Lecture 14: Feedback

14·1 Momentum vs Energy feedback
14·2 Stellar winds
14·3 Supernovae - free expansion
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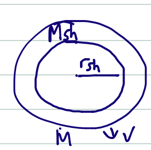
14·1 Feedback Types

Type	Momentum Budget	E/p
Outflows	$10\,\mathrm{km\,s^{-1}}\,M_\odot^{-1}$	p
HII regions	varies	p
Rad pressure	$200\,\mathrm{km\,s^{-1}}\,M_\odot\,\mathrm{yr}^{-1}$	p?
Supernovae	$50\,\mathrm{km\,s^{-1}}\,M_\odot\,\mathrm{yr}^{-1}$	E
Winds	$100\,\mathrm{km\,s^{-1}}\,M_\odot\,\mathrm{yr}^{-1}$	E

In momentum conserving feedback the gas is heated to temperatures where it can cool efficiently $T < 10^5\,K$ and so only momentum is conserved.

In supernovae (SN) the gas is shock heated to $\sim 10^8\,K$ at which point the cooling time of the gas is so long that there are no radiative losses.

Consider an expanding shell



E

$M_{sh}\,\dot{r}_{sh} = \dot{M} v^2 t$

p

$M_{sh}\,\dot{r}_{sh} = \dot{M} v t$

Energy conserving greater by a factor of $v/\dot{r}_{sh}$
↳ significant force in shaping the ISM.

However it should be noted that geometry can play a role in energy conserving case. If the energy is trapped it will drive surrounding gas outwards like a piston. If there are a lot of "holes" in the medium the energy can escape.

14·2 Stellar Winds

O-type stars $1500 \leq V_w \lesssim 2500$ $\mathrm{km\,s^{-1}}$
$10^{-6.5} < \dot{M} < 10^{-5}$ $M_\odot\,\mathrm{yr}^{-1}$

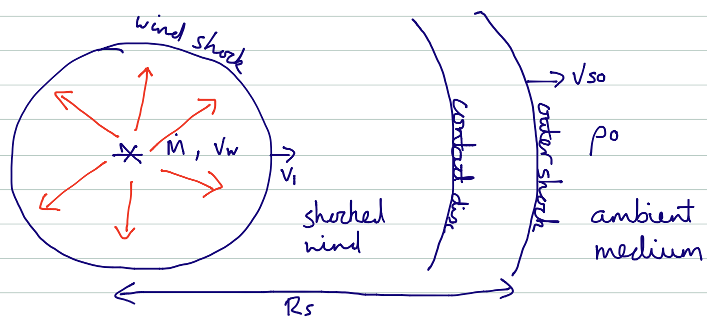
B-type stars $300 < V_w < 1500$ $km\,s^{-1}$
$10^{-7} < \dot{M} < 10^{-6}$ $M_\odot\,yr^{-1}$

cool evolved stars $15 < V_w < 30$ $km\,s^{-1}$
$10^{-7} < \dot{M} < 10^{-4}$ $M_\odot\,yr^{-1}$
M giants ↑ ↑ AGB

- Hot stars – winds radiation driven
  Surface temperatures $10^4\,K - 10^5\,K$ and no convection zone to heat a corona, Radiative flux $\propto \sigma T^4$

- Solar type stars $\dot{M} \sim 10^{-14}\,M_\odot\,yr^{-1}$ – pressure driven
  Outward force comes from pressure gradient associated with the high temperature corona

Hot OB stars winds are the most significant in shaping the ISM



– ionising radiation has already created an HII bubble (we will assume that the HII is at rest).

– $V_w \gg C_s$ drives a shock in the HII region, the outer shock

– shocked ambient accumulates in a shell behind the shock front.

