

Notes for Thursday Discussion

Energy in turbulence: $L_{\text{kin}} \sim \frac{1}{2} M v_T^2 \frac{v_T}{h} \sim 10^{39} - 10^{40} \text{ erg/s}$

Energy in SNe (MW SFR): $L \sim 3 \times 10^{41} \text{ erg/s}$

Energy in accretion: $L \sim \frac{GM_{\text{in}}}{r} \sim M v_r^2 \sim 3-10 \times L_{\text{kin}}$

So, plenty of energy to power ISM turbulence, but does it couple?

Some Facts about Star Formation

- Most massive stars form in clusters
- Massive clusters dominate star formation, $\frac{dN}{dM_{\alpha}} \propto M_{\alpha}^{-2}$
- More massive GMCs likely turn a larger fraction of their mass into stars (higher ϵ_*) $M_{\alpha} \approx \epsilon_* M_{\text{GMC}} \approx \epsilon_* \pi h^2 \Sigma_0$
 $\approx 10^5 M_{\odot} \left(\frac{\epsilon_*}{0.01} \right) \left(\frac{h}{100 \text{ pc}} \right)^2 \left(\frac{\Sigma_0}{300 M_{\odot} \text{ pc}^{-2}} \right)$

Superbubbles (Weaver '77, Mac Low '88, King '17, Fredding '18)

$M_{\alpha} > 10^3 M_{\odot} \rightarrow$ fully sampled IMF

$$N_{\text{Sne}} = \frac{M_{\alpha}}{m_*}, \text{ for Kraupa, } m_* = 100 M_{\odot}$$

Sne rate roughly constant from 3-40 Myr, so $\Delta t_{\text{SN}} = \frac{t_{\text{life}}}{N_{\text{Sne}}}$

$$E_{\text{SB}} = E_{\text{SN}} \frac{t}{\Delta t_{\text{SN}}}, \quad L_{\text{SB}} = \dot{E}_{\text{SB}} = \frac{\dot{E}_{\text{SN}}}{\Delta t_{\text{SN}}}$$

So, like Sedov-Taylor, but with steadily increasing energy in blastwave

$$\begin{aligned} \text{Expansion velocity } V &\propto \frac{R_c}{t}; \quad M_{\text{SB}} \propto R^3 \rho_{\text{amb}} \rightarrow E_{\text{SB}} \propto \frac{R^5 \rho_{\text{amb}}}{t^2} = \frac{E_{\text{SN}} t}{\Delta t_{\text{SN}}} \\ \Rightarrow R_{\text{ad}} &\propto \left(\frac{E_{\text{SN}}}{\rho_{\text{amb}} \Delta t_{\text{SN}}} \right)^{1/5} t^{3/5} = 60 \text{ pc} \left[\frac{E_{\text{SN}}}{\Delta t_{\text{SN}}, \rho_{\text{amb}}, 10} \right]^{1/5} t^{3/5} \end{aligned}$$

$$V_{ad} = \frac{dR}{dt} = 35 \text{ km/s} \left[\frac{E_{Si}}{\Delta t_{SN,6} \rho_{amb,0}} \right]^{1/5} t_6^{-2/5} \quad \Delta t_{SN,6} = \Delta t_{SN} / \text{Myr}$$

$$P_{ad} = M_{sh} V_{ad} = \frac{4\pi}{3} R_0^3 \rho_{amb} V_{ad}$$

$$\text{Momentum per SN} \quad \hat{P}_{ad} = P_{ad} \frac{\Delta t_{SN}}{t}$$

Relatively soon, a radiatively-cooling shell will form

$$t_{sf} \approx 2 \times 10^4 \text{ yr} \quad E_{Si}^{0.28} \rho_{amb,0}^{-0.71} \Delta t_{SN,6}^{-0.28}$$

$$\text{So, } r(t_{sf}) = 5.5 \text{ pc} \quad E_{Si}^{0.37} \rho_{amb,0}^{-0.62} \Delta t_{SN,6}^{-0.37}$$

$$\text{Find that } \hat{P}(t_{sf}) \sim 2 \times 10^5 M_\odot \text{ km/s} \quad E_{Si}^{0.91} \rho_{amb,0}^{-0.082} \Delta t_{SN,6}^{0.087}$$

This is very similar to the momentum from a single SN remnant

Typically get no more than 50% increase in \hat{P} after shell formation

Once a shell forms, energy quickly radiates away at the edge of the bubble
however, the interior remains hot and overpressurized relative to the ISM.

Classical solution for post-radiative SB is like PDS stage of SNR

$$\text{Momentum eq: } \frac{d}{dt} \left(M_{sh} \frac{dR}{dt} \right) = 4\pi R^2 P_{hot} \quad , \quad P_{hot} = \frac{L_{hot} (\gamma-1)}{\frac{4}{3}\pi R^3}$$

$$\text{Assuming interior is adiabatic, energy eq: } \frac{dL_{hot}}{dt} = L_{SB} - 4\pi R^2 P_{hot} \frac{dR}{dt} \quad , \quad \gamma = 5/3$$

$$\text{Algebra} \rightarrow r \propto \left[\frac{L_{SB} t^3}{P_{amb}} \right]^{1/5} \quad (\text{as before, but coefficient is } 5/3)$$

Sims. typically show that, the adiabatic expansion stage holds, but there are significant radiative losses within the interior during PDS stage.

So, shell momentum, rather than internal energy, increases linearly.

Using a momentum eqn. with a source term from mean momentum per SN, p_* :

$$\frac{d}{dt} \left(M_{\text{sh}} \frac{dr}{dt} \right) = \frac{p_*}{\Delta t_{\text{SN}}} \quad \text{algebra} \rightarrow r_{\text{mds}} = \left[\frac{3 p_*}{\Delta t_{\text{SN}} 8\pi P_{\text{amb}}} \right]^{1/4} t^{1/2}$$

$$\text{Putting in numbers... } r_{\text{mds}} = 34 \text{ pc} \left[\frac{p_{*,5}}{\Delta t_{\text{SN},6} P_{\text{amb},0}} \right]^{1/4} t^{1/2}$$

$$v_{\text{mds}} = \left[\frac{3 p_*}{\Delta t_{\text{SN}} 8\pi P_{\text{amb}}} \right]^{1/2} r^{-1} = 5.8 \text{ km/s} \left[\frac{p_{*,5}}{\Delta t_{\text{SN},6} P_{\text{amb},0}} \right]^{1/2} r^{-1} \quad (r \equiv r_{100 \text{ pc}})$$

Two criteria for breakout: $r > h$ by t_{ire} (easily satisfied)

$$v_{\text{mds}}(h) / v > dv \quad (\text{Does bubble reach pressure equilibrium with ISM})$$

$$\frac{v_{\text{mds}}(h)}{dv} = \left[\frac{3 p_*}{\Delta t_{\text{SN}} P_{\text{amb}} 8\pi h^2} \right]^{1/2}, \text{ where } P_{\text{amb}} \equiv P_{\text{amb}} dv^2$$

\rightarrow More massive clusters break out

Fielding '18 derive this in terms of a critical cluster formation efficiency:

$$\epsilon_{*,\text{crit}} \sim 0.015 \left(\frac{dv}{10 \text{ km/s}} \right)^2 \left(\frac{h}{100 \text{ pc}} \right)^{-1} \left(\frac{p_*}{10^5 M_0 \text{ km/s}} \right)^{-1}$$

Winds

$$\eta_m = \frac{\dot{m}_{\text{wind}}}{\dot{m}_*}, \quad \eta_p = \frac{\dot{p}_{\text{wind}}}{\dot{p}_{\text{SN}}}, \quad \eta_e = \frac{\dot{E}_{\text{wind}}}{\dot{E}_{\text{SN}}}$$

What do the simulations say?

Before breakout, η_m and η_e are low ($\eta_m < 0.1$, $\eta_e \sim 0.01$)

η_p is large $\sim 20-40$ due to work done in ST phase

After breakout, η_m and η_e are much higher ($\eta_e \sim 10-50\%$)

$\eta_m \sim 0.1-1$; η_p is small, ~ 1

\rightarrow SNe energy is not coupling to ISM, but is driving winds

Within winds, momentum transfers from hot to warm phases via mixing,

can produce $v_{\text{warm}} \sim 800 \text{ km/s}$

Thompson 76

Hot wind, $n \propto r^{-2}$, $P/\rho^{\gamma} = K \rightarrow T \propto r^{4/3}$ ($\gamma = 5/3$)

$$t_{\text{cool}} \propto T^{1/2}/n \propto r^{1/3}, \quad t_{\text{adv}} \propto \frac{r}{v} \propto r$$

$$\text{so } \frac{t_{\text{cool}}}{t_{\text{adv}}} \propto r^{1/3} \quad \text{while Bremsstrahlung dominates}$$

$$\text{But at } T < 10^7 \quad \Lambda(T) \propto T_7^{-0.7}$$

$$t_{\text{cool}} \propto r^{-4/15}, \quad \frac{t_{\text{cool}}}{t_{\text{adv}}} \propto r^{-19/15}$$