Dynamics of supernova ejecta

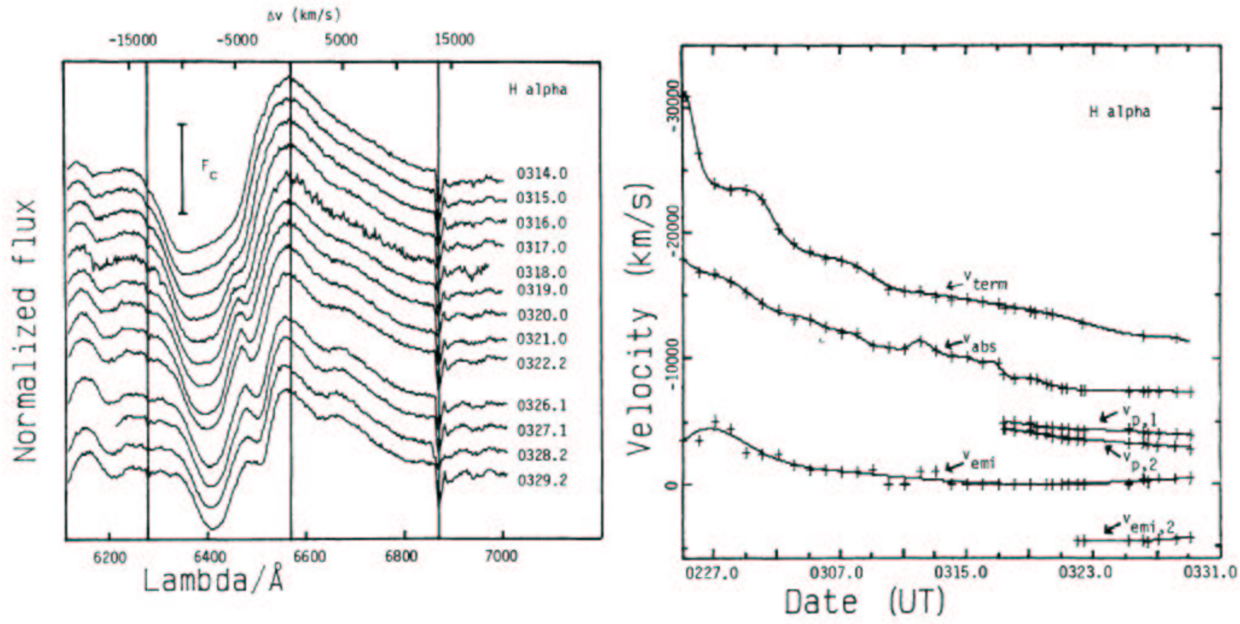
- **Supernovae**
  - Core-collapse SNe
    - supergiant with mass $\geq 8M_{\odot}$
    - circumstellar material from stellar wind
    - type II, Ib, Ic
    - several solar masses of matter ejected
    - compact remnant (neutron star)
  - Thermonuclear explosion SNe
    - white dwarf in close binary system
    - no circumstellar material
    - type Ia
    - ≈ 1 solar mass of matter ejected
    - no compact remnant
  - Ejection velocities $V_{\rm e}$ on the order of 10000 km s^{-1}
  - Initial kinetic energy of ejecta $E_* \approx 10^{44}$ J
    total energy released by type II SNe ≈ 100 times larger
    (carried away by neutrinos)

- **Phases of supernova remnant evolution**
  - **Initial phase**
    * free expansion phase
    * magnetohydrodynamic shock forms in ISM
    * mean free path of ejected protons ≈ 500 pc
      $\rightarrow$ weak magnetic field (a few μG) necessary to prevent them from escaping
    * synchrotron radiation is observed at radio wavelengths
    * IS gas is compressed by shock "sweeping" through at speed $= V_{\mathrm{e}}$
    * shock radius $R = V_{\mathrm{e}} t$
      as long as mass of ejected material is larger than mass of swept-up IS gas
    * reverse shock forms in ejected material
    * phase ends when swept-up mass equals ejected mass