– second shock where the stellar wind is decelerated

– shocked wind lies between wind shock and shocked ambient material with a contact discontinuity separating them.

wind begins at $t=0$
mechanical power in wind $\dot{\epsilon} = \dot{M} V_w^2 / 2$

1) free expansion $R_s = V_w t$
ends when wind mass and swept up mass are comparable

$$\dot{M} t = \frac{4\pi}{3} \rho_0 (V_w t)^3$$

$$\Rightarrow t_0 = \left(\frac{3\dot{M}}{4\pi \rho_0 V_w^3}\right)^{1/2}$$
$$= 2.5 \left(\frac{n}{10^3}\right)^{-1/2} \left(\frac{\dot{M}}{10^{-6}}\right)^{1/2} \left(\frac{V_w}{10^8}\right)^{-3/2} \text{yr}$$

very short time so free expansion brief

2) Energy conserving phase

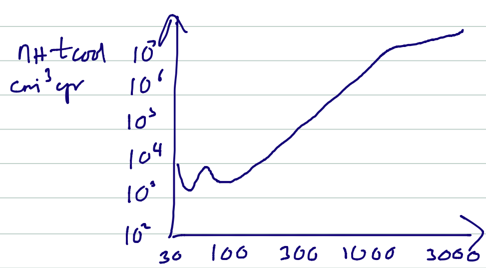
$$E(t) = \tfrac{1}{2}\dot{M} t V_w^2$$

assume power law behavior for radius

$$R_s = A t^\eta \Rightarrow V_s = \eta R_s / t$$

outer shock speed decreases with time

For a steady shock the peak temperature occurs immediately behind the shock. If the gas can cool this will further compress the gas.



$80 < V_s < 1200$ km s^{-1}

$$n_H t_{cool} = 7000 \left(\frac{V_s}{100 \text{ km s}^{-1}}\right)^{3.4}$$

Shocks with $V_s \lesssim 100$ km s^{-1} cool rapidly

The outer shock quickly stops being energy conserving and a thin shell forms at the shock boundary.

However behind the shock the cooling is isobaric

$$t_{cool} = \frac{5 n k T}{2 \Lambda}$$

and $T \sim 10^7$ K and n is low $\Rightarrow$ long cooling time

3) Expansion driven by pressure from the hot gas. Energy losses come only from work done on the outer shell.

$$R_s \sim 0.85 \left(\frac{50 \dot{M} V_w^2}{27\pi \rho_0}\right)^{1/5} t^{3/5} \qquad V_s = \eta \frac{R_s}{t}$$

Over time the expansion velocity drops as does the compression ratio

When $V_s \sim C_s \sim 15\ \mathrm{km\,s^{-1}}$ the shock ends and dissipates as an acoustic wave. The inner shocked stellar wind will be left behind as an inner bubble of X-ray emitting plasma.

For an O7 star the Strömgren radius $= 3 \times 10^{18}\ n_s^{-2/3}$ cm easily encloses the stellar wind bubble.

14.3 Supernovae

While stellar winds affect the ISM over only a small radius SN have a very strong effect.

SN ejects a mass M_{ej} with a kinetic energy $E_0 = 10^{51}$ erg

Type Ia SN : $M_{ej} \sim 1.4\ M_\odot$ (collapse of white dwarf above Chandrasekhar limit)

Type II SN : $M_{ej} \sim 10-20\ M_\odot$ (core collapse of massive star)

1) free expansion stage (assuming a uniform surrounding medium)

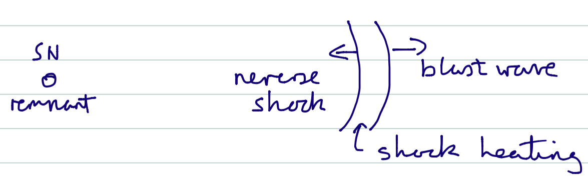
Ejecta will have a range of velocities with the outermost material moving fastest. The rms velocity of the ejecta is

$$\langle v_{ej}^2 \rangle^{1/2} = \left(\frac{2E_0}{M_{ej}}\right)^{1/2} = 10^4\ \mathrm{km\,s^{-1}} \left(\frac{E}{10^{51}\,\mathrm{erg}}\right)^{1/2} \left(\frac{M_\odot}{M_{ej}}\right)^{1/2}$$

so again this drives a fast shock into the circumstellar medium.

In the first days the density of the ejecta far exceeds that of the ISM and the ejecta expands ballistically.

