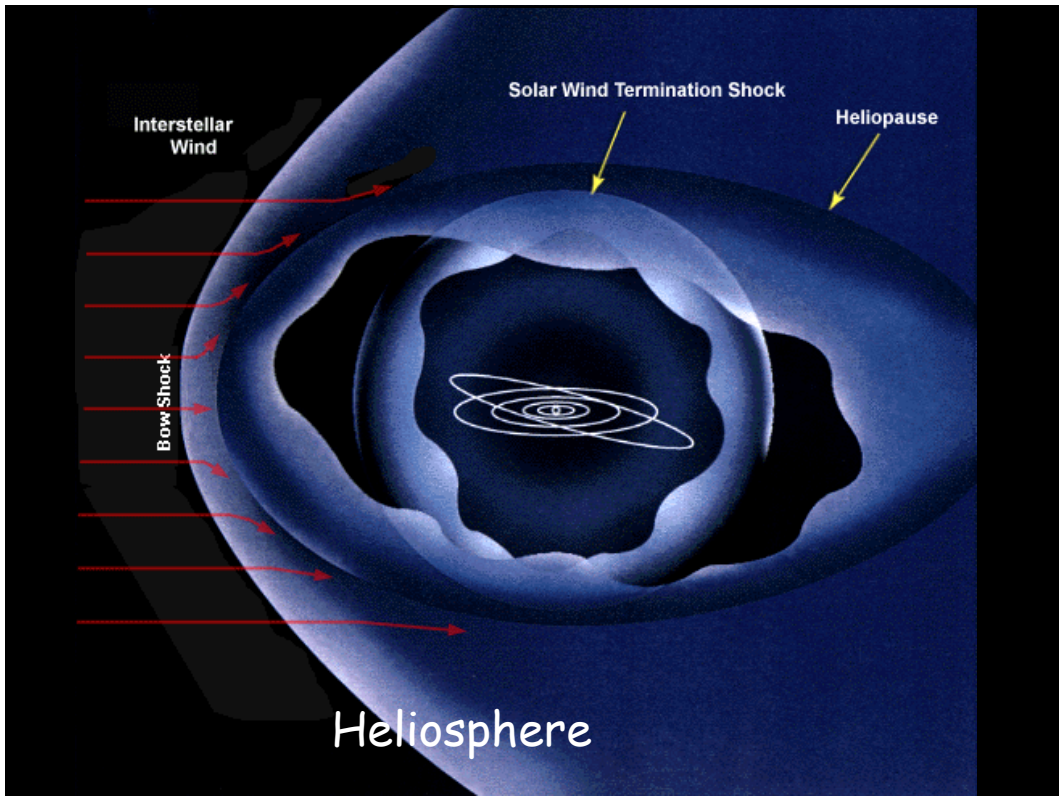
# Examples of Astrophysical shocks

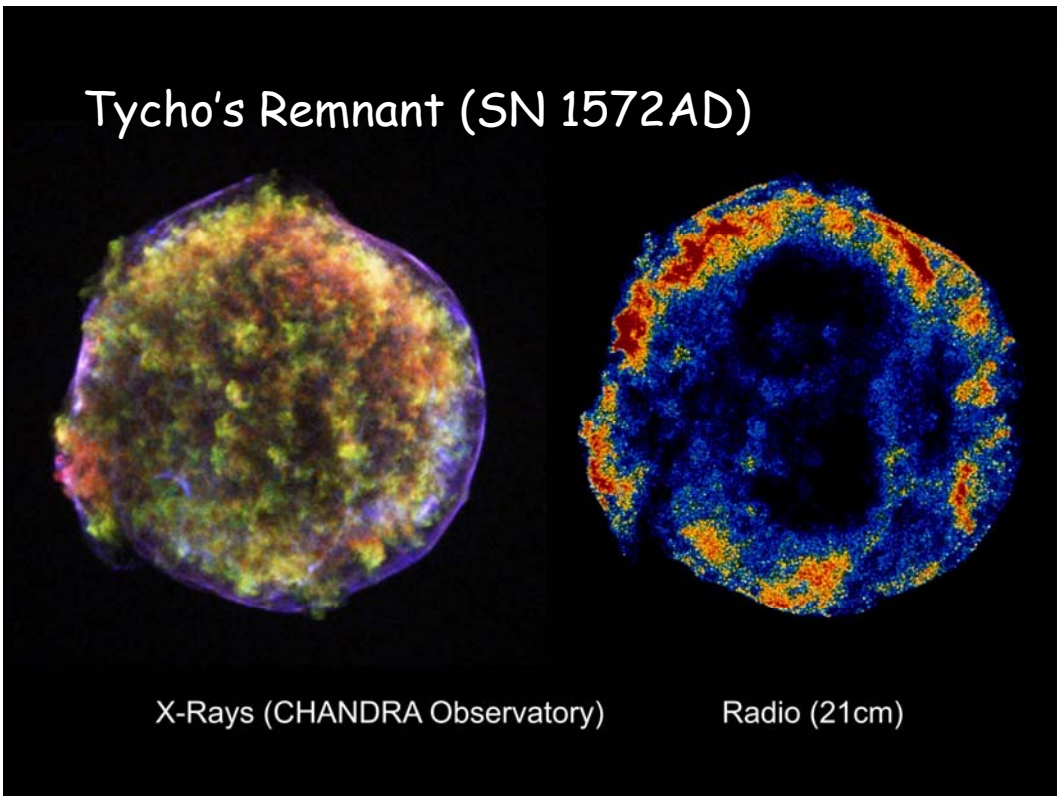
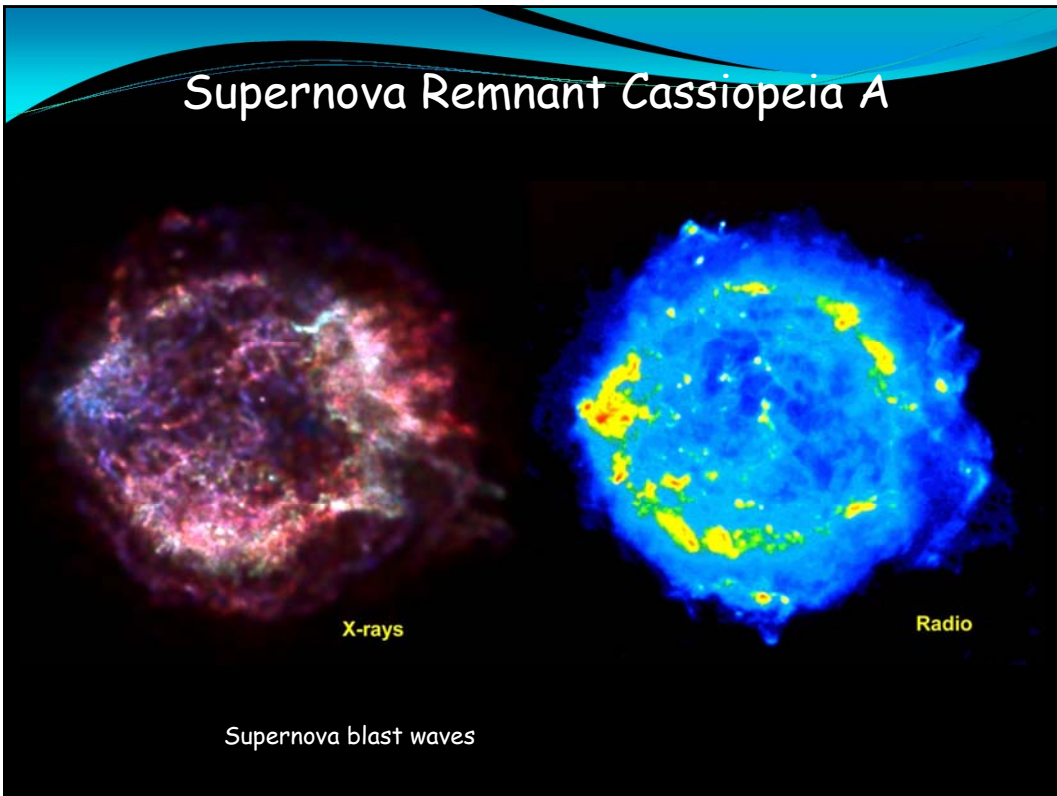


