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
    * $\approx 1$ solar mass of matter ejected
    * no compact remnant
  - Ejection velocities $V_e$ 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 $\approx 100$ 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 $\approx 500$ pc
      $\rightarrow$ weak magnetic field (a few $\mu$G) necessary to prevent them from escaping
    * synchrotron radiation is observed at radio wavelengths
    * IS gas is compressed by shock “sweeping” through at speed $= V_e$
    * shock radius $R = V_e t$
      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
      \[
      \frac{4\pi}{3} R_e^3 \rho_0 = M_e
      \]
    * e.g. $n_0 = 10^6$ m$^{-3}$
    * SN II: $M_e = 4M_\odot \rightarrow R_e = 3.4$ pc
      $V_e = 5000$ km s$^{-1}$ $\rightarrow t_e \approx 700$ yr
    * SN Ia: $M_e = 0.25M_\odot \rightarrow R_e = 1.3$ pc
      $V_e = 20000$ km s$^{-1}$ $\rightarrow t_e \approx 60$ 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

shocked IS gas
shocked ejecta

unshocked IS gas
$n_0 \approx 10^6 \text{ m}^{-3}$

unshocked ejecta

$V \approx 10000 \text{ km/s}$

reverse shock

contact discontinuity

MHD shock
– **Adiabatic phase**  
* reverse shock travels inwards and passes away  
* $M_e < \text{mass of swept-up IS gas}$  
  $\rightarrow$ ejected material negligible  
* expanding bubble of hot, shocked IS gas  
* initial shock velocity $= \text{Ve}$  
  $\rightarrow$ high post-shock temperature:  
  $$T_S = \frac{3}{16} \frac{1/2 \cdot m_u V_e^2}{k} \approx 10^9 \text{ K for } V_e = 10000 \text{ km s}^{-1}$$  
  $\rightarrow$ low cooling rate $\rightarrow$ adiabatic expansion  
* assume instantaneous release of a large amount of energy into surrounding gas of uniform density  
* energy conservation  
  $\rightarrow$ shock radius $R_S$ and velocity $V_S$ as a function of time  
* from Sedov-solution: $E_{\text{th}} \approx 0.70E_*$ $(E_{\text{kin}} \approx 0.30E_*)$, $P_S \approx 2.1\langle P \rangle$ (average gas pressure of expanding bubble)  
* post-shock pressure for strong adiabatic shock and pressure of ideal monoatomic gas  
  $$P_S = \frac{3}{4} \rho_0 V_s^2 \quad \langle P \rangle = \frac{2}{3} \cdot \frac{E_{\text{th}}}{4\pi R_S^3/3}$$  
  $$\rightarrow V_S = \frac{dR_S}{dt} \approx \left(2.1 \frac{2}{3\pi} \frac{0.7E_*}{\rho_0}\right)^{1/2} R_S^{-3/2}$$  
integration with lower limits = 0 for $R_S$ and $t$  
  $$\rightarrow R_S \approx \left(\frac{5}{2}\right)^{2/5} \left(\frac{E_*}{\pi \rho_0}\right)^{1/5} t^{2/5} \quad \rightarrow V_S \propto t^{-3/5}$$
Radiative phase

* post-shock temperature decreases because of decreasing velocity:
\[ T_S = \frac{3}{32} \frac{m_u V_S^2}{k} \approx 10^6 \text{ K} \quad \text{for } V_S = V_0 = 300 \text{ km s}^{-1} \]
→ higher cooling rate, increases with temperature
* cooling further enhanced by increasing density in thin shell behind shock
→ catastrophic cooling phase
* isothermal phase, “snowplough” phase
* \( R_0 \approx 20 \text{ pc} \), \( t_0 \approx 25000 \text{ yr} \), \( M_0 \approx 700M_\odot \)
for \( E_* = 10^{44} \text{ J} \) and \( n_0 = 10^6 \text{ m}^{-3} \)
* momentum conservation of shell,
assume all mass interior to shock to be in shell
→ shell/shock radius \( R_S \) and velocity \( V_S \) as a function of time
* main difference to wind model:
no continuous supply of energy
\[ \frac{4}{3} \pi R_S^3 \rho_v V_S = \frac{4}{3} \pi R_0^3 \rho_0 V_0 \]
\[ R_S^3 dR_S = R_0^3 V_0 dt \]
integration with lower limits = \( R_0 \) and \( t_0 \)
→ \[ \frac{1}{4} (R_S^4 - R_0^4) = R_0^3 V_0 (t - t_0) \]
\[ R_S = R_0 \left( 1 + 4 \frac{V_0}{R_0} (t - t_0) \right)^{1/4} \]
\[ V_S = V_0 \left( 1 + 4 \frac{V_0}{R_0} (t - t_0) \right)^{-3/4} \]
\[ R_S \propto t^{1/4}, \quad V_S \propto t^{-3/4} \quad \text{for } t \gg \frac{R_0}{V_0} \]
– **End of the life of supernova remnants**
  dispersion into ISM when $V_S = V_f \approx 10 \text{ km s}^{-1}$
  $\approx$ random speed of ISM clouds
  $\rightarrow t_f \approx 10^6 \text{ yr}, R_f \approx 60 \text{ pc}, M_f \approx 10^4 M_\odot$

– **Efficiency of energy conversion**
  * fraction $g$ of initial energy $E_*$ converted
    into kinetic energy of the ISM
    \[
    g = \frac{(1/2)M_fV_f^2}{E_*} \approx 0.02
    \]
  $\rightarrow$ 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 ($10^5 - 10^6 \text{ K}$) when SNR disperses
    $\rightarrow$ also distributed into ISM
    $\rightarrow$ hot phase of ISM, also called “coronal gas”
  * low density ($< 10^4 \text{ m}^{-3}$) $\rightarrow$ large scale height
  * observed in soft X-rays and in UV spectra of hot stars
**Self-similar wave (Sedov)**

![Graph showing the self-similar wave (Sedov) with curves for different ratios: $v/v_S$, $\rho/\rho_S$, and $P/P_S$.](image)

- $v/v_S$, $\rho/\rho_S$, and $P/P_S$ as functions of $r/R_S$.