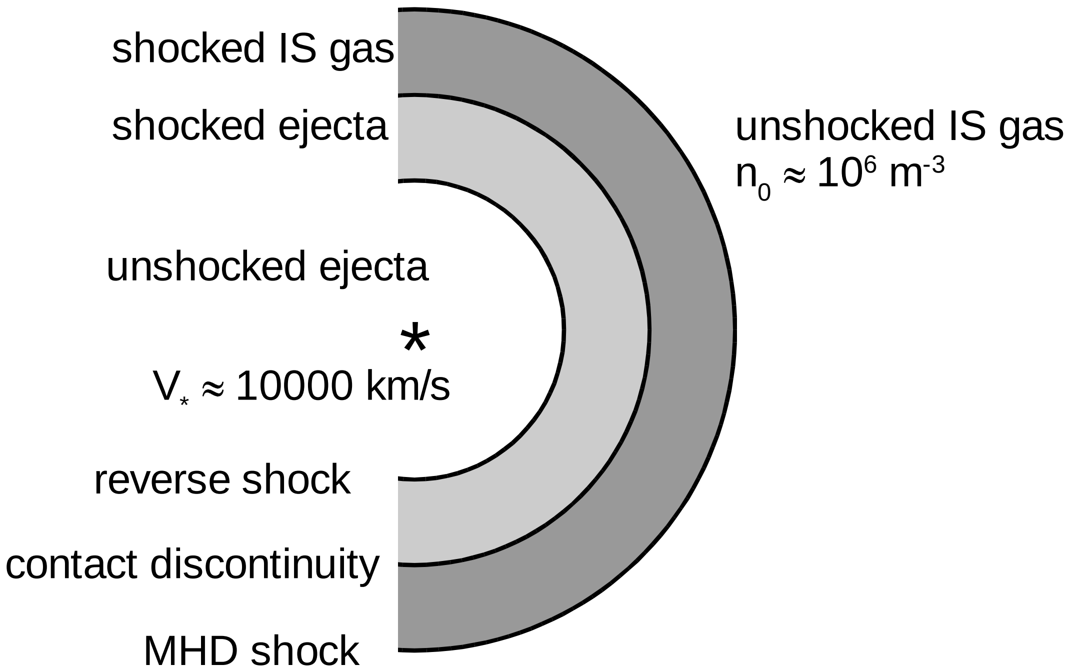
$$\frac{4\pi}{3} R_{\mathrm{e}}^3 \rho_0 = M_{\mathrm{e}}$$

    * e.g. $n_0 = 10^6$ m^{-3}
    * SN II: $M_{\mathrm{e}} = 4 M_{\odot} \rightarrow R_{\mathrm{e}} = 3.4$ pc
      $V_{\mathrm{e}} = 5000$ km s^{-1} $\rightarrow t_{\mathrm{e}} \approx 700$ yr
    * SN Ia: $M_{\mathrm{e}} = 0.25 M_{\odot} \rightarrow R_{\mathrm{e}} = 1.3$ pc
      $V_{\mathrm{e}} = 20000$ km s^{-1} $\rightarrow t_{\mathrm{e}} \approx 60$ yr
    * material behind shock fronts heated to very high temperatures $\rightarrow$ thermal bremsstrahlung observed at X-ray wavelengths

SN 1987A (Feb 23) velocity measurements
(Hanuschik & Dachs 1987)



