PROPAGATION OF SUPERNOVA BLAST WAVES THROUGH THE ISM

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OUTLINE

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- Phases in the propagation of a blast wave
  - ⋆ Free expansion phase
  - ⋆ Sedov-Taylor phase

    → Self-similar driven wave (SSDW)
  - ⋆ Snowplow phase
  - ⋆ Fadeaway
- Multi-D effects
  - ⋆ Instabilities
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  - ⋆ Inhomogeneities
  - ⋆ Mixing
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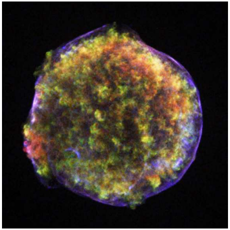
BLAST WAVES → SUPERNOVA REMNANTS

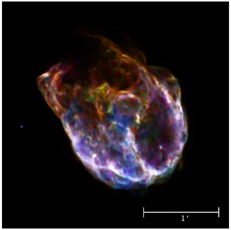
Supernova explosions drive cold and dense supernova ejecta with *highly supersonic* velocities into the ambient medium. The blast wave strikes nearby layers of gas and dust, Heat and energy released will create a supernova remnant.

$$E_{K,ej} \sim 10^{51}\,\mathrm{ergs}$$
$$M_{ej} \sim 1{,}4 M_{\odot} \text{ Type Ia}$$
$$M_{ej} \sim 10 - 20 M_{\odot} \text{ C-C}$$
$$\langle v_{ej}^2 \rangle^{1/2} = \left(\frac{2E_0}{M_{ej}}\right)^{1/2}$$
$$10^4 - 5000\,\mathrm{km/s} \gg 1 - 10\,\mathrm{km/s}$$

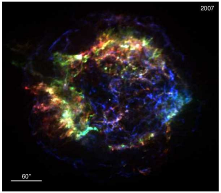
Reynolds(2008)



Chandra X-ray RGB composite image of Tycho SNR.



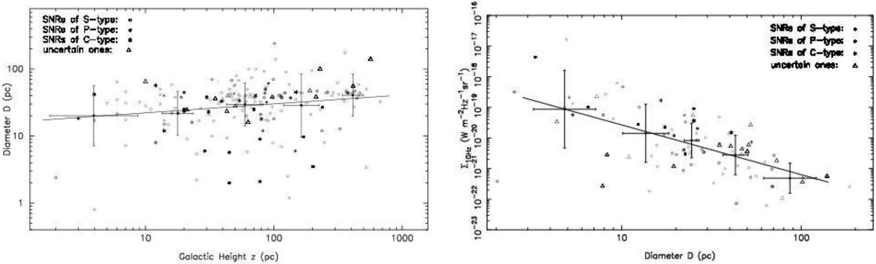
Chandra X-ray RGB composite image of N132D.



Chandra X-ray RGB composite image of CasA.

SOME FEATURES OF SNRS ...

- $\sim$ 270 SNRs in the Milky Way (Green 2006)



Xu et al. (2005)

- SNRs are the most bright radio sources detected, featuring a steep nonthermal spectrum: $S_\nu \propto \nu^\alpha$, $\alpha - 0{,}5$
  $\Rightarrow$ cosmic-ray particles and synchroton radiation (Shklovskii 1953)
- Shock heating to $\sim 10^6 K$ → *Chandra* and XMM-Newton perform X-ray observations of SNRs and emission line spectrum of heavy metal elements.
- Supernova outbursts contribute to the enrichment of heavy chemical elements.
- Origin of the Solar System might be related to a supernova explosion. Evidence from Xe isotopes in meteorites and outer regions of the Sun (Sabu & Manuel 1976).
- Star formation might be induced by supernova explosions. (Nagakura et al. 2009)

I. FREE EXPANSION PHASE: 10^{2-3}yr

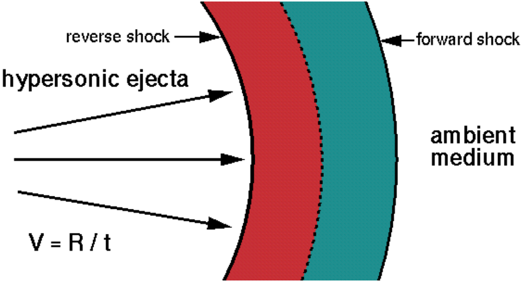
$\langle v_{ej}^2 \rangle^{1/2} \gg c_S$

$M \gtrsim 10^3$

$\Rightarrow$ Expanding ejecta drive a fast shock into de ambient medium. Ejecta initially expand almost freely and rapidly cool adiabatically to very low temperatures.