**SNR evolution** for $E_\star = 10^{44}$ J, $n_0 = 10^6$ m$^{-3}$

- $M_e = 4 M_{\odot}$, $V_e = 5000$ km s$^{-1}$

**Log-log graph** showing $R_S$ vs. $\log(t \text{ [yr]})$:

- $\alpha = 1/4$ for dispersion
- $\alpha = 2/5$ for snowplough
- $\alpha = 1$ for free expansion

**Sedov–Taylor** dispersion
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 \( u_c \approx 10 \) km s\(^{-1}\)
  - density \( n_H \approx 3 \cdot 10^7 \) m\(^{-3}\)
  - cloud radius \( R_c \) on average 2.5 pc \( \rightarrow \) mass \( M_c \approx 50 M_\odot \)
  - number of clouds along a line of sight
    \( N_L \) on average 6 kpc\(^{-1}\)
  - number of clouds in galactic disk
    \[
    V_{\text{disk}} = R_{\text{disk}}^2 \pi h_{\text{disk}} \approx (10 \text{kpc})^2 \pi 250 \text{pc} \approx 7.9 \cdot 10^{10} \text{pc}^3 \approx 2.35 \cdot 10^{60} \text{m}^3
    \]
    \[
    N_c = N_L \frac{V_{\text{disk}}}{LR_c^2 \pi} \approx 2.4 \cdot 10^7
    \]
  - fraction of disk volume occupied by clouds
    \[
    \alpha = \frac{N_c V_c}{V_{\text{disk}}} \approx 0.02
    \]
• Cloud-cloud collisions
  – supersonic → shock waves → dissipation of kinetic energy
  – collision rate
    \[ \dot{N}_{\text{coll}} \approx \frac{N^2_c u_c R^2_c \pi}{V_{\text{disk}}} \]
  – energy dissipated in one collision
    is kinetic energy of both clouds
    \[ E_{\text{coll}} \approx M_c u_c^2 \]
  – energy loss rate per unit volume
    \[ \mathcal{L} \approx \frac{\dot{N}_{\text{coll}} E_{\text{coll}}}{V_{\text{disk}}} \approx \frac{N^2_c R^2_c \pi M_c u_c^3}{V^2_{\text{disk}}} \approx 2 \cdot 10^{-28} \text{J m}^{-3} \text{s}^{-1} \]
  – system of clouds in steady state requires resupply
    of kinetic energy
    → energy gain from supernova explosions
    with \( E_* = 10^{44} \text{ J} \) and conversion efficiency \( g \)
  – galactic supernova rate \( \approx 3 \) per century
    (see review article by van den Bergh & Tammann, 1991,
    ARA&A 29, 363) \( \rightarrow t_{\text{ex}} \approx 30 \text{ yr} \)
  – energy gain rate per unit volume
    \[ \mathcal{G} \approx g \frac{E_*}{V_{\text{disk}} t_{\text{ex}}} \approx g \cdot 4.5 \cdot 10^{-26} \text{J m}^{-3} \text{s}^{-1} \]
    \[ g = 0.02 \rightarrow \mathcal{G} \approx 1.4 \cdot 10^{-27} \text{J m}^{-3} \text{s}^{-1} \]
Pressure equilibrium in the ISM

- Five main ISM phases

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

- Pressure equilibrium between 1, 3, 4, partly 5
- Expected when considering sound crossing times $t_c = L/c_s$
- Diffuse neutral cloud: $t_c \approx 5 \cdot 10^6$ yr
- Coronal gas: $c_s \approx 90$ km s$^{-1}$, scale height $\approx 300$ pc
  $\rightarrow t_c \approx 6 \cdot 10^6$ yr
- Warm intercloud medium: $c_s \approx 10$ 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 → stellar winds + supernovae distributed over time

• Supernovae dominate the dynamics of the region

• Act similar to a wind with \( \frac{1}{2} \dot{M}_* V_* = \frac{E_*}{t_{\text{ex}}} \)

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

• \( E_* = 10^{44} \text{ J}, t_{\text{ex}} = 3 \cdot 10^5 \text{ yr}, n_0 = 10^6 \text{ m}^{-3} \)

• Lifetime of lowest mass (8 \( M_\odot \)) star: \( t \approx 10^8 \text{ yr} \)
  → \( R(10^8 \text{ yr}) \approx 1000 \text{ pc}, R(10^7 \text{ yr}) \approx 280 \text{ pc} \)

• Evolution of superbubbles influenced by variation of density with distance \( z \) from galactic plane

\[
n(z) = n_0 \exp\left(-\frac{|z|}{h_0}\right) \quad h_0 \approx 100 \text{ pc}
\]

→ \( R = R(t, z), \dot{R} = \dot{R}(t, z) \)

• \( |z| \uparrow \rightarrow n \downarrow \rightarrow R, \dot{R} \uparrow \)
Distortion of a superbubble

\[ n = n_0 \exp \left( -\frac{|z|}{h_0} \right) \]

\[ h_0 \approx 100 \text{ pc} \]

\[ n_0 \approx 10^6 \text{ m}^{-3} \]