Cometary bow-shocks

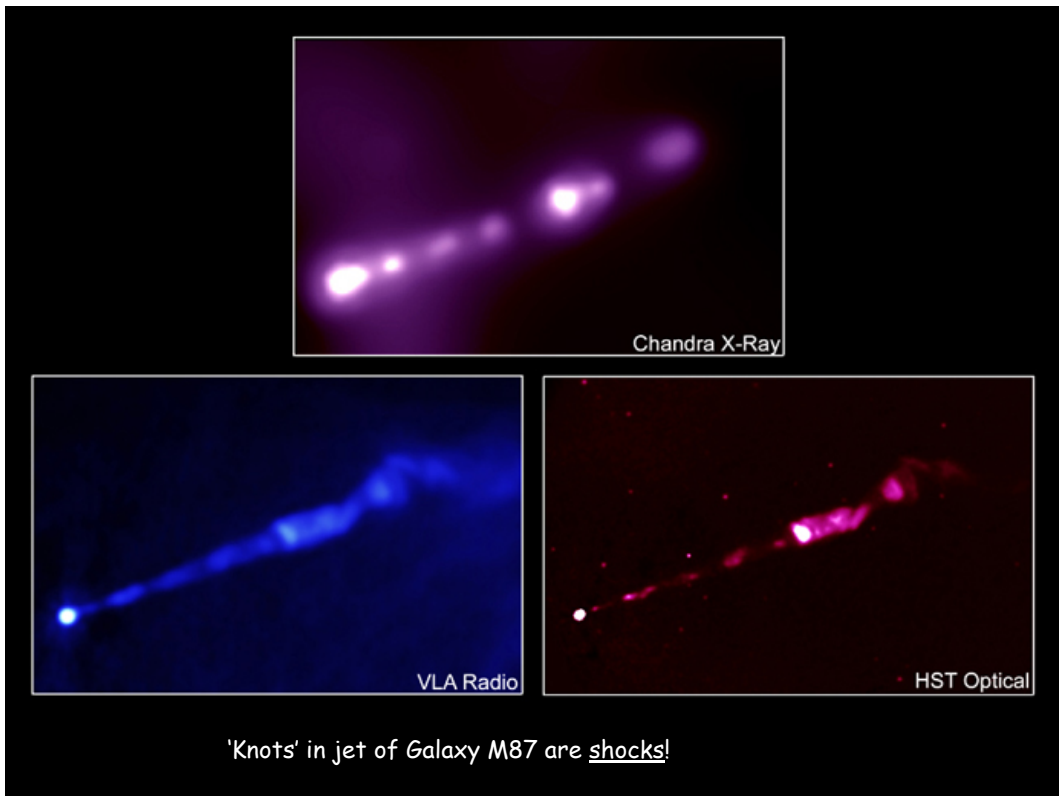
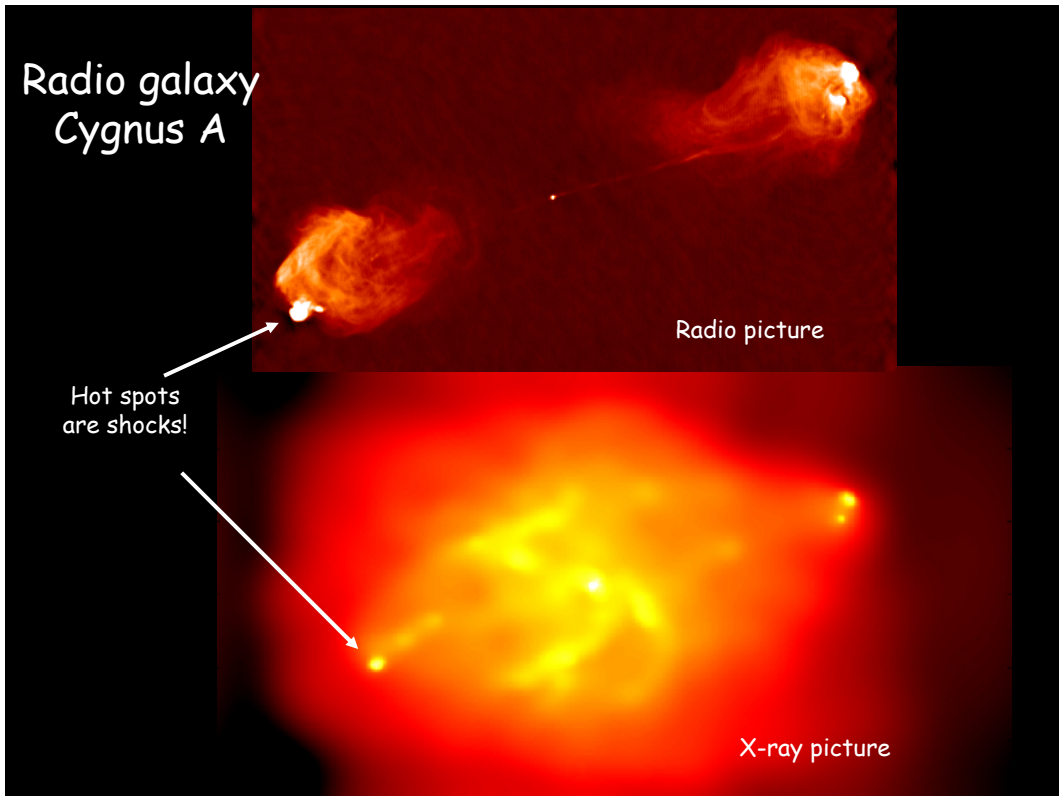


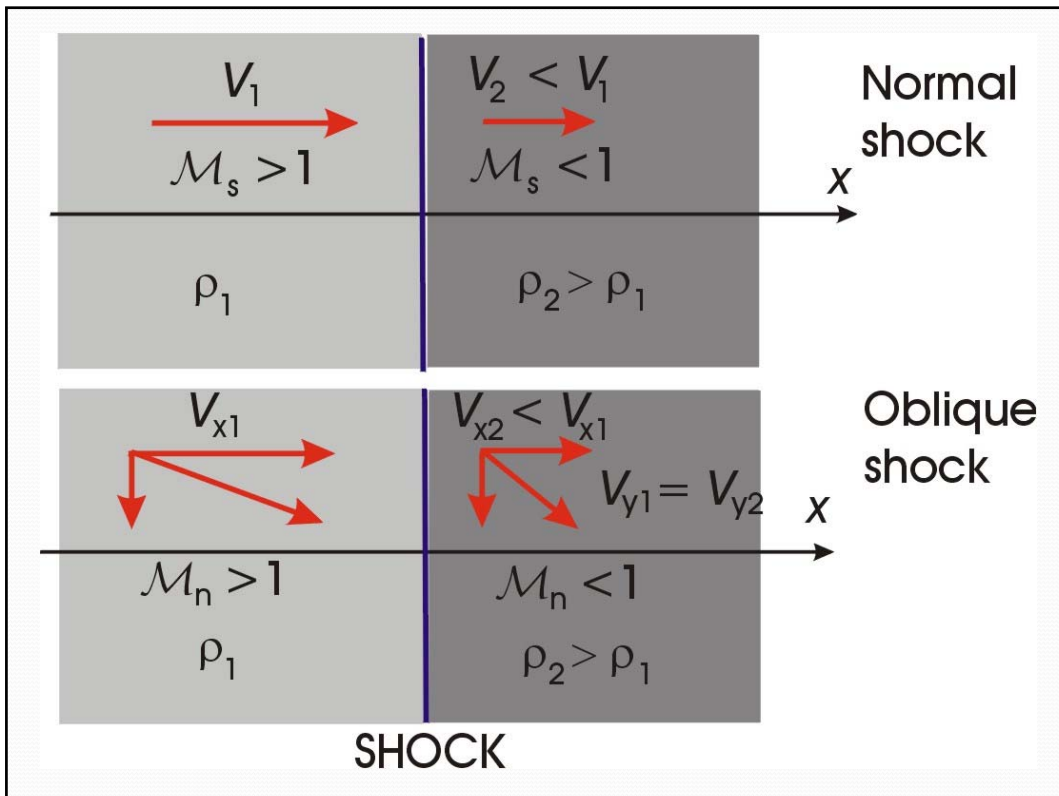
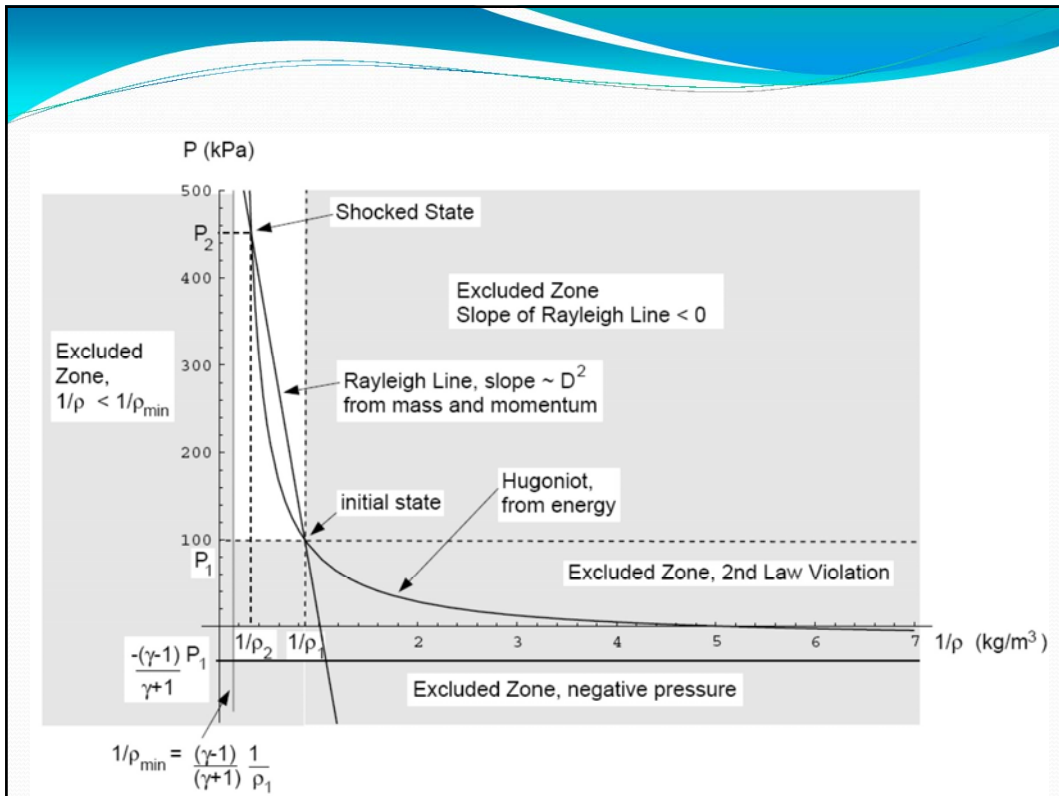
Earth's bow shock











## Summary : Shock Physics

Across an infinitely thin steady shock you have, in the shock frame where the shock is at rest, the following Rankine-Hugoniot Jump conditions:

Mass-flux conservation

$$\rho_1 V_{n1} = \rho_2 V_{n2}$$

Momentum-flux conservation

$$\rho_1 (V_{n1})^2 + P_1 = \rho_2 (V_{n2})^2 + P_2$$

$$V_{t1} = V_{t2}$$

Energy-flux conservation

$$\frac{1}{2}(V_{n1})^2 + \frac{\gamma P_1}{(\gamma-1)\rho_1} = \frac{1}{2}(V_{n2})^2 + \frac{\gamma P_2}{(\gamma-1)\rho_2}$$

## Summary: Rankine-Hugoniot relations (for normal shock)

Fundamental parameter:  
Mach Number

$$\mathcal{M}_s \equiv \frac{\text{shock speed}}{\text{sound speed}} = \frac{V_1}{c_{s1}}$$

R-H Jump Conditions  
relate the up- and downstream  
quantities at the shock:

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\mathcal{M}_s^2}{(\gamma-1)\mathcal{M}_s^2 + 2} \Rightarrow \frac{\gamma+1}{\gamma-1}$$

$$\frac{P_2}{P_1} = \frac{2\gamma\mathcal{M}_s^2 - (\gamma-1)}{\gamma+1}$$

## From normal shock to oblique shocks:

All relations remain the same if one makes the replacement:

$$V_1 \Rightarrow V_{n1} = V_1 \cos \theta_1 ,$$

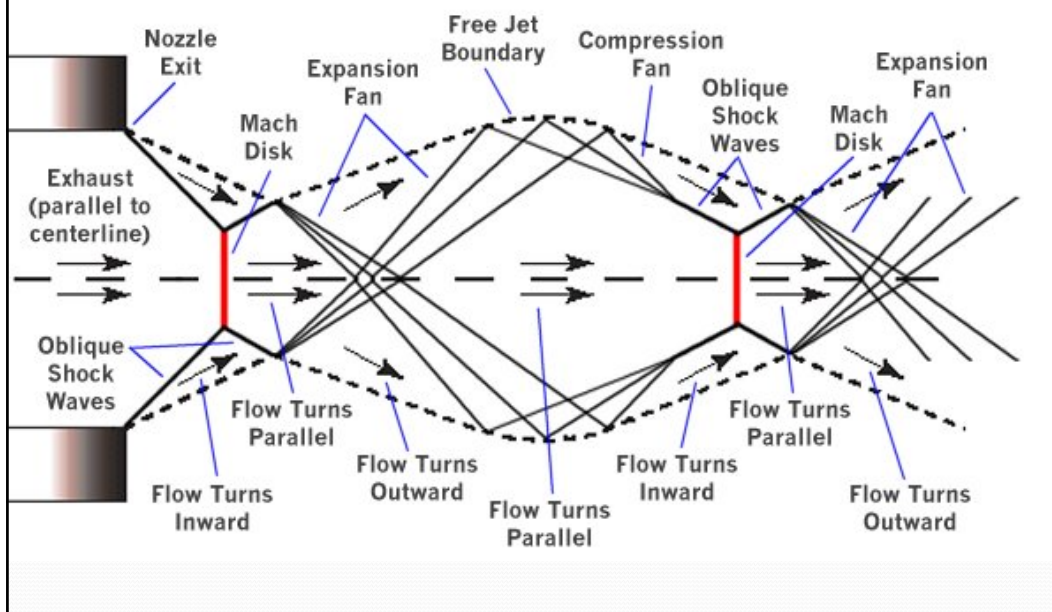
$$\mathcal{M}_S \Rightarrow \mathcal{M}_n = V_{n1} / c_{s1} = \mathcal{M}_S \cos \theta_1$$

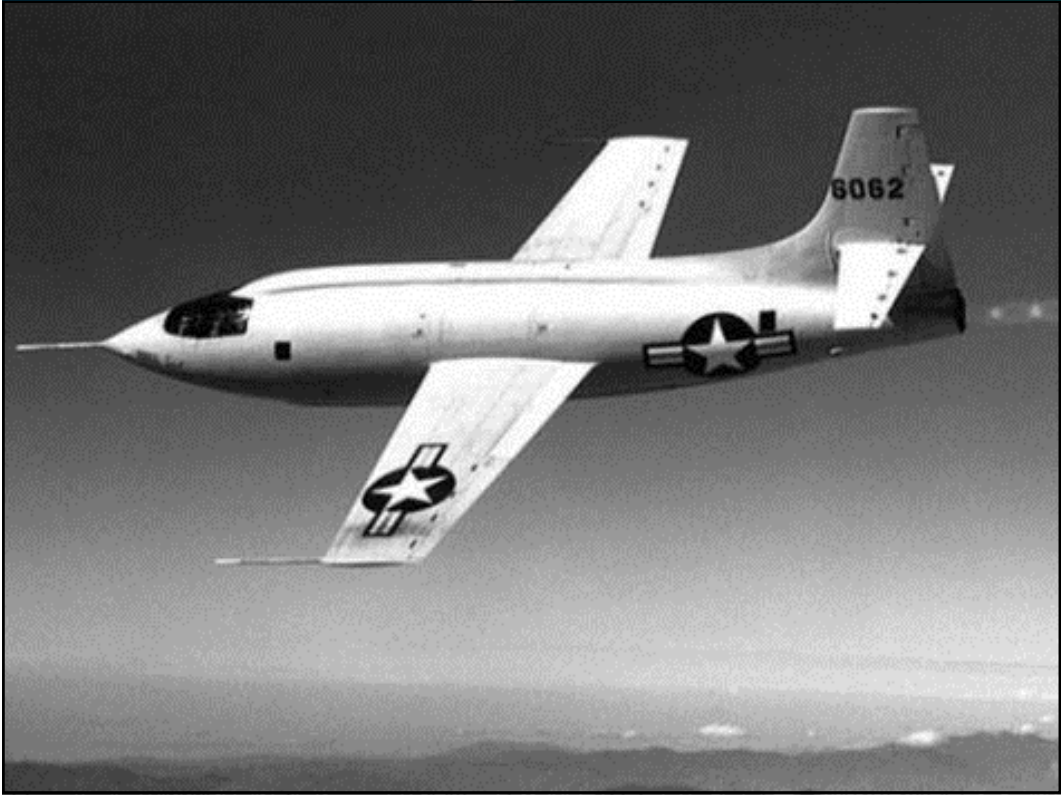
$\theta$  is the angle between upstream velocity and normal on shock surface

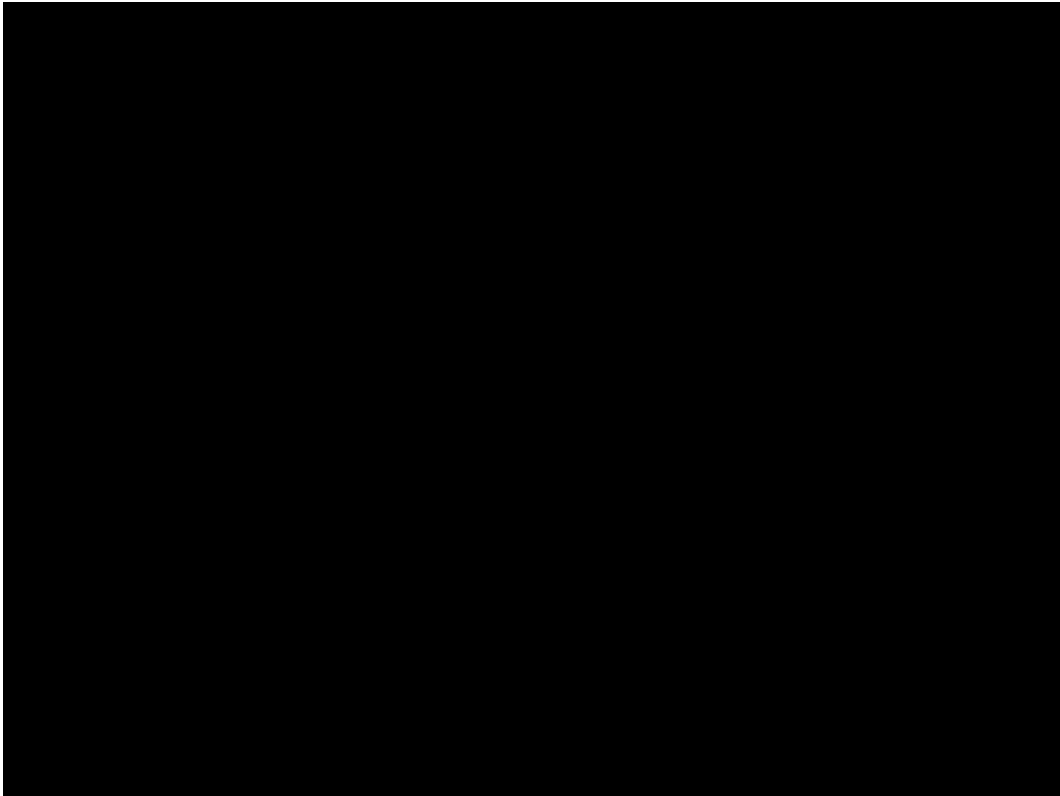
Tangential velocity along shock surface is unchanged

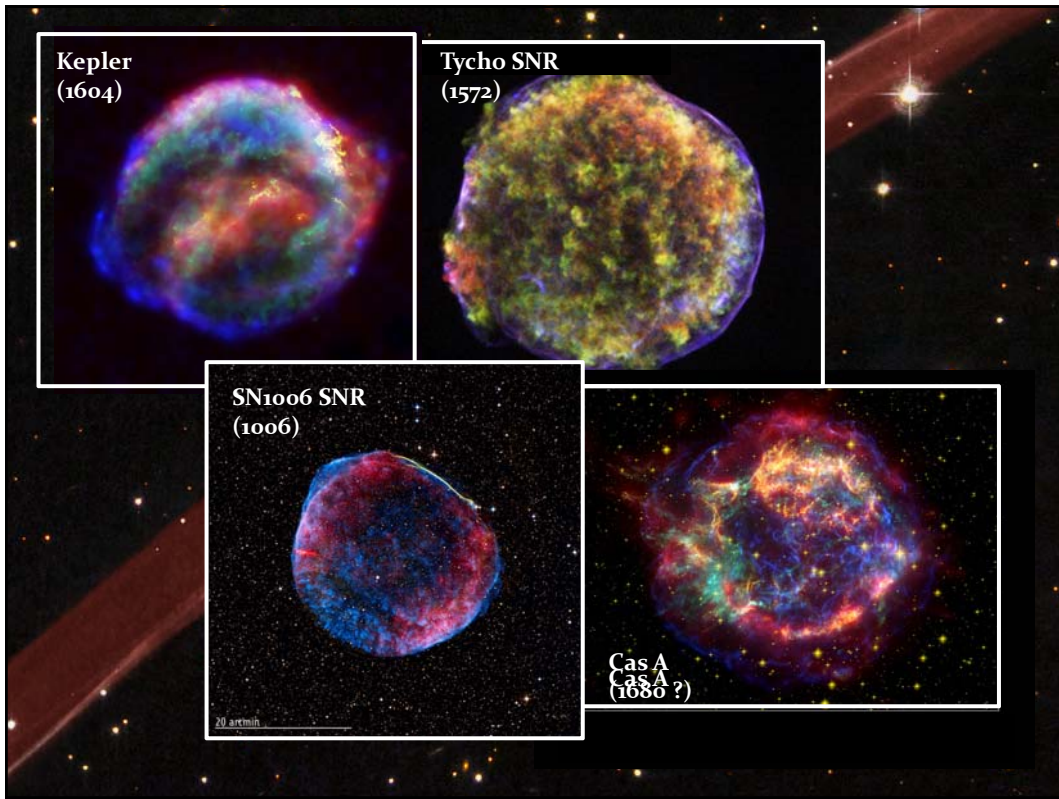
$$V_{t1} = V_1 \sin \theta_1 = V_{t2} = V_2 \sin \theta_2$$