Flow pattern in initial phase of SNR evolution



– **Adiabatic phase**

- reverse shock travels inwards and passes away
- M_e < mass of swept-up IS gas
  → ejected material negligible
- expanding bubble of hot, shocked IS gas
- initial shock velocity = V_e
  → high post-shock temperature:
  $$T_\mathrm{S} = \frac{3}{16}\frac{1/2 \cdot m_\mathrm{u} V_\mathrm{e}^2}{k} \approx 10^9 \text{ K} \quad \text{for } V_\mathrm{e} = 10000 \text{ km s}^{-1}$$
  → low cooling rate → adiabatic expansion
- assume instantaneous release of a large amount of energy into surrounding gas of uniform density
- detailed treatment in book of Sedov (1959, *Similarity and Dimensional Methods in Mechanics*, New York: Academic Press) gives self-similar solution for structure interior to shock
- energy conservation
  → shock radius R_S and velocity V_S as a function of time
- from Sedov-solution: $E_\mathrm{th} \approx 0.70 E_*$ ($E_\mathrm{kin} \approx 0.30 E_*$),
  $P_\mathrm{S} \approx 2.1 \langle P \rangle$ (average gas pressure of expanding bubble)
- post-shock pressure for strong adiabatic shock and pressure of ideal monoatomic gas
  $$P_\mathrm{S} = \frac{3}{4}\rho_0 V_s^2 \qquad \langle P \rangle = \frac{2}{3} \cdot \frac{E_\mathrm{th}}{4\pi R_\mathrm{S}^3/3}$$
  $$\rightarrow V_\mathrm{S} = \frac{\mathrm{d}R_\mathrm{S}}{\mathrm{d}t} \approx \left(2.1 \frac{2}{3\pi} \frac{0.7 E_*}{\rho_0}\right)^{1/2} R_\mathrm{S}^{-3/2}$$
  integration with lower limits = 0 for R_S and t
  $$\rightarrow R_\mathrm{S} \approx \left(\frac{5}{2}\right)^{2/5} \left(\frac{E_*}{\pi \rho_0}\right)^{1/5} t^{2/5} \qquad \rightarrow V_\mathrm{S} \propto t^{-3/5}$$

– **Radiative phase**

* post-shock temperature decreases because of decreasing velocity:
  $$T_{\rm S} = \frac{3}{32}\frac{m_{\rm u} V_{\rm S}^2}{k} \approx 10^6 \text{ K} \quad \text{for } V_{\rm S} = V_0 = 300 \text{ km s}^{-1}$$
  → higher cooling rate, increases with temperature
* cooling further enhanced by increasing density in thin shell behind shock
  → catastrophic cooling phase
* isothermal phase, "snowplough" phase
* $R_0 \approx 20$ pc , $t_0 \approx 25000$ yr, $M_0 \approx 700 M_\odot$
  for $E_* = 10^{44}$ J and $n_0 = 10^6$ m^{-3}
* momentum conservation of shell,
  assume all mass interior to shock to be in shell
  → shell/shock radius $R_{\rm S}$ and velocity $V_{\rm S}$
  as a function of time
* main difference to wind model:
  no continuous supply of energy
  $$\frac{4}{3}\pi R_{\rm S}^3 \rho_0 V_{\rm S} = \frac{4}{3}\pi R_0^3 \rho_0 V_0$$
  $$R_{\rm S}^3 {\rm d}R_{\rm S} = R_0^3 V_0 {\rm d}t$$
  integration with lower limits = R_0 and t_0
  $$\rightarrow \frac{1}{4}(R_{\rm S}^4 - R_0^4) = R_0^3 V_0 (t - t_0)$$
  $$R_{\rm S} = R_0 \left(1 + 4\frac{V_0}{R_0}(t - t_0)\right)^{1/4}$$
  $$V_{\rm S} = V_0 \left(1 + 4\frac{V_0}{R_0}(t - t_0)\right)^{-3/4}$$
  $$R_{\rm S} \propto t^{1/4}, \quad V_{\rm S} \propto t^{-3/4} \qquad \text{for } t \gg \frac{R_0}{V_0}$$

– **End of the life of supernova remnants**
dispersion into ISM when $V_{\rm S} = V_{\rm f} \approx 10$ km s^{-1}
$\approx$ random speed of ISM clouds
$\rightarrow t_{\rm f} \approx 10^6$ yr, $R_{\rm f} \approx 60$ pc, $M_{\rm f} \approx 10^4 M_\odot$

– **Efficiency of energy conversion**

∗ fraction g of initial energy E_* converted into kinetic energy of the ISM

$$g = \frac{(1/2) M_{\rm f} V_{\rm f}^2}{E_*} \approx 0.02$$

$\rightarrow$ higher than for conversion of stellar UV energy but lower than for wind model