$\rho_{ej} \propto t^{-3} \Rightarrow$ Pressure of the shocked ambient material eventually exceeds the thermal pressure of the ejecta.

$\Rightarrow$ Ambient medium is accelerated, compressed and heated. It pushes back into the ejecta, creating a *reverse shock*.



- Slows down the ejecta.
- Increases their temperature, which had decreased during adiabatic expansion.

II. SEDOV-TAYLOR PHASE: 10^4yr

$$R_1 = \left(\frac{3M_{ej}}{4\pi\rho_0}\right)^{1/3}$$

$$t_1 \approx \frac{R_1}{\langle v_{ej}^2\rangle^{1/2}}$$

The reverse shock has reached the center of the remnant! Pressure in the remnant is higher than in the surrounding medium.

"Point explosion" → injection of E_0 into low temperature ρ_0 medium (Sedov 1959; Taylor 1950).

SELF-SIMILARITY SOLUTION in *spherical coordinates*

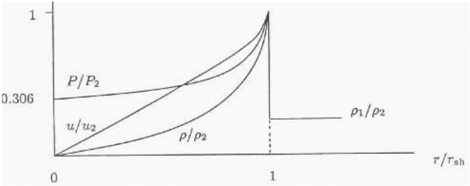
$$v_S \propto t^{3/5} \propto R_S^{-3/2}$$

$$p = p_0 R_S^{-3} f_1(r/R_S)$$
$$u = R_S^{-3/2}\phi_1(r/R_S)$$
$$\rho = \rho_0\psi(r/R_S)$$

Motion	$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r}$	$\phi'(\eta-\phi) = \frac{f'}{\gamma\psi} - \frac{3}{2}\phi$
Continuity	$\frac{\partial\rho}{\partial t} + u\frac{\partial\rho}{\partial r} + \rho(\frac{\partial u}{\partial r} + \frac{2u}{r}) = 0$	$\frac{\psi'}{\psi} = \frac{\phi'+2\phi/\eta}{\eta-\phi}$
State	$(\frac{\partial}{\partial t} + u\frac{\partial}{\partial r})(p\rho^{-\gamma}) = 0$	$3f + \eta f' + \frac{\gamma\psi'}{\psi}f(\phi-\eta) - \phi f' = 0$

$$f'[(\eta-\phi)^2 - f/\psi] = f[-3\eta + \phi(3+\gamma/2) - 2\gamma\phi^2/\eta]$$

$f' \rightarrow \phi' \rightarrow \psi'$ providing f, ϕ, ψ known for some η.



taken from Shu, The Physics of Astrophysics, II, Fig.17.3, $\gamma = 5/3$

$$R_S = 1.54 \times 10^{19}\mathrm{cm}\, E_{51}^{1/5}\, n_0^{-1/5} \left(\frac{t}{10^3\mathrm{yr}}\right)^{\mathbf{2/5}}$$

$$v_S = 1950\,\mathrm{km\,s^{-1}}\, E_{51}^{1/5}\, n_0^{-1/5} \left(\frac{10^3\mathrm{yr}}{\mathbf{t}}\right)^{\mathbf{3/5}}$$

$$T_S = 5.25 \times 10^{7}\mathrm{K}\, E_{51}^{2/5}\, n_0^{-2/5} \left(\frac{10^3\mathrm{yr}}{t}\right)^{\mathbf{6/5}}$$

Leaving the Sedov-Taylor phase → radiative losses become important, the adiabatic approximation breaks down.
1/3 of the energy will have been radiated by

$$t_{\mathrm{rad}} = 49.9 \times 10^{3}\mathrm{yr}\, E_{51}^{\mathbf{4/17}}\, n_0^{\mathbf{-9/17}}$$

$$R_S \sim 30pc$$

Blondin et al. 1998

I./II. SSDW SOLUTION: THE INTERACTION REGION

Chevalier (1982) found a more general self-similar solution that describes the interaction region for both phases I and II.

Uniformly expanding medium: $\rho = t^{-3}(r/tg)^{-n}$

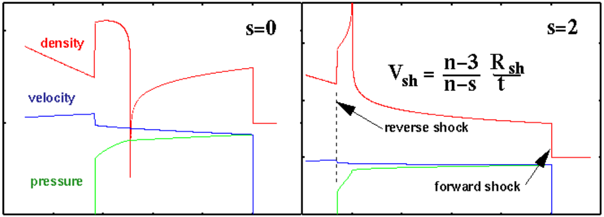
Stationary ambient medium: $\rho = qr^{-s}$

$s > 3, n > 5$, Sedov-Taylor: $n = 5$

Type Ia $\rightarrow s = 0$ (uniform)

Type II $\rightarrow s = 2$ (CSM)

$R_S \propto t^{(n-3)/(n-s)}$



Blondin (2000)

Alternative solution: based on numerical simulations, Dwarkadas & Chevalier (1998) argue that $\rho_{ej} \propto t^{-3} exp(-v/v_0)$ is a better fit for Type Ia. Not self-similar, existence of typical lengthscale. Solution evolves from SSDW to Sedov-Taylor.