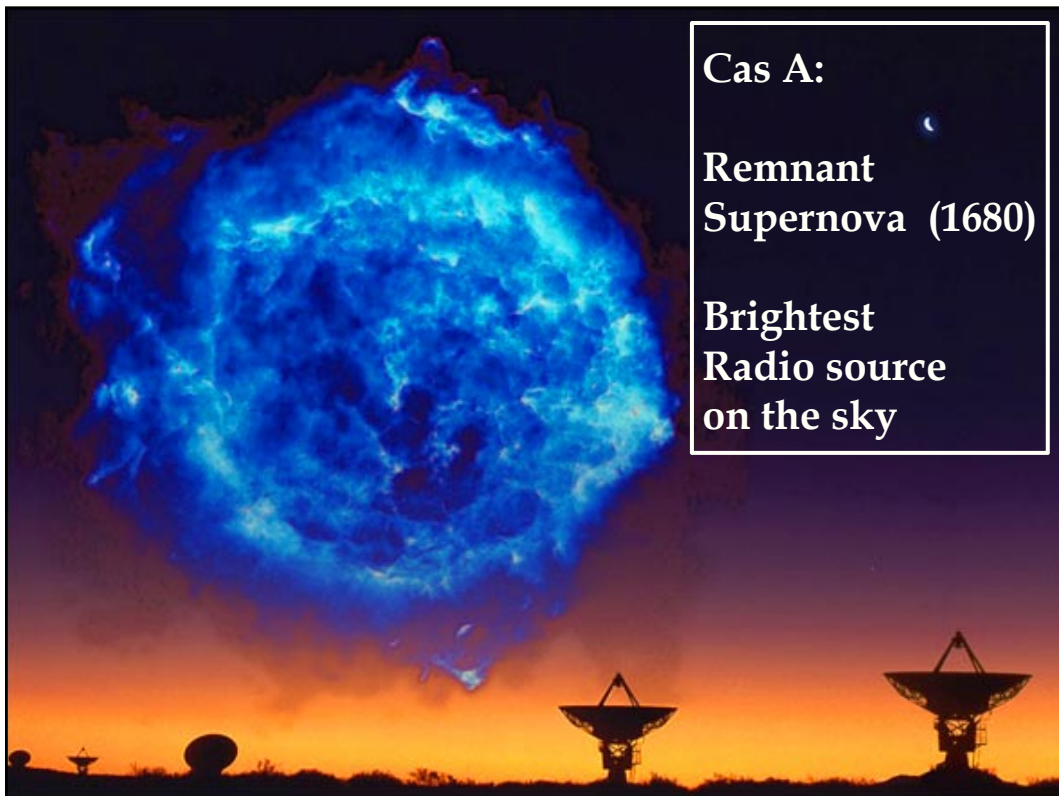
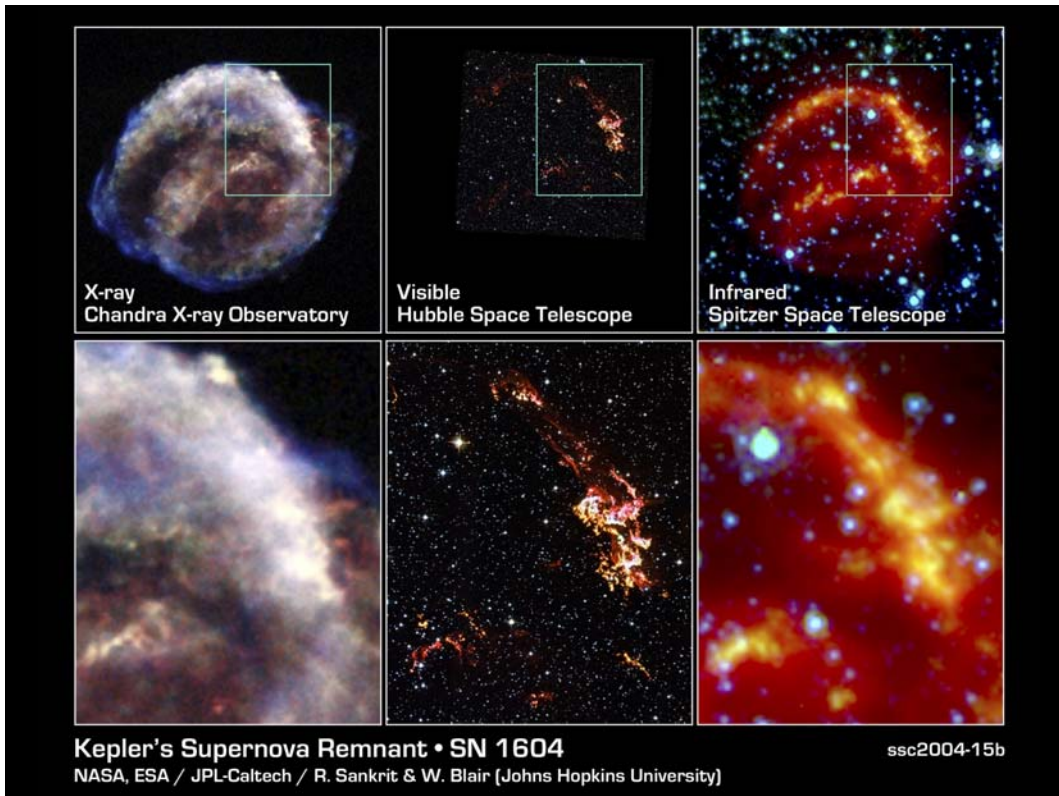
## Example from Jet/Rocket engines



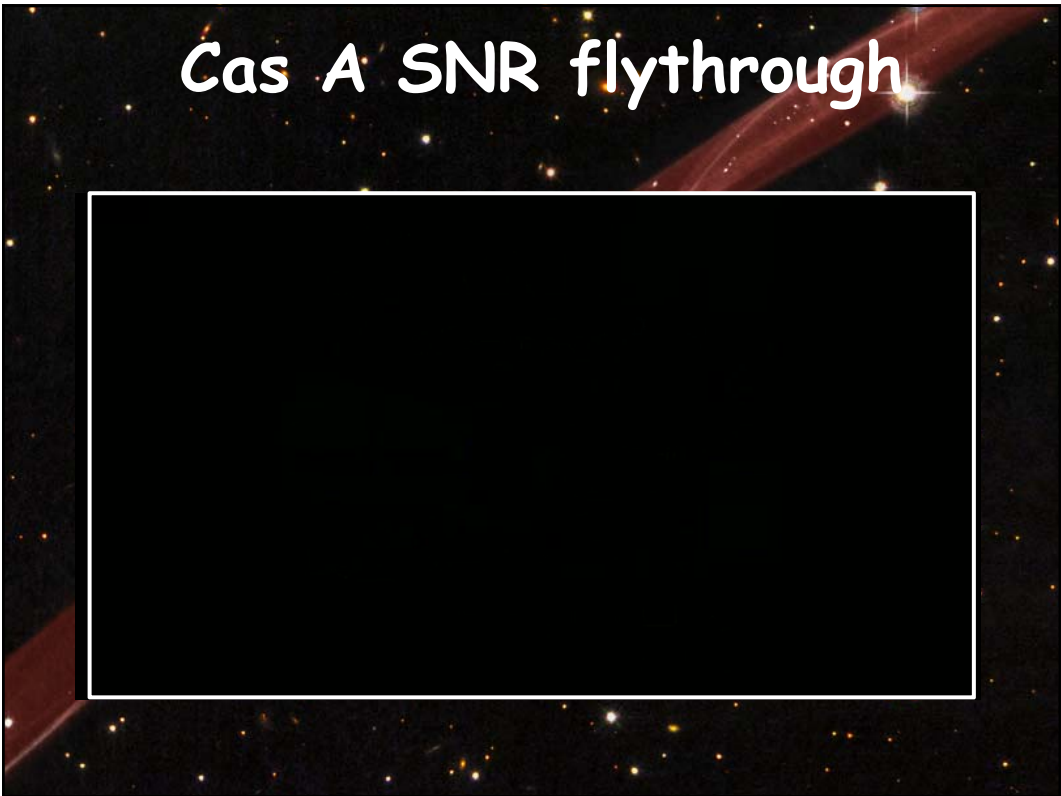
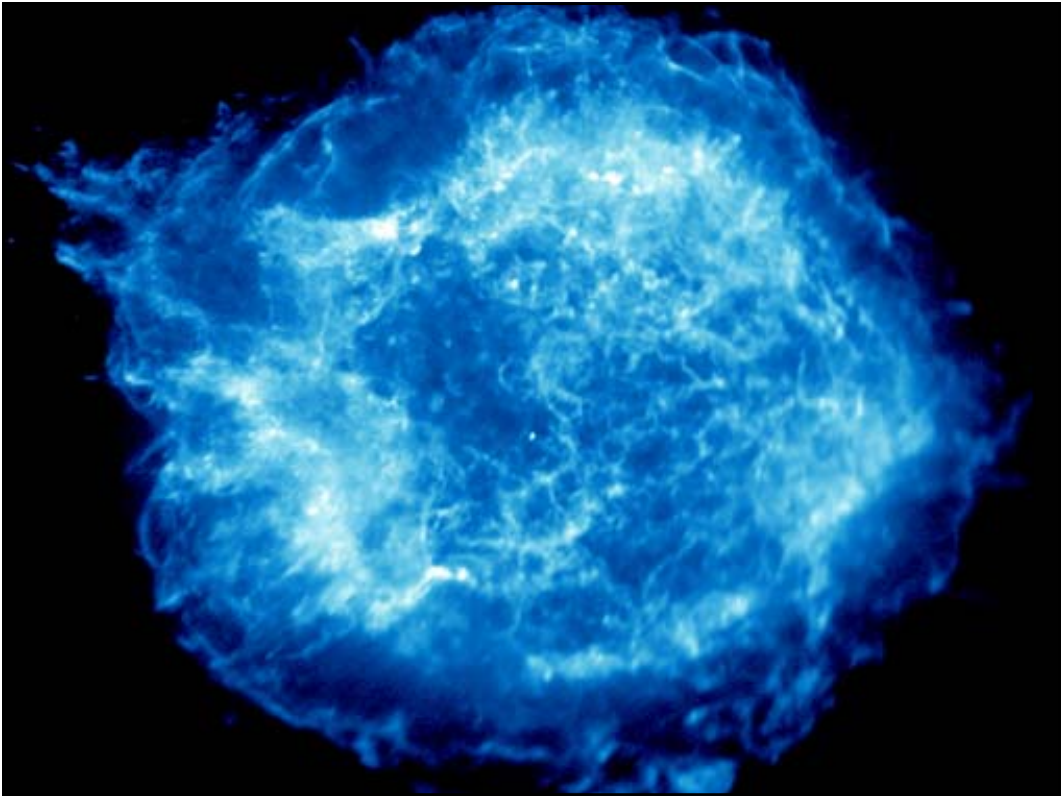