– **Hot medium**

∗ remnant filled with hot medium at end of adiabatic phase

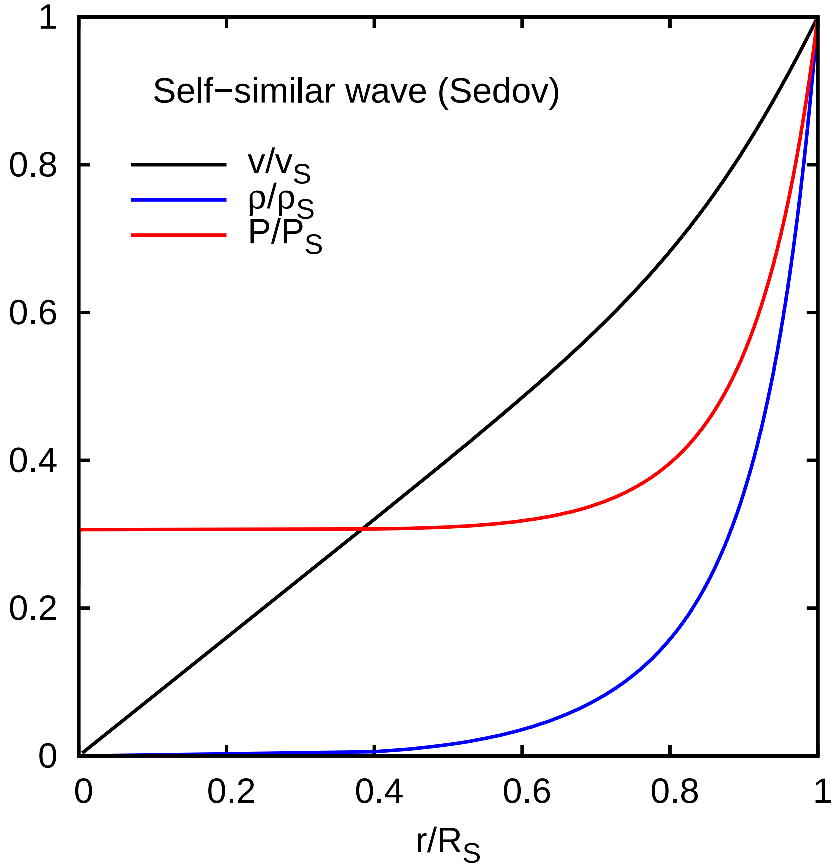
∗ cools adiabatically during the isothermal phase

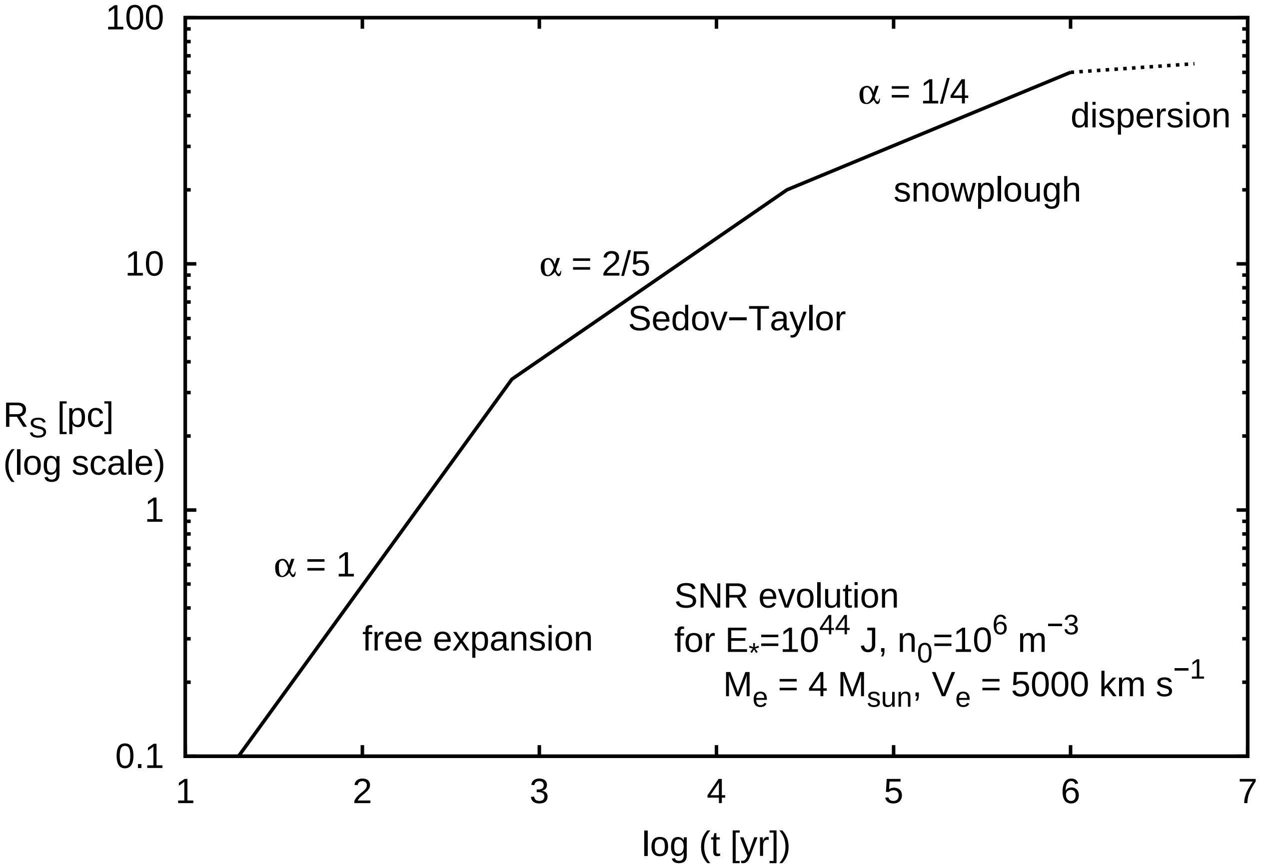
∗ effects of this medium on dynamics of isothermal phase neglected