III. SNOWPLOW: 10^9yr

Radiative cooling becomes significant!

- Pressure behind the shock drops
- Shock briefly stalls
- Very hot gas at the interior of the SNR did not have time to cool
- Expansion continues

Dense shell of cool gas enclosing a hot central volume where radiative losses are negligible. Its mass increases as it sweeps up ambient gas.

$$R_S \approx R_S(t_{\rm rad})(t/t_{\rm rad})^{2/7}$$

$$v_S \approx \frac{2}{7}\frac{R_S(t_{\rm rad})}{t_{\rm rad}}\left(\frac{t}{t_{\rm rad}}\right)^{-5/7}$$

IV. FADEAWAY

At the beginning of the snowplow phase, $v_S \sim 10^2 \mathrm{km\,s^{-1}}$.
Shock front slows down → until $v_S \sim c$

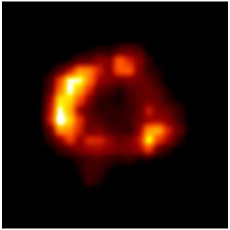
$\Rightarrow$ Shock wave turns into a sound wave.

Characteristic time/length:

$$t_{\mathrm{fade}} \approx 1.88 \times 10^6 \mathrm{yr}\, E_{51}^{27/85}\, n_0^{-31/85} \left(\frac{c_S}{10 \mathrm{km\,s^{-1}}}\right)^{-7/5}$$

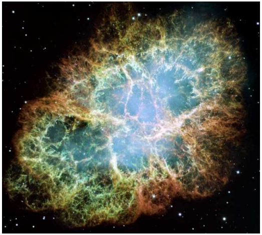
$$R_{\mathrm{fade}} \approx 2.08 \times 10^{20} \mathrm{cm}\, E_{51}^{27/85}\, n_0^{-21/85} \left(\frac{c_S}{10 \mathrm{km\,s^{-1}}}\right)^{-2/5}$$

$$R_{\mathrm{fade}} \sim 60\,\mathrm{pc}$$



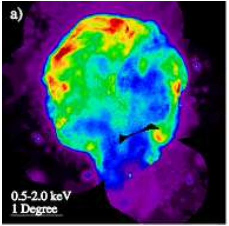
Chandra X-ray image of 1987A

Free expansion



HST view of the Crab Nebula

Sedov-phase

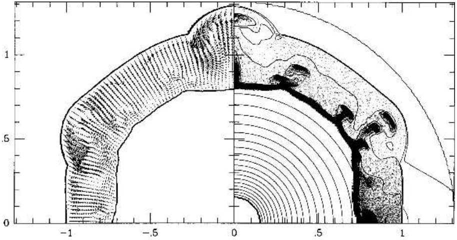


ROSAT X-ray image of Cygnus Loop

Snowplow

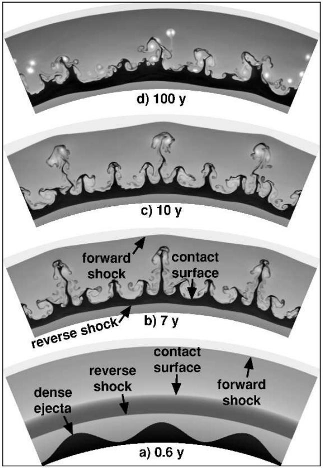
INSTABILITIES

- Convective or Rayleigh-Taylor instability



- Impulsive or Richtmyer-Meshkov instability: interface between fluids of differing density is impulsively accelerated small amplitude perturbations grow and might contribute to mixing.

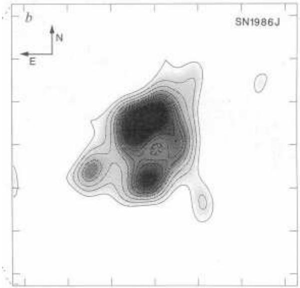
But mixing region does not reach front shock → CasA ?