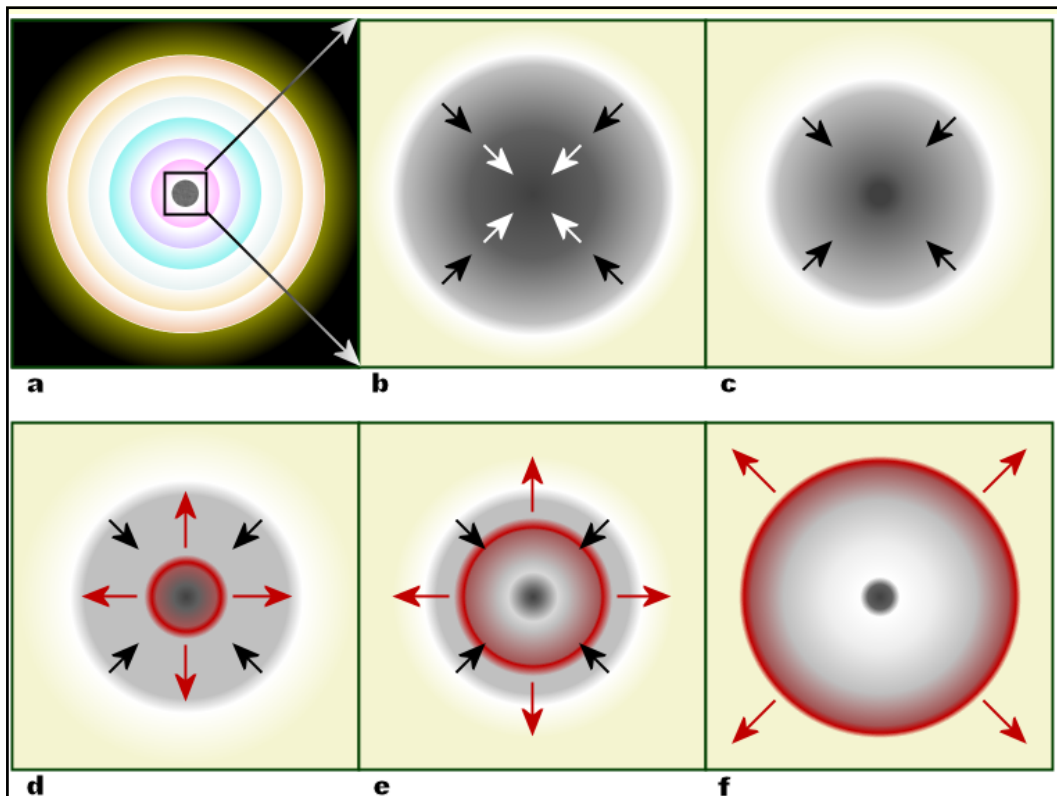
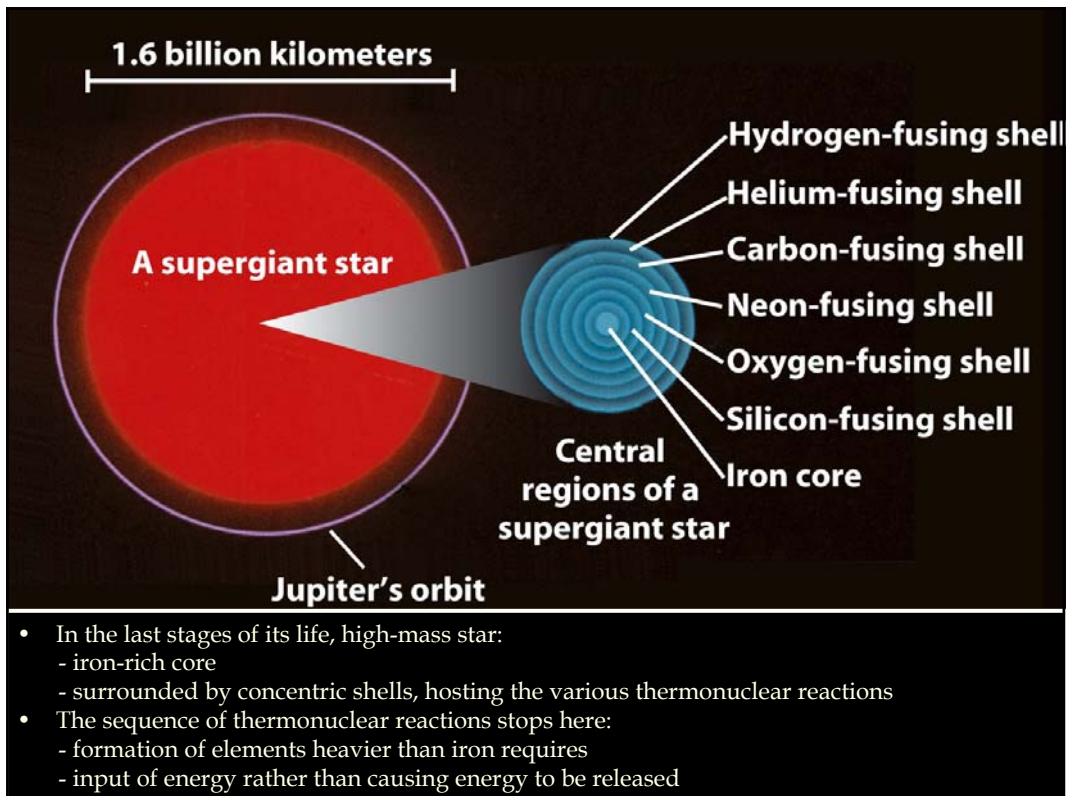


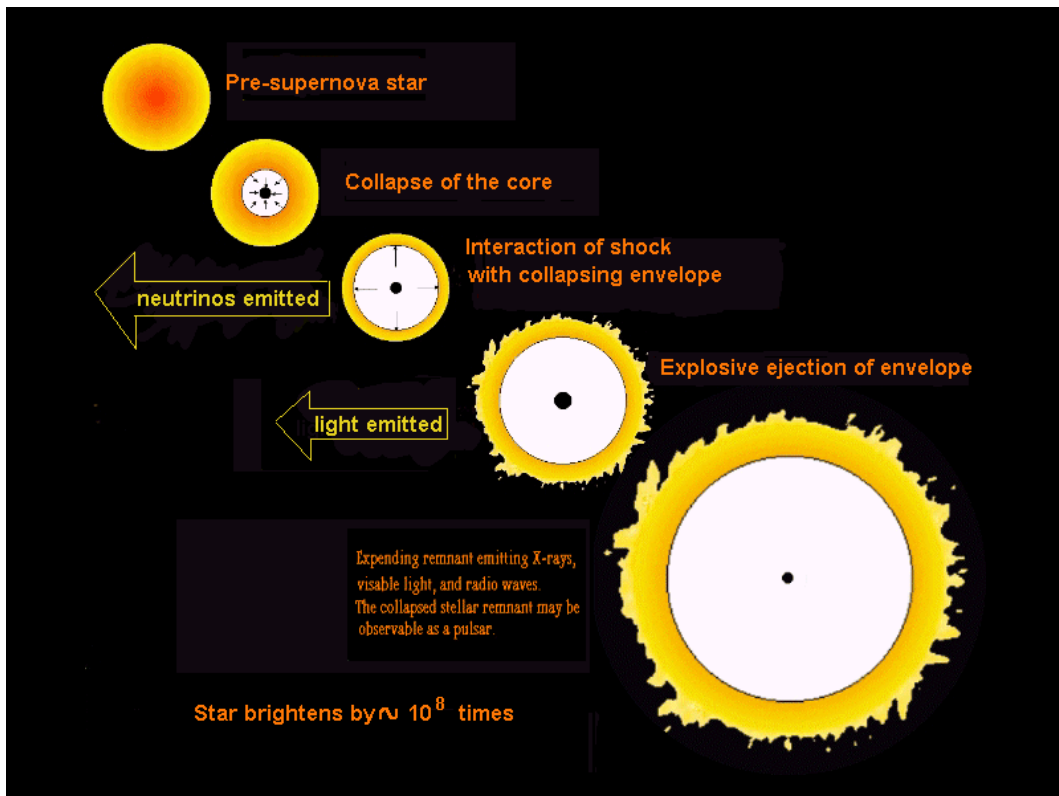


## Theory of Supernova Blast Waves

<u>Supernovae:</u>	
Type Ia	Subsonic deflagration wave turning into a supersonic detonation wave in outer layers.  <u>Mechanism:</u> explosive carbon burning in a mass-accreting white dwarf
Type Ib-Ic & Type II	<u>Core collapse</u> of massive star

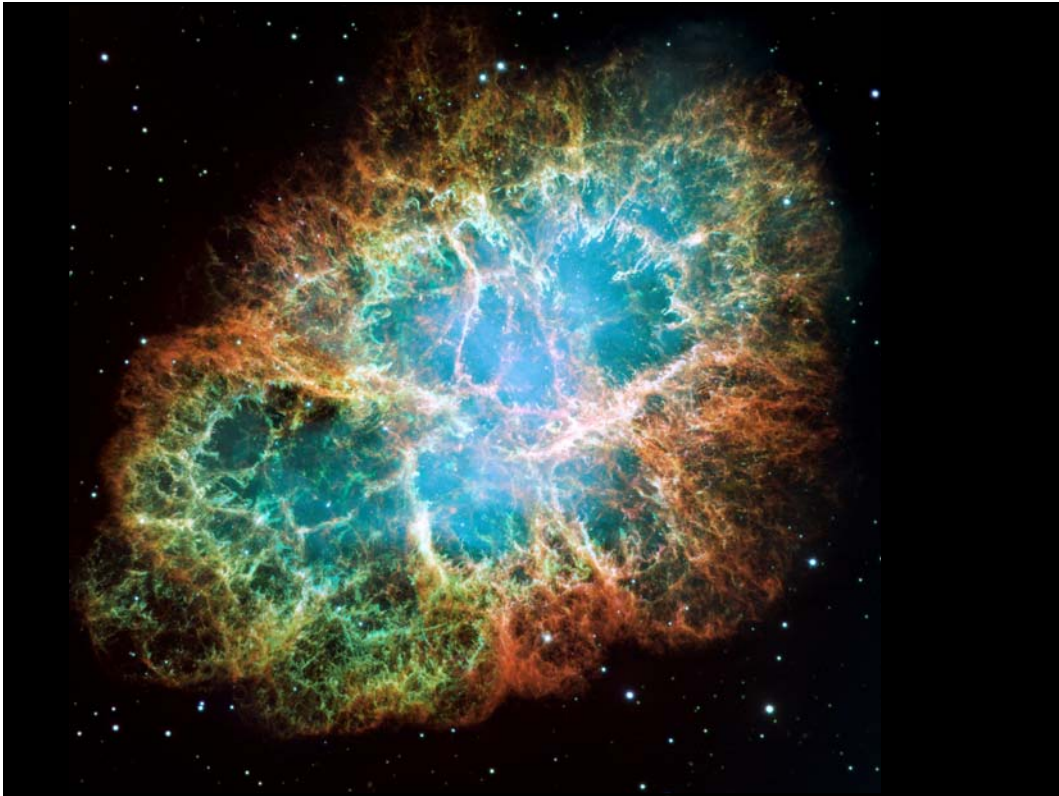
## Core-Collapse SN

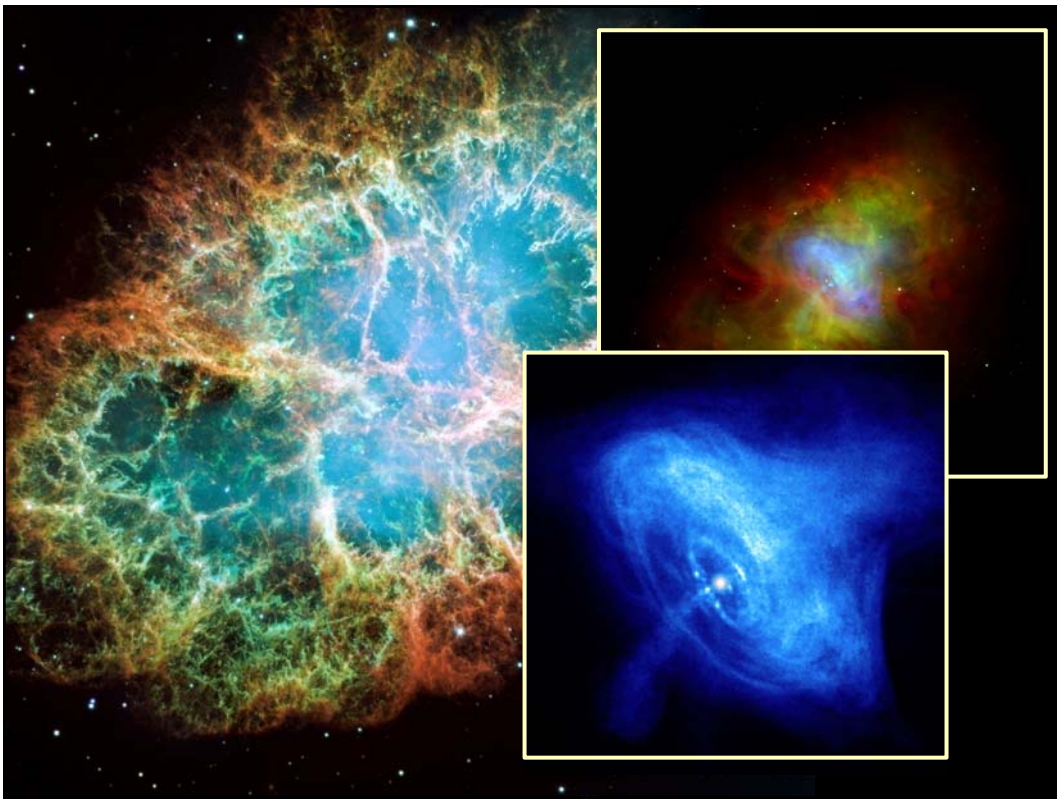




## Supernova II Explosion: SN1054





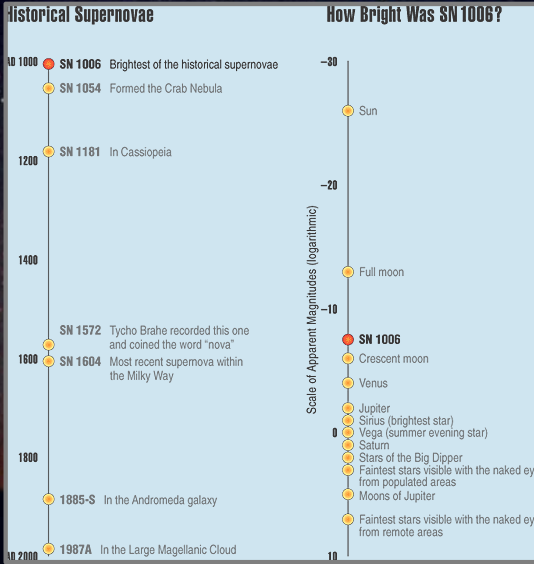


# Thermonuclear SN (Supernova Ia)

## SN1006

Supernova SN1006:  
brightest stellar event recorded in history

# SN1006



**Supernova SN1006:**

- brightness:  $m = -7.5$
- distance:  $d=2.2$  kpc
- recorded: China, Egypt, Iraq, Japan, Switzerland, North America

**Supernova SN1006:**  
brightest stellar event recorded in history

# SN1006

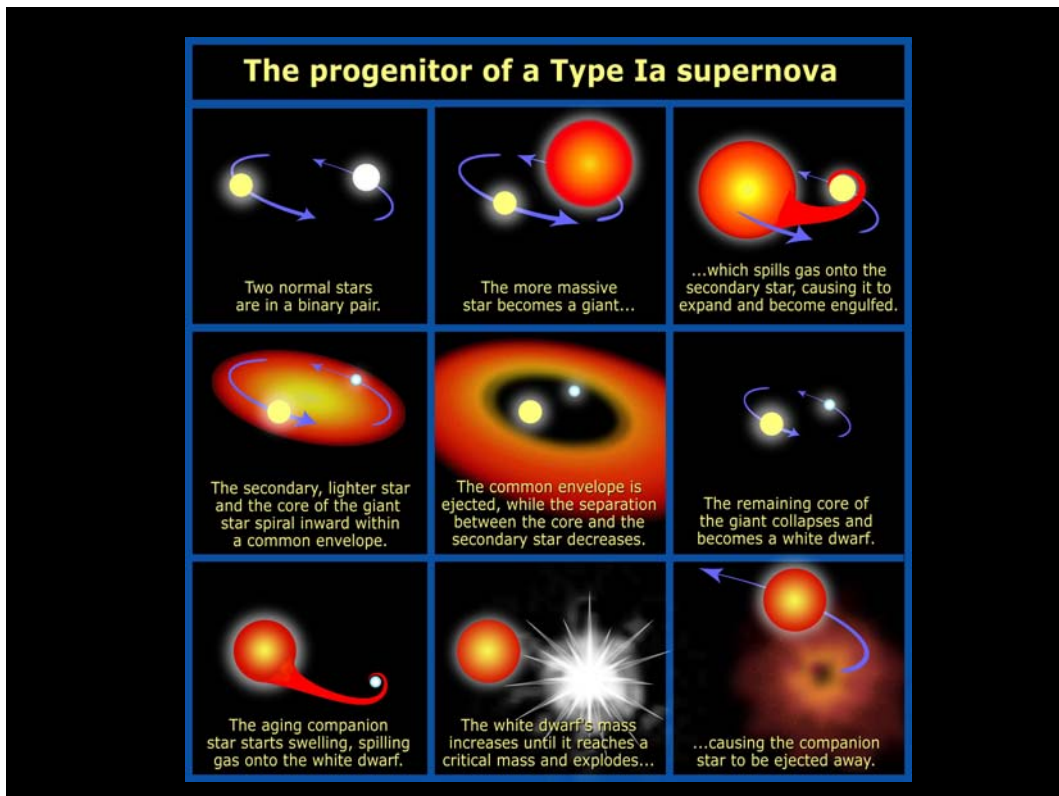


**Supernova SN1006:**

- brightness:  $m = -7.5$
- distance:  $d=2.2$  kpc
- recorded: China, Egypt, Iraq, Japan, Switzerland, North America

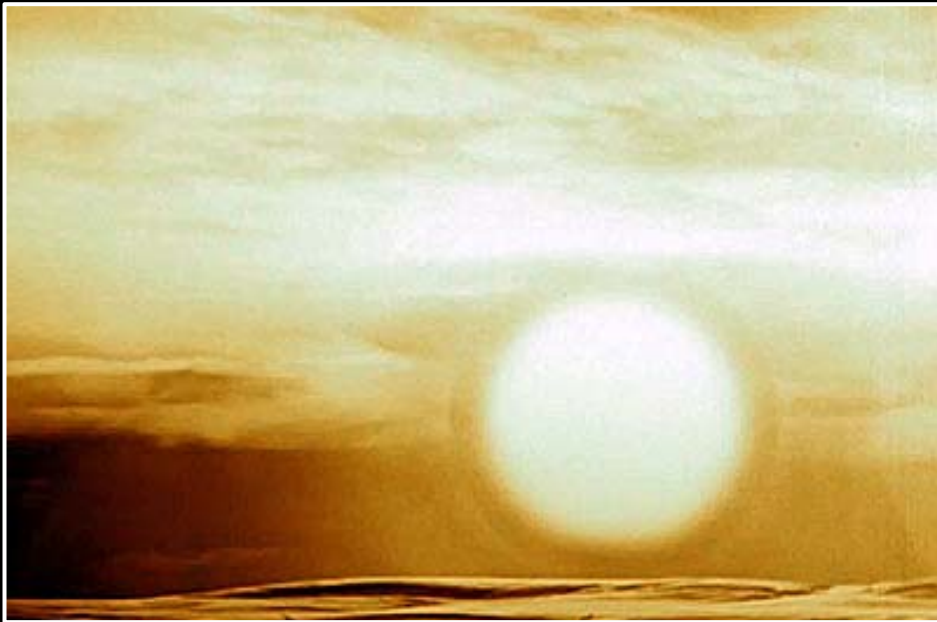
**Supernova SN1006:**  
brightest stellar event recorded in history





# Blast Waves

## Tsar Bomba Nuclear Explosion



# Tsar Bomba Nuclear Explosion



# Tsar Bomba Nuclear Explosion



## Hiroshima, the Shockwave



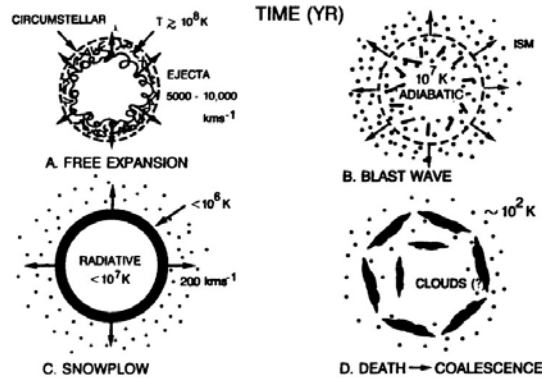
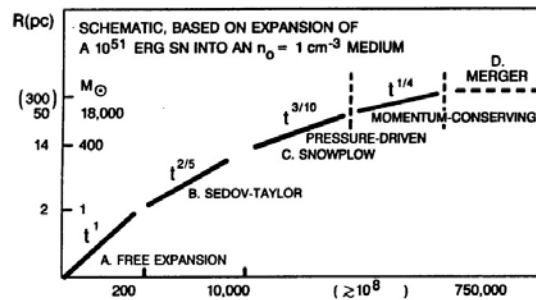
Sedov-Taylor  
Expansion Law

# Blast waves

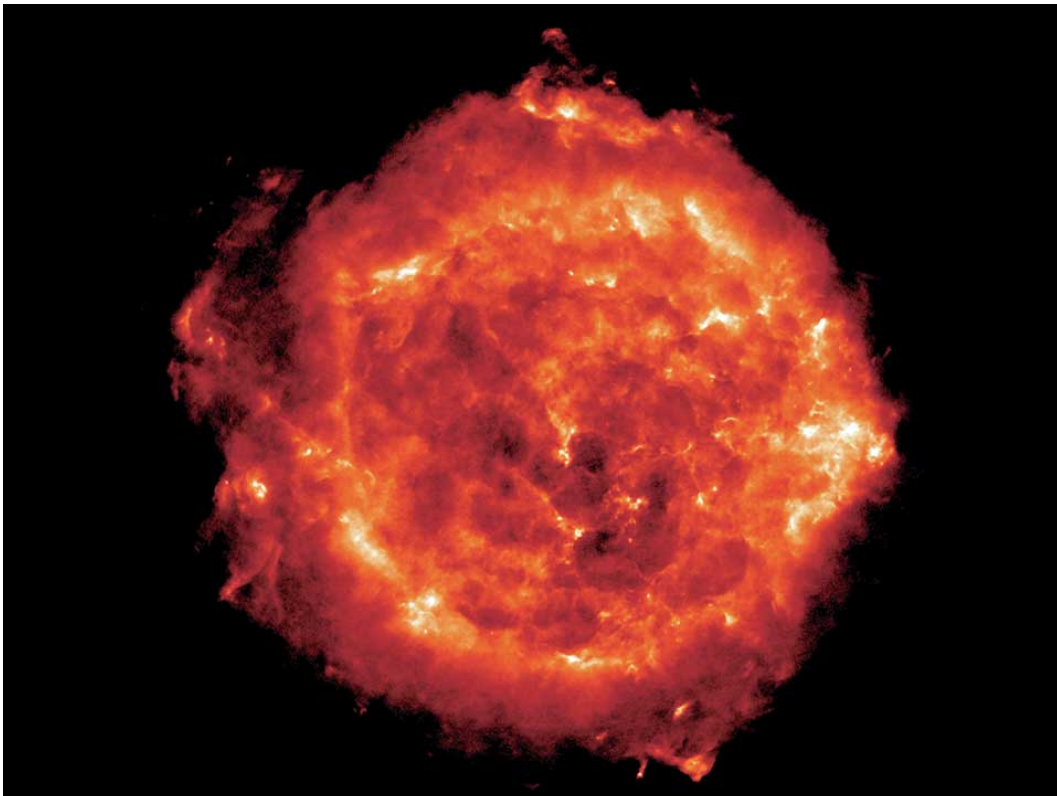
## Main properties:

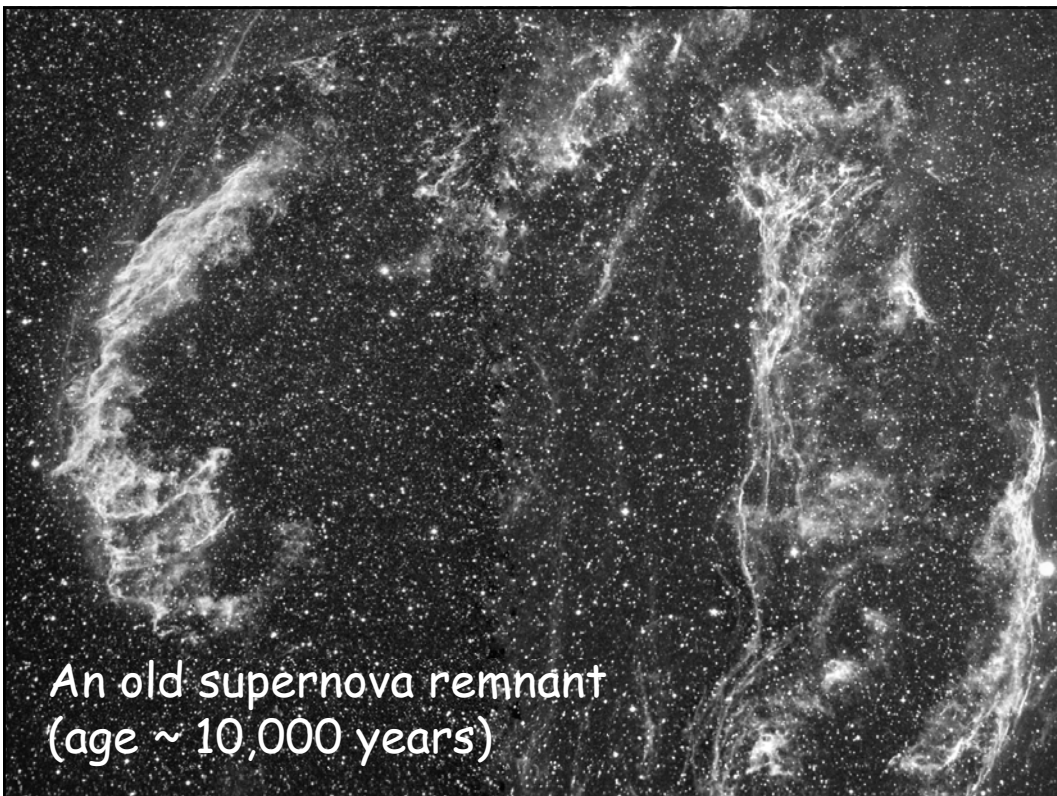
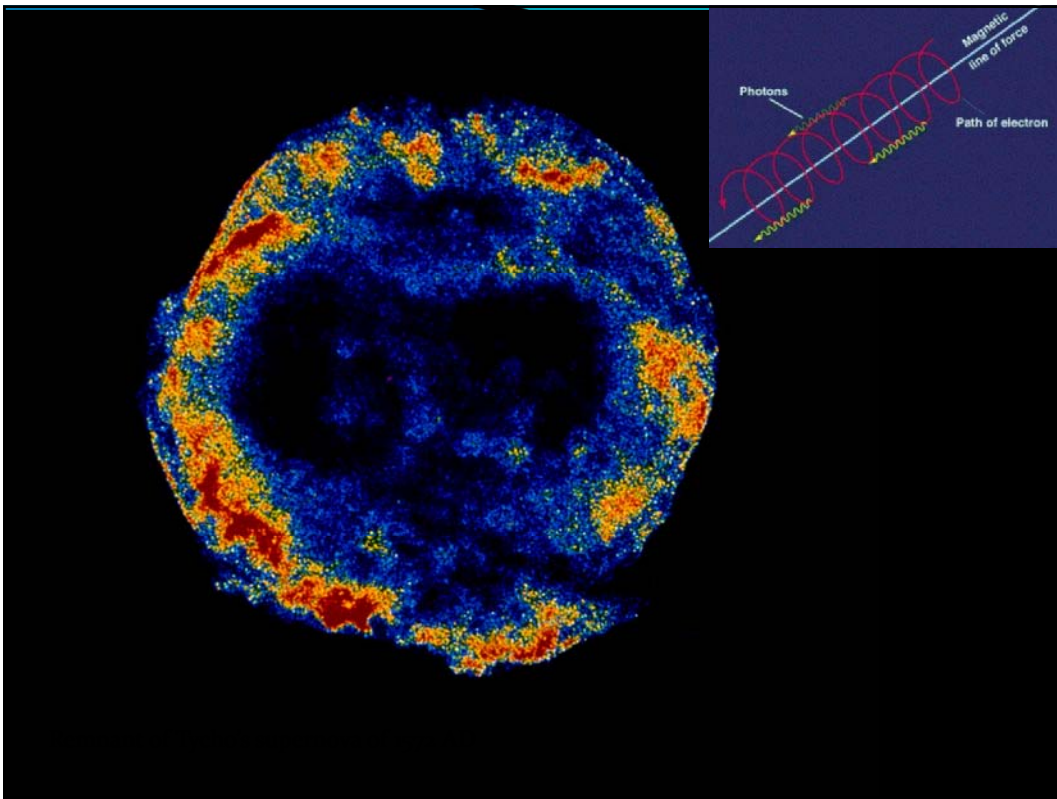
1. Strong shock propagating through the Interstellar Medium, or through the wind of the progenitor star;
2. Different expansion stages:
  - Free expansion stage ( $t < 1000$  yr)  $R \propto t$
  - Sedov-Taylor stage ( $1000 \text{ yr} < t < 10,000$  yr)  $R \propto t^{2/5}$
  - Pressure-driven snowplow ( $10,000 \text{ yr} < t < 250,000$  yr)  $R \propto t^{3/10}$

## STANDARD SNR EVOLUTION



# Tsar Bomba Nuclear Explosion







## Free-expansion phase

Energy budget:

$$|E_{\text{grav}}| = \frac{3}{5} \frac{GM_c^2}{R_c} \approx 10^{53} \text{ erg} \Rightarrow \begin{cases} 99\% \text{ into neutrino's} \\ 1\% \text{ into mechanical energy} \end{cases}$$

Expansion speed:

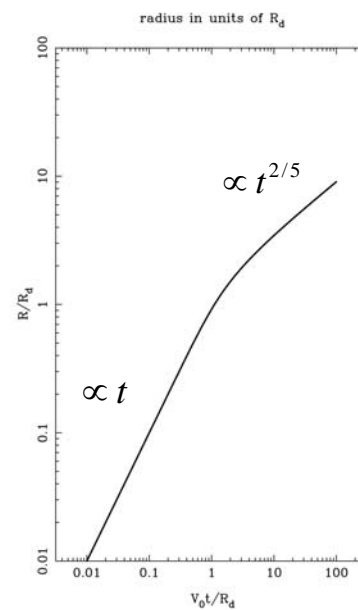
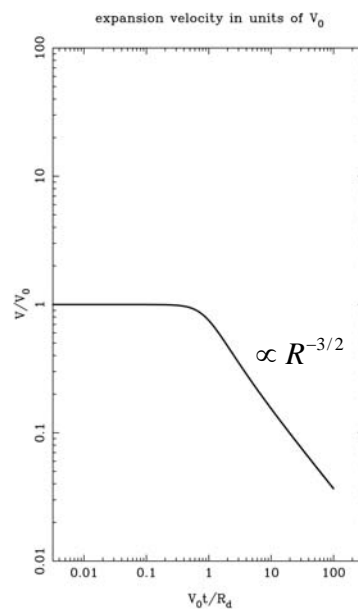
$$V_{\text{exp}} \approx \sqrt{\frac{2E_{\text{mech}}}{M_{\text{ej}}}} = 3000 \left( \frac{E_{\text{mech}}}{10^{51} \text{ erg}} \right)^{1/2} \left( \frac{M_{\text{ej}}}{10 M_{\odot}} \right)^{-1/2} \text{ km/s}$$

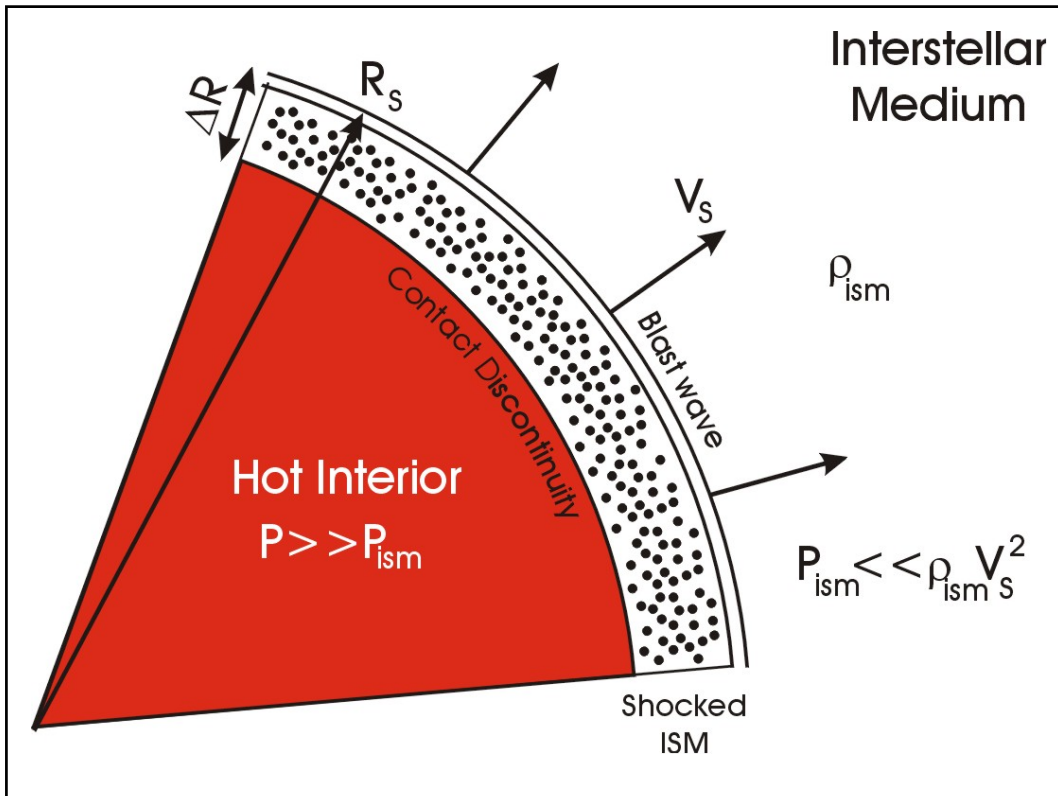


## Sedov-Taylor stage

- Expansion starts to decelerate due to swept-up mass
- Interior of the bubble is reheated due to reverse shock
- Hot bubble is preceded in ISM by strong blast wave

$$V_s = \sqrt{\frac{2E_{\text{snr}}}{M_{\text{ej}}}} \times \left( \frac{1}{1 + (R/R_d)^3} \right)^{1/2} = V_0 \left( \frac{1}{1 + (R/R_d)^3} \right)^{1/2}$$





Shock relations for strong (high-Mach number) shocks:

$$\left. \begin{aligned} \frac{\rho_2}{\rho_1} &= \frac{(\gamma+1)\mathcal{M}_s^2}{(\gamma-1)\mathcal{M}_s^2+2} \Rightarrow \frac{\gamma+1}{\gamma-1} \\ \frac{P_2}{P_1} &= \frac{2\gamma\mathcal{M}_s^2-(\gamma-1)}{\gamma+1} \Rightarrow \frac{2\gamma}{\gamma+1}\mathcal{M}_s^2 \end{aligned} \right\} \text{as } \mathcal{M}_s^2 \equiv \left(\frac{V_1}{c_{s1}}\right)^2 = \frac{\rho_1 V_1^2}{\gamma P_1} \Rightarrow \infty$$

$$\Leftrightarrow P_2 = \frac{2}{\gamma+1} \rho_1 V_1^2$$

Interstellar Medium

Hot Interior  
 $P \gg P_{\text{ism}}$

Contact Discontinuity

Blast wave

Shocked ISM

$\Delta R$

$R_s$

$v_s$

$\rho_{\text{ism}}$

$P_{\text{ism}} \ll \rho_{\text{ism}} V_s^2$

$$P_2 \approx \frac{2\gamma}{\gamma+1} \mathcal{M}_s^2 P_1 = \frac{2}{\gamma+1} \rho_{\text{ism}} V_s^2$$

Pressure behind strong shock (blast wave)

$$P_i = (\gamma - 1) e_i \approx (\gamma - 1) \frac{E_{\text{SNR}}}{\frac{4\pi}{3} R_s^3}$$

Pressure in hot SNR interior

Interstellar Medium

Hot Interior  
 $P \gg P_{\text{ism}}$

Contact Discontinuity

Blast wave

Shocked ISM

$\Delta R$

$R_s$

$v_s$

$\rho_{\text{ism}}$

$P_{\text{ism}} \ll \rho_{\text{ism}} V_s^2$

At contact discontinuity:  
equal pressure on both sides!

$$\frac{2}{\gamma+1} \rho_{\text{ism}} V_s^2 \approx (\gamma - 1) \frac{E_{\text{SNR}}}{\frac{4\pi}{3} R_s^3}$$

This procedure is allowed because of high sound speeds in hot interior and in shell of hot, shocked ISM:  
No large pressure differences are possible!

Interstellar Medium

At contact discontinuity: equal pressure on both sides!

$$\frac{2}{\gamma + 1} \rho_{\text{ism}} V_s^2 \approx (\gamma - 1) \frac{E_{\text{SNR}}}{\frac{4\pi}{3} R_s^3}$$

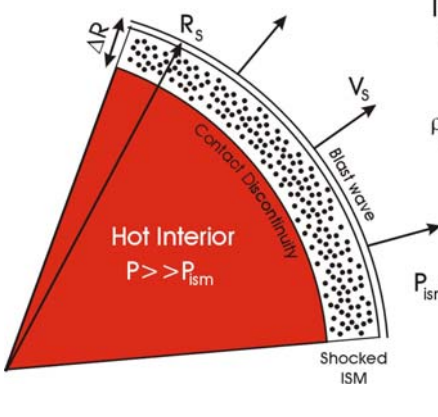
Relation between velocity and radius gives expansion law!

$$V_s = \frac{dR_s}{dt} \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} R_s^{-3/2}$$

Interstellar Medium

$$R_s^{3/2} dR_s \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} dt$$

Step 1: write the relation as difference equation



Interstellar Medium

$\rho_{\text{ism}}$

$P_{\text{ism}} \ll \rho_{\text{ism}} V_s^2$

Hot Interior  
 $P \gg P_{\text{ism}}$

Contact Discontinuity

Blast wave

Shocked ISM

$\Delta R$

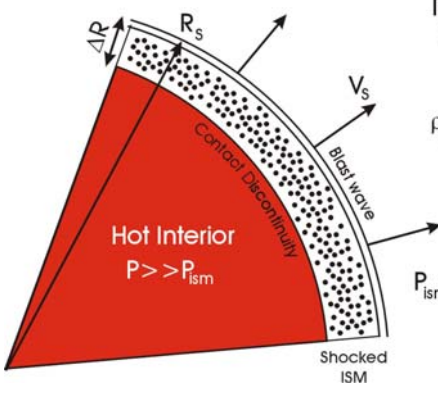
$R_s$

$V_s$

$$R_s^{3/2} dR_s \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} dt$$

$$\frac{2}{5} d(R_s^{5/2}) \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} dt$$

Step 2: write as total differentials and.....



Interstellar Medium

$\rho_{\text{ism}}$

$P_{\text{ism}} \ll \rho_{\text{ism}} V_s^2$

Hot Interior  
 $P \gg P_{\text{ism}}$

Contact Discontinuity

Blast wave

Shocked ISM

$\Delta R$

$R_s$

$V_s$

$$R_s^{3/2} dR_s \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} dt$$

$$\frac{2}{5} d(R_s^{5/2}) \approx \sqrt{\frac{8\pi}{3(\gamma^2 - 1)}} \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/2} dt$$

.....integrate to find the Sedov-Taylor solution

$$R_s(t) \approx C_\gamma \left( \frac{E_{\text{snr}}}{\rho_{\text{ism}}} \right)^{1/5} t^{2/5},$$

$$C_\gamma = \left( \frac{5}{2} \right)^{2/5} \left( \frac{8\pi}{3(\gamma^2 - 1)} \right)^{1/5} \approx 1.96$$

# Sedov & Taylor