∗ still rather hot ($10^5 - 10^6$ K) when SNR disperses
$\rightarrow$ also distributed into ISM
$\rightarrow$ hot phase of ISM, also called “coronal gas”

∗ low density ($< 10^4$ m^{-3}) $\rightarrow$ large scale height

∗ observed in soft X-rays and in UV spectra of hot stars


Self−similar wave (Sedov)
v/v_S
ρ/ρ_S
P/P_S
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
r/R_S


100
10
1
0.1
R_S [pc]
(log scale)
α = 1/4
dispersion
snowplough
α = 2/5
Sedov−Taylor
α = 1
free expansion
SNR evolution
for E*=10^44 J, n_0=10^6 m^−3
M_e = 4 M_sun, V_e = 5000 km s^−1
1
2
3
4
5
6
7
log (t [yr])

Dynamics of diffuse neutral clouds

- **Properties of neutral clouds**
  - observed in 21 cm line, and Na I D or Ca II K lines
  - consist mainly of HI at $T \approx 70$ K
    $\rightarrow$ sound speed $\lesssim 1$ km s^{-1}
  - space velocity $u_\mathrm{c} \approx 10$ km s^{-1}
  - density $n_\mathrm{H} \approx 3 \cdot 10^7$ m^{-3}
  - cloud radius R_c on average 2.5 pc $\rightarrow$ mass $M_\mathrm{c} \approx 50 M_\odot$
  - number of clouds along a line of sight
    N_L on average 6 kpc^{-1}
  - number of clouds in galactic disk

$$V_\mathrm{disk} = R_\mathrm{disk}^2 \pi h_\mathrm{disk} \approx (10\mathrm{kpc})^2 \pi 250\mathrm{pc} \approx 7.9 \cdot 10^{10} \mathrm{pc}^3 \approx 2.35 \cdot 10^{60} \mathrm{m}^3$$

$$N_\mathrm{c} = N_\mathrm{L} \frac{V_\mathrm{disk}}{L R_\mathrm{c}^2 \pi} \approx 2.4 \cdot 10^7$$

  - fraction of disk volume occupied by clouds

$$\alpha = \frac{N_\mathrm{c} V_\mathrm{c}}{V_\mathrm{disk}} \approx 0.02$$

- **Cloud-cloud collisions**
  - supersonic → shock waves → dissipation of kinetic energy
  - collision rate

$$\dot{\mathcal{N}}_{\rm coll} \approx \frac{N_{\rm c}^2 u_{\rm c} R_{\rm c}^2 \pi}{V_{\rm disk}}$$