As the density of the ejecta drops $\propto t^{-3}$ the pressure of the shocked circumstellar material exceeds the thermal pressure of the ejecta and drives a reverse shock.



The reverse shock, shock heats the ejecta which had been cooled by adiabatic expansion.

Reverse shock important when the ejecta mass becomes equal to the swept up mass. This occurs at a radius

$$R_1 = \left(\frac{3 M_{ej}}{4\pi \rho_0}\right)^{1/3} = 5.88 \times 10^{18}\,\text{cm} \left(\frac{M_{ej}}{M_\odot}\right)^{1/3} n_0^{-1/3}$$

at a time

$$t_1 \approx \frac{R_1}{\langle v_{ej}^2 \rangle^{1/2}} = 186\,\text{yr} \left(\frac{M_{ej}}{M_\odot}\right)^{5/6} \left(\frac{E}{10^{51}\text{erg}}\right)^{-1/2} n_0^{-1/3}$$

This is the end of the free expansion wave

2) Sedov - Taylor phase

For $t \gtrsim t_1$ the reverse shock has reached the centre of the remnant and the ejecta is very hot.

$$P_{in} >> P_{out}$$

Now approximate expansion as a point explosion injecting only energy E_0 into a uniform-density, zero temperature medium of density ρ_0 we neglect
1) finite mass of ejecta
2) radiative losses
3) pressure of ambient medium

Suppose

$$R_S = A\, E^\alpha \rho^\beta t^\eta$$

determine the powers from dimensional analysis by equating the powers to which mass, length and time appear

$$E = MR^2/t \qquad \rho = M/R^3$$

$$M^0 R\, t^0 = \left(\frac{MR^2}{t^2}\right)^\alpha \left(\frac{M}{R^3}\right)^\beta t^\eta$$

$$M^0 R^1 t^0 = \frac{M^\alpha R^{2\alpha}}{t^{2\alpha}} \frac{M^\beta}{R^{3\beta}} t^\eta$$

$\Rightarrow$

Mass: $0 = \alpha + \beta$
Length: $1 = 2\alpha - 3\beta$
Time: $0 = -2\alpha + \eta$

solve to get $\alpha = 1/5$, $\beta = -1/5$, $\eta = 2/5$

$$R_S = A\, E^{1/5} \rho_0^{-1/5} t^{2/5}$$

the exact solution is

$$R_s = 1.54 \times 10^{19} \text{ cm } E_{51}^{1/5} \, n_0^{-1/5} \, t_3^{2/5} \qquad t_3 = t/10^3 \text{yr}$$

$$V_s = 1950 \text{ km s}^{-1} \, E_{51}^{1/5} \, n_0^{-1/5} \, t_3^{-3/5} \qquad E_{51} = E/10^{51} \text{erg}$$

$$T_s = 5.25 \times 10^7 \text{ K } E_{51}^{2/5} \, n_0^{-2/5} \, t_3^{-6/5}$$

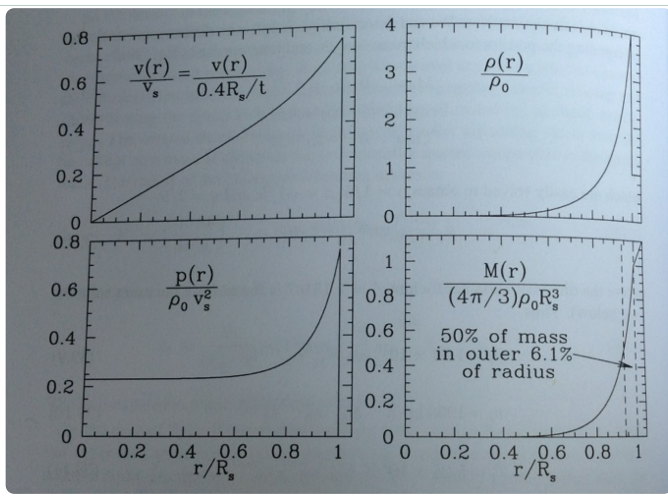
assuming the remnant has a similarity solution

i.e. $\rho(r) = \rho_0 f(x)$ $f(x), g(x), h(x)$ dimensionless functions

$v(r) = \frac{R_s}{t} g(x)$

$P(r) = \frac{\rho_0 R_s^2}{t^2} h(x)$

If the above relations are put into the fluid equations and solved numerically to obtain the Sedov - Taylor solutions, which the gas approaches.



Sedov - Taylor solutions

Draine 2012

The Sedov - Taylor phase will end when radiative losses become significant. To estimate we idealize the cooling function as

$$\Lambda \approx C \, (T/10^6 \text{ K})^{-0.7} \, n_H n_e \qquad C = 1.1 \times 10^{-22} \text{ erg cm}^3 \text{ s}^{-1}$$

$$\frac{dE}{dt} = -\int_0^{R_s} \Lambda \, 4\pi r^2 dr$$

$$= -1.2 \, C \, (n_H)_0^2 \left(\frac{10^6 \text{ K}}{T_s}\right)^{0.7} \frac{4\pi}{3} R_s^3 \left\langle \left(\frac{\rho}{\rho_0}\right)^2 \left(\frac{T_s}{T}\right)^{0.7} \right\rangle$$

$\langle\ldots\rangle$ = 1.87 when energy losses are small use R_s and V_s from Seldov Taylor solution

$$\Delta E(t) = -1.2\,C\,\frac{4\pi}{3}\,n_H^2\,.\,1.817\int_0^t dt\,R_s^3\left(\frac{T_s}{10^6}\right)^{-0.7}$$

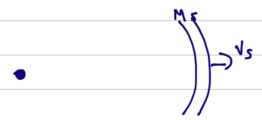
we leave the Seldov-Taylor solution when $\Delta E/E_0 \sim -1/3$
so can solve for the cooling time when the gas will become radiative

$$t_{rad} = 49.3\times10^3\,\text{yr}\;E_{51}^{0.22}\;n_0^{-0.55}$$
$$R_{rad} = 7.32\times10^{19}\,\text{cm}\;E_{51}^{0.29}\;n_0^{-0.42}$$

3) Snowplough phase

at $t = t_{rad}$ the expansion stalls but quickly pressure from the hot interior drives the expansion onwards as in the case of stellar winds

Called the snowplough phase as the mass in the cool outer shell increases as it sweeps up the ambient gas.



gas cools by adiabatic expansion

$$PV^{\gamma} = \text{const}$$
$$P \propto V^{-\gamma} \propto R_s^{-3\gamma} = R_s^{-5} \qquad \text{if } \gamma = 5/3$$

$\Rightarrow$ internal pressure evolves as

$$P_i = P_0(t_{rad})\left(\frac{R_{rad}}{R_s}\right)^5$$

which increases the radial momentum of the shell as

$$\frac{d}{dt}\left(M_s V_s\right) \approx P_i\,4\pi R_s^2 \qquad\qquad P = F/A$$
$$= 4\pi\,P_0(t_{rad})\,R_{rad}^5\,R_s^{-3}$$

assuming power law solution $R_s \propto t^{\eta}$

$$\Rightarrow \quad \text{Force} \propto R_s^{-3}$$
$$M\,R/t^2 \propto R^{-3}$$
$$R^4/t^2 \propto R^{-3}$$
$$t^{4\eta}/t^2 \propto t^{-3\eta}$$

from dimensional analysis assuming ρ = constant

$$\Rightarrow \quad 4\eta - 2 = -3\eta$$
$$\eta = 2/7$$

Therefore the expansion can be approximated as

$$R_s \approx R_s(t)\left(t/t_{rad}\right)^{2/7}$$

$$V_s \approx \frac{2}{7}\frac{R_s}{t} = \frac{2}{7}\frac{R_s(t_{rad})}{t_{rad}}\left(\frac{t}{t_{rad}}\right)^{-5/7}$$

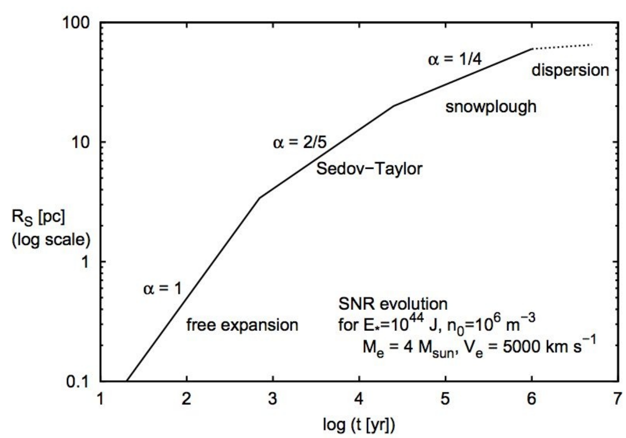
pressure modified snowplough phase
$R_s(t)$ continuous from Sedov-Taylor phase
$V_s(t)$ discontinuous drop by 30%.

4) Fade away
Beginning of snowplough $V_s \sim 150\ \mathrm{km\,s^{-1}} \Rightarrow$ strong shock
proceeds until $V_s \sim C_s$
Mach no $\downarrow$ $\quad \rho_2/\rho_1 \rightarrow 1$
↳ shock fades away to an acoustic wave

$$V_s = C_s$$
$$\frac{2}{7}\frac{R_s(t_{rad})}{t_{rad}}\left(\frac{t}{t_{rad}}\right)^{-5/7} = C_s$$

$$\Rightarrow t_{fade} \approx \left(\frac{2/7\ R_{rad}/t_{rad}}{C_s}\right)^{7/5} t_{rad}$$
$$\approx 1.87\times10^{6}\,\mathrm{yr}\ E_{51}^{0.32}\, n_0^{-0.37}\left(\frac{C_s}{10\,\mathrm{km\,s^{-1}}}\right)^{-7/5}$$

$$R_{fade} \approx 2.07\times10^{20}\,\mathrm{cm}\ E_{51}^{0.32}\ n_0^{-0.37}\left(\frac{C_s}{10\,\mathrm{km\,s^{-1}}}\right)^{-2/5}$$



$R_s > 50$ pc

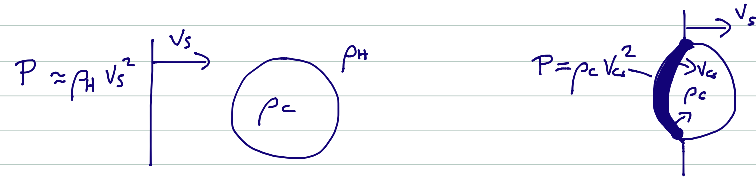
substantial effect on the ISM

14.4 SN in an inhomogeneous medium

Consider a more realistic ISM where most of the volume is in a hot phase with discrete cold clouds within it.

Blastwave propagates more rapidly in the low density medium ρ_H
$n_H \approx 0.005\ \mathrm{cm^{-3}}$ $\quad T = 10^6$ K

When the blastwave comes in contact with a cloud it applies a pressure $P \sim \rho_H V_s^2$ to the cloud surface. The overpressure drives a shock in the cloud at speed V_{cs}



$$\rho_H V_s^2 = \rho_c V_{cs}^2$$

$$\Rightarrow \quad V_{cs} = \sqrt{\frac{\rho_H}{\rho_c}} \; V_s$$

for $n_H = 0.005\,\mathrm{cm^{-3}}$ and $n_c \simeq 30\,\mathrm{cm^{-3}}$ a $1500\,\mathrm{km\,s^{-1}}$ blastwave gives $V_{cs} \sim 13\,\mathrm{km\,s^{-1}}$

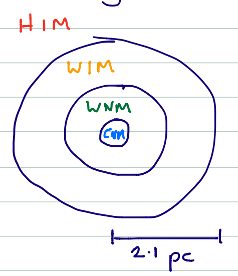
If the cloud is not self-gravitating the resulting velocity gradients can shred the cloud provided the magnetic field does not hold it together.

After the blastwave passes the cloud is surrounded by very hot shock heated gas. Thermal conduction can start to evaporate the cloud.

14.5 Three phase model of the ISM

An initially uniform ISM consisting of warm HI transformed by SN into a medium of low density hot gas and dense shells of cold gas.

McKee & Ostriker 1977 envisaged a three phase ISM of cold clouds surrounded by warmer material



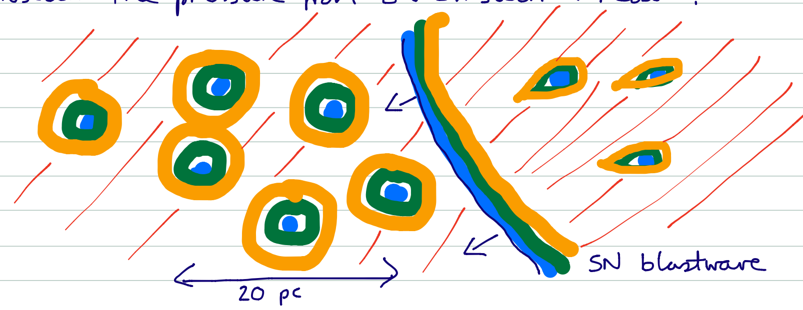
CNM → Cold neutral
$T = 80\,\mathrm{K}$ $\quad n = 42\,\mathrm{cm^{-3}}$
$x = 10^{-3}$

WNM ; Warm neutral
$T = 8000\,\mathrm{K}$ $\quad n = 0.37\,\mathrm{cm^{-3}}$
$x = 0.15$

WIM : Warm ionised
$T = 8000\,\mathrm{K}$ $\quad n = 0.25\,\mathrm{cm^{-3}}$
$x = 0.68$

HIM ; Hot ionised
$T = 4.5 \times 10^5\,\mathrm{K}$ $\quad n = 3.5 \times 10^{-3}\,\mathrm{cm^{-3}}$
$x = 1.0$

Consider the pressure from SN on such a medium.



If $P_{ISM} \downarrow$ $\quad R_{SN} \uparrow$ $\Rightarrow$ ISM pressure increases

continue until an equilibrium is reached when the pressure in the ISM is the same as in the SNR.

The number of SN that will explode within a volume V_{fade}

$$N_{SN} = S \frac{4\pi}{3} R_f^3 t_f$$

from Milky Way $S \sim 1.2 \times 10^{-13} pc^{-3} yr^{-1}$
$N_{SN} \sim 1.1$

A value of $N_{SN} = 1$ expected if ISM in pressure equilibrium due to SN

If $P = 1.4\, n_H m_H c_s^2$

$$N_{SN} = S \, {}^{4\pi}/_{3} \, R_{fade}^3 \, t_{fade}$$

substitute for c_s

$$= 0.24\, S_{-13}\, E_{51}^{1.27}\, n_0^{-1.11} \left(\frac{c_s}{10\, km\, s^{-1}}\right)^{-13/5}$$

$$= 0.48\, S_{-13}\, E_{51}^{1.27}\, n_0^{-0.19}\, p_4^{-1.3}$$

$$S_{-13} = \frac{S}{10^{-13}\, pc^{-3}\, yr^{-1}}$$

$$P_4 = \frac{P/k}{10^4\, cm^{-3}\, K}$$

for $N_{SN} = 1$

$$\frac{P}{k} = S_{-13}^{0.77}\, n_0^{-0.15} \times 5700\, cm^{-3}\, K$$

Only a weak dependence on n_0
- for typical values $n_0 \sim 1$, $S_{-13} = 1.2$ $\rightarrow$ $P/k = 6600\, cm^{-3}\, K$
- observed value $P/k = 3800\, cm^{-3} K$

Main features of the McKee & Ostriker model
1) Pressurisation of the ISM by SN
2) Mass exchange between phases. Cold clouds evaporated and converted to diffuse gas. Diffuse gas swept up by SN into cold dense gas
3) Injection of high-velocity clouds by fragmentation of dense SN shell.

Finally SN may provide an explanation for the low star formation rate in the galaxy. A higher SF rate would increase the SN rate increasing the fraction of the ISM in the hot ionised phase. This would then decrease the amount of cold dense gas, and correspondingly the SF rate. Simulations of galactic star formation confirm this result e.g Shetty et. al. 2010, Hopkins et. al. 2013