Kane et al. (1999)

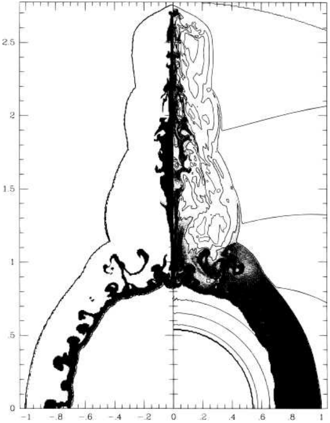
ASYMMETRIES IN THE AMBIENT MEDIUM

Although most of SNRs seem to be spherically symmetric, there are some exceptions.



VLA radio image of SN 1986J (Bartel et al. 1991)

For relatively mild asymmetries sufficiently peaked at the pole, a very nonlinear effect produces large asymmetries that might be labelled as jets.



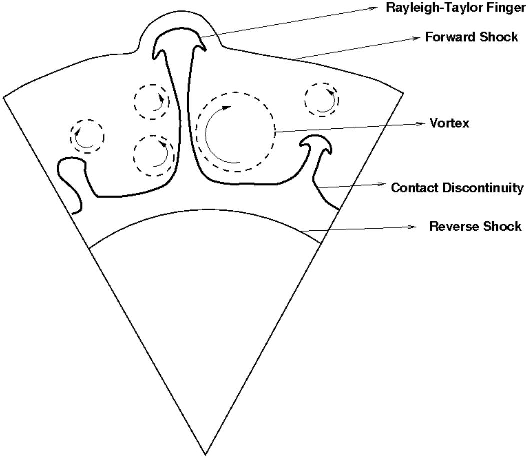
Effects of asymmetry of the CSM on the shape of young SNR following the SSDW model. (Blondin, Lundqvist & Chevalier 1996)

INHOMOGENEITIES IN THE AMBIENT MEDIUM

Interaction of the blast wave with small cloudlets in the CSM.

Small-scale anisotropies enhance vorticity within SSDW and effectively lengthen the fingers produced by convective instability.

Jun, Jones & Norman (1996)

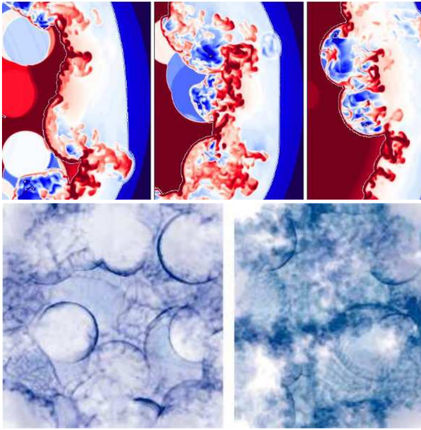


MIXING IN SNRS

Extensive mixing of radioactive material in SN ejecta, mostly freshly synthesized Ni. The mixing is not complete → two-phase SN ejecta structure.

SN 1987A: inhomogeneities in the form of Fe-Ni bubbles (inferred from observations of Fe, Co, and Ni lines by Li et al. 1993).

Filling factor of the ejecta volume ∼ 0,5



Blondin,Borkowski & Reynolds (2001)

PARTICLE ACCELERATION

Radio emission from SNRs indicates the presence of ultrarelativistic electrons ($E \sim 10^4 m_e c^2$).

Where do these electrons come from?
NOT from compression at shock front.

- spectrum is incorrect
- SNRs have radio brightness too high to be explained by this mechanism

⇒ diffusive shock acceleration (DSA) (Reynolds & Chevalier 1981; Drury 1983)

THE MAIN IDEA: particle velocities in the collisionless shock wave are randomized by *magnetic irregularities* in the post-shock medium. Some of those particles are scattered back into the pre-shock region and might be reflected back again.

Chandra false color image of SN1006.

CONCLUSIONS AND QUALMS

- Blast waves from SN Type Ia / II,Ib/c expand into de ISM / CSM leaving behind a supernova remnant. The first stages of the expansion can be described self-similarly and consist of a front shock and a reverse shock.
- Multi-D is necessary to account for effects such as instabilities in the shock waves (Raleigh-Tayor, Richtmyer-Meshkov), consequences of asymmetries in the CSM or interactions with cloudlets present in the ambient medium.
- Ejecta clumps can be transported outward of the front shock by turbulence.
- 3D simulations: formation of Ni-Fe bubbles ("macroscopic mixing") such as those seen in 1987A is one of the consequences of this process.

CONCLUSIONS AND QUALMS

- SNRs might be the origin of cosmic rays. Particles would be accelerated at the front shock by magnetic irregularities in the ambient medium.
- Particle acceleration could be the explanation for the nonthermal emission radio spectrum of SNRs.
- We have neglected magnetic fields and we have studied the hydrodynamics of SNR remnants. It has been suggested that interstellar magnetic fields can even be amplified by SNRs (see for instance Ellison & Vladimirov 2008).

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