  - energy dissipated in one collision is kinetic energy of both clouds

$$E_{\rm coll} \approx M_{\rm c} u_{\rm c}^2$$

  - energy loss rate per unit volume

$$\mathcal{L} \approx \frac{\dot{\mathcal{N}}_{\rm coll} E_{\rm coll}}{V_{\rm disk}} \approx \frac{N_{\rm c}^2 R_{\rm c}^2 \pi M_{\rm c} u_{\rm c}^3}{V_{\rm disk}^2} \approx 2 \cdot 10^{-28} {\rm Jm}^{-3}{\rm s}^{-1}$$

  - system of clouds in steady state requires resupply of kinetic energy
    → energy gain from supernova explosions
    with $E_* = 10^{44}$ J and conversion efficiency g
  - galactic supernova rate ≈ 3 per century
    (see review article by van den Bergh & Tammann, 1991, ARA&A 29, 363) → $t_{\rm ex} \approx 30$ yr
  - energy gain rate per unit volume

$$\mathcal{G} \approx g \frac{E_*}{V_{\rm disk} t_{\rm ex}} \approx g \cdot 4.5 \cdot 10^{-26} {\rm Jm}^{-3}{\rm s}^{-1}$$

$$g = 0.02 \rightarrow \mathcal{G} \approx 1.4 \cdot 10^{-27} {\rm Jm}^{-3}{\rm s}^{-1}$$

Pressure equilibrium in the ISM

- Five main ISM phases

Phase	n [m^{-3}]	T [K]	$P = nkT$ [N m^{-2}]
1. Coronal gas	$< 10^4$	$5 \cdot 10^5$	$< 10^{-13}$
2. HII regions	$\gtrsim 10^8$	10^4	$\gtrsim 10^{-11}$
3. Warm intercloud medium	10^6	8000	10^{-13}
4. Diffuse neutral clouds	$10^7 - 10^9$	70	$10^{-14} - 10^{-12}$
5. Molecular clouds	$> 10^8$	20	$> 10^{-14}$

- pressure equilibrium between 1, 3, 4, partly 5
- expected when considering sound crossing times $t_\mathrm{c} = L/c_\mathrm{s}$
- diffuse neutral cloud: $t_\mathrm{c} \approx 5 \cdot 10^6$ yr
- coronal gas: $c_\mathrm{s} \approx 90$ km s^{-1}, scale height ≈ 300 pc
  $\rightarrow t_\mathrm{c} \approx 6 \cdot 10^6$ yr
- warm intercloud medium: $c_\mathrm{s} \approx 10$ km s^{-1}
  $\rightarrow$ sound waves travel distances of many times the diameter of neutral clouds

Superbubbles

- Groups of massive stars with range of masses
  $\rightarrow$ stellar winds + supernovae distributed over time
- Supernovae dominate the dynamics of the region
- Act similar to a wind with $\frac{1}{2}\dot{M}_* V_* = E_*/t_{\rm ex}$

$$R(t) = \left(\frac{125}{154\pi}\right)^{1/5} \left(\frac{E_*}{t_{ex} n_0 m_H}\right)^{1/5} t^{3/5}$$

- $E_* = 10^{44}$ J, $t_{\rm ex} = 3 \cdot 10^5$ yr, $n_0 = 10^6$ m^{-3}
- Lifetime of lowest mass ($8\ M_\odot$) star: $t \approx 10^8$ yr
  $\rightarrow R(10^8 \text{yr}) \approx 1000$ pc, $R(10^7 \text{yr}) \approx 280$ pc
- Evolution of superbubbles influenced by variation of density with distance z from galactic plane

$$n(z) = n_0 \exp(-\frac{|z|}{h_0}) \qquad h_0 \approx 100 \text{ pc}$$

$\rightarrow R = R(t, z), \dot{R} = \dot{R}(t, z)$

- $|z| \uparrow \ \ \rightarrow n \downarrow \ \ \rightarrow R, \dot{R} \uparrow$

Distortion of a superbubble