Supernovae Feedback in Galaxy Formation

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1. What is feedback?
2. Why do we need/want feedback?
3. How does SN feedback work?
   - Analytic arguments
   - Feedback in simulations
4. Outstanding issues
What is feedback?

- **Feedback** is a process that **regulates the growth of galaxies**
- Many kinds of feedback have been discussed in the literature
  - **SN feedback**
    - SN goes off, heats the ISM, halts further star formation
  - **AGN feedback**
    - AGN releases energy that couples to gas, prevents star formation
  - **Photoheating from UV background**
    - (not really *feedback* as you might normally think of it)
    - Reionization heats the gas in the IGM to \( \sim 10^4 \text{K} \)
      - Therefore, DM halos with a “virial temperature” less than \( 10^4 \text{K} \) cannot retain any baryons. \( 10^4 \text{K} \sim 20 \text{km/s at } z_{\text{reion}} \)
        - Halos today with masses \( < 10^{10} \text{ M}_{\odot} \) should not contain baryons, including stars, because of this effect
Why do we need feedback?

- Halo mass function
- Stellar mass function
- Integrated star formation efficiency

Clusters (Virgo, Coma)

- Dwarf galaxies
- MW, M31, L*

\[ \log \left( \frac{M_{\text{stars}}}{M_{\text{total}}} \right) \]

\[ \log (\text{halo mass}) \]
Recall: the effective yield, $y_{\text{eff}}$, equals the true nucleosynthetic yield for a closed box model of galactic chemical evolution.

- It should therefore be constant unless inflows and/or outflows are important.

- Lower $y_{\text{eff}}$ in low mass galaxies means metal-enriched outflows.

Observational hints of feedback: I

\[ y_{\text{eff}} = \frac{Z_{\text{gas}}}{\ln (1/f_{\text{gas}})} \]
Moderate density regions of the Universe (e.g. the IGM) are metal-enriched. But there is no star formation in such regions.

- Metal-enriched winds can deposit metals into the IGM.

Probing the importance of winds and feedback at high redshift (z~2)

$\delta_{\text{gas}} = \text{overdensity of gas with respect to the mean density}$

Springel & Hernquist 2003
M82

- Massive starburst galaxy with obvious evidence of outflows

X-rays

Hα
Numerology

- \( \varepsilon_{\text{SN}} \sim 10^{51} \) ergs
- \( 10^{49} \) ergs from SNII per \( 1M_{\odot} \) of stars formed
  - For a standard IMF, i.e. one SN per \( 100M_{\odot} \)
- \( E_{\text{bind}} \sim M_{g}V_{h}^{2} \sim GM_{g}M_{h}/R_{h} \sim M_{h}^{5/3} \)
  - GMC: \( M \sim 10^{5} M_{\odot}, R \sim 50 \) pc → \( E_{\text{bind}} \sim 10^{49} \) ergs
    - One SN can in principle unbind a typical GMC
  - For \( M_{h}=10^{12} M_{\odot}, M_{g}=10^{10} M_{\odot}, R=1 \) kpc → \( E_{\text{bind}} \sim 10^{57} \) ergs
    - For \( \sim L^{*} \) galaxies, a single SN will not unbind the galaxy, but \( E_{\text{bind}}/\varepsilon_{\text{SN}} \) is not that different from unity

- We don’t care about SNIIa b/c they do not deposit their energy near the star-forming region
Types of massive star feedback

• UV photons
  – UV photon energy generated over the lifetime of massive stars is \( \sim 100x \) greater than \( \varepsilon_{SN} \)
    • If this energy can couple to the gas (via radiation pressure on dust), potential for lots of energy deposition (via momentum), perhaps driving **galactic winds**

• Stellar winds (mass-loss)
  – Important only for the most massive stars for the first few Myr after a star formation event

• SN explosions
  – Energy can be deposited thermally or kinetically, or, most likely, both
SN feedback: not in isolation

The standard picture for isolated SN evolution:

1. Free expansion
   - Ends when $M_{\text{swept}} \sim M_{\text{eject}}$, ($t=200$ yr, $R=1$ pc)
2. Adiabatic phase (Sedov phase)
   - Ends when radiative losses become important ($10^{4-5}$ yr, $R=30$ pc)
3. Snowplow phase (approximately momentum conserving)
   - Ends when the shock velocity is comparable to the local sound speed ($t=10^6$ yr, $R=100$ pc)

The standard picture is not applicable to galaxies!
- Within $10^6$ yr, another SN is likely to go off within 100 pc, for MW SNR
  - Therefore, within $\sim$Myr every point in the ISM will have experienced a SN blastwave (McKee & Ostriker 1977)
- Qualitatively changes the feedback
SN feedback on galactic scales

Total SN energy deposited into gas:

\[ E_{SN,\text{tot}}(t) \sim E_0 \ SFR \ t_{rad} \]

\[ SFR \sim \frac{M_{\text{gas}}}{t_{ff}} \]

Condition for gas removal:

\[ E_{SN,\text{tot}} > M_{\text{gas}} \ V^2 \]

\[ E_0 M_{\text{gas}} t_{rad} \gg M_{\text{gas}} V^2 \]

\[ t_{rad} \propto n^{-9/17} \]

\[ V < 100 f(\epsilon_{SN}, g, E_0, \text{etc}) \ \text{km/s} \]

At low velocities, SN feedback can unbind galaxies

Condition on the potential

Dekel & Silk 1986
SN feedback in simulations: early attempts

• Hydrodynamic simulations of the formation and evolution of galaxies cannot simultaneously resolve the SN blastwave (pc scales) and the cosmological environment (Mpc scales)
  – “subgrid” recipes are required

• Early hydrodynamic simulations of galaxy formation attempted to model SN feedback by dumping $10^{51}$ ergs of thermal energy into the nearest grid cell (or SPH particle), e.g. Katz 1992
  – The cells nearest to the SN are the densest (a necessary condition for star formation), and so the cooling rate, which scales as $n^2$, is very large
    • The net result is that the SN energy is radiated away instantly, and therefore has no effect on the ISM
    • This results in a “cooling catastrophe”, i.e., too many stars form
A number of completely ad hoc prescriptions were then adopted to fix the overcooling problem:

1. Simply turn off cooling for some amount of time, until the SN energy diffuses over a large enough volume to act as feedback
2. Dump the SN energy into kinetic energy
   - e.g. Navarro & White 1993
   • This can, in principle, drive a wind
   • Winds might be driven by the collective action of many SN, as an overpressured hot bubble expands
3. Simplistic recipes for a multiphase ISM
   - e.g. Yepes et al. 1997, Springel & Hernquist 2003
   • SN energy is then shared between the hot and cold components
   • