Halo Heating: Feedback from Star Formation and AGN

Physics 235
Extragalactic Astrophysics
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Overcooling Problem

- Early theory of galaxy formation (White & Rees 1978 MNRAS)
  - Predicted most of the gas in galaxy sized halos ($M < 10^{12} M_0$) should have cooled and formed stars.
  - But only 20% of the baryons in such halos are observed to be in a cold collapsed phase.
  - Some process must heat the halo gas to slow down star formation.
- Poses a fundamental problem for galaxy evolution theory
- Solution involves heating from stars and possibly AGN.

Mass scale at $t = 2 t_{ta}$ is has collapsed.

Gas has not cooled in halos with $t_{cool} > t_{dyn}$. 
Feedback

• Gas heating by non-gravitational processes
• Called *feedback* because the heating rate depends on the star formation rate and/or the accretion rate on the SMBH.
• Model it by adding terms to the fluid equations
  – Inject mass, momentum, and energy
  – And metals
• Halo energy sources include
  – Supernova explosions
  – Stellar winds
  – Stellar radiation
  – Cosmic rays
M82: Anatomy of a Galactic Wind

Optical: Warm (10^4 K) gas photo-ionized by massive stars and shocks.

X-rays: Hot (10^7 K) plasma does work via thermal pressure

Infrared: Cold molecular gas and dust.
Simulations of Multi-Phase Winds

Hopkins, Quataert, & Murray 2012
Simultaneous Outflow and Inflow

Brook+2011 (SPH/GASOLINE) 200 kpc x 200 kpc box at $z=0.5$

Accretion of high angular momentum gas

Outflows blow out perpendicular to gas disks

Future stars

Outflows

$z=0.5$
Feedback from a Stellar Population

Starburst 99 Code (Leitherer Group at STScI)

Fig. 113
Mechanical luminosity vs. time. Star-formation law: instantaneous.
$M = 10^6 M_\odot$
$M_{\text{low}} = 1 M_\odot$

Fig. 114
Mechanical luminosity vs. time. Star-formation law: continuous.
Star formation rate $= 1 M_\odot \text{yr}^{-1}$
$M_{\text{low}} = 1 M_\odot$
Supernova Feedback

Stars with initial masses > 8 $M_\odot$ end their lives in a core-collapse supernova. In the early stages of the explosion, the stellar ejecta plow through the ISM with little resistance,

$$R \approx 5000 \text{ km/s } \times t.$$  

A shock will form when the mass of swept-up ISM becomes comparable to the mass of SN ejecta. For 100 $M_\odot$ of debris,

$$t_{sh} \approx 1730 \text{ yr when } R \approx 8.8 \text{ pc}.$$  

The propagation of the shock wave generated from the release of a large amount of energy (1 foe = $10^{51}$ ergs) during a short period of time admits a self-similar solution.

[ Blastwave solution on board]

$$R = 83 \text{ pc } (E_{51}/n_0)^{1/5} t_6^{2/5} \text{ and } v = 67 \text{ km/s } (E_{51}/n_0)^{1/5} t_6^{-3/5}.$$  

Supernova Feedback

• Shock velocity decreases with time, so post-shock temperature will decrease. We know that this is accompanied by an increase in the gas cooling rate.

• Eventually the radiative cooling losses behind the shock are faster than the cooling due to the expansion of the remnant.

• The gas immediately behind the shock drops in T and P. The very hot interior gas pushes this post-shock gas up against the shell. A dense, radiating shell forms.

• Momentum conserving phase (a.k.a. Snowplow phase)
  – Assume all the swept-up material lies in this thin shell
  – Neglect the push of the hot interior gas

  [Blackboard] \[ R \sim t^{1/4} \]

  ➢ Thermal energy is radiated away.
  ➢ Estimate KE transferred to ISM when shell merges with ISM.
Supernova Feedback

• If we end up with 5% of the SN KE being transferred to the ISM, then supernova feedback is not very efficient.

• How much of the explosion energy can be thermalized depends on the timescale of thermalization relative to the cooling timescale.
  – Can get $f_{th} \approx 1$ if supernova remnants overlap before they reach the radiative stage.
  – Three phase ISM of McKee & Ostriker
    • $Q = [\text{SN rate} / \text{volume}] * [\text{volume of SNR}] * [\text{lifetime}]$ is called the porosity parameter.
    • For a uniform medium with constant $Q$, the time averaged fraction of the medium filled with hot gas is $f_{\text{hot}} = Q / (1 + Q)$
  – High SFR/area $\Rightarrow$ high porosity
Wind-Blown Bubbles (Weaver+1977)

- For continuous energy injection, the solution is similar to the SN blastwave.
  - \( R = 65.9 \text{ pc} \left[ \frac{L_{38}}{n_0} \right]^{1/5} \left[ t_6 \right]^{3/5}, \) and
  - \( V = 38.6 \text{ km/s} \left[ \frac{L_{38}}{n_0} \right]^{1/5} \left[ t_6 \right]^{-2/5} \)
Ejection from Gravitational Potential

• Requires $E_{\text{crit}} \geq 0.5 \ M_{\text{ej}} \ (v_{\text{ecs}})^2$

• The escape velocity from the center of an NFW halo is $\approx (6c)^{1/2} \ V_h$, where $c$ is the halo concentration parameter and $V_h$ the halo virial velocity.

• $E_{\text{sn}} = M_* \ [\#\text{SN/stellar mass}] \ [10^{51} \ \text{ergs}] \ \varepsilon$, where $\varepsilon$ is the fraction of SNe energy radiated away.

• Equating $E_{\text{sn}} = E_{\text{crit}}$, we find that even efficient thermalization has trouble ejecting 80% of the baryons from a Milky Way mass halo.

\[ \frac{M_{\text{ej}}}{M_*} \approx 0.4 \ \varepsilon \ (10/c) \ (200 \ \text{km} \ \text{s}^{-1} / V_h)^2 \]

• Notice that the efficiency increases rapidly for decreasing halo mass.
Impact of Winds on Galaxies

Dekel & Silk 1986

The diagram illustrates the relationship between density and velocity, showing the formation of dwarfs versus "normal" galaxies in CDM halos. The critical velocity $V_{\text{crit}}$ marks the boundary between gas loss and no loss for galaxies. The shaded region represents galaxies where cooling is less than the freefall time, indicating potential rapid cooling.
Superbubble Blowout vs. Blow Away

- What happens when the bubble outgrows the ISM?
  - $R \approx b$, where $b$ is the gas scale height
  - The gas scale height in the Milky Way is $\sim 150$ pc; values in dwarf galaxies can reach 1 kpc
  - The stellar scale height is $\sim 300$ pc (with variation by stellar age) in the Milky Way
- Shell accelerates & becomes unstable
- Rarefaction wave may quench shock in the ISM.

DeYoung+1994

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Superbubble Blowout vs. Blow Away

- $10^6$ supernovae would completely remove the ISM from a $10^9 M_0$ galaxy with $R = 3$ kpc.
Supernova Feedback: Reheating vs. Ejection

• In Milky Way mass galaxies, reheating is more efficient than ejecting gas.
• Reheating gas from $10^4$ K to the virial temperature requires an energy
  \[ E = \frac{3}{2} \frac{k}{m} M_{\text{gas}} (T_h - T_0) = \frac{3}{4} M_{\text{gas}} (V_h)^2 \left(1 - \frac{T_0}{T_h}\right) \]
• Equating the supernova energy to this reheating requirement indicates
  \[ \frac{M_{\text{gas}}}{M_*} \approx 17 \varepsilon \left(\frac{200 \text{ km s}^{-1}}{V_h}\right)^2 \left(1 - \frac{T_0}{T_h}\right)^{-1}. \]
• Supernova can reheat 17 $\varepsilon$ of ISM (or CGM) for every solar mass of stars formed.
  - $M(\text{reheat}) / M(\text{eject}) \approx \left(\frac{V_{\text{esc}}}{V_h}\right)^2 \approx 6c$
This solution ignores the gravitational potential.

**Fig. 1** The wind solution as a function of $r/R$, where $R$ is the radius of the region of mass production $\dot{M}$ and energy production $\dot{E}$. The dimensionless variables are $u^* = u/(\dot{M}^{-1/2}\dot{E}^{1/2})$, $\rho^* = \rho/(\dot{M}^{3/2}E^{-1/2}R^{-2})$, and $P^* = P/(\dot{M}^{1/2}\dot{E}^{1/2}R^{-2})$. For $|\log (r/R)| > 0.5$, the solution is described by the expressions in Table 1.
AGN Feedback

• $E_{\text{AGN}} \sim 0.1 \ M_{\text{BH}} \ c^2$, where it is assumed that 10% of the rest-mass energy is radiated away.

• Suppose that a fraction $\varepsilon_{\text{AGN}}$ of the radiation reheats gas. Since $M_{\text{BH}} \approx 0.002 \ M_{\text{bulge}}$, one finds

$$\frac{E_{\text{AGN}}}{E_{\text{SN}}} \sim 36 \ \frac{\varepsilon_{\text{AGN}}}{\varepsilon} \times \left( \frac{M_{\text{bulge}}}{M_*} \right).$$

• AGN feedback is therefore most effective in massive galaxies with large spheroidal stellar components.

• Two types
  – AGN, or ejective mode, feedback
  – Radio mode, or heating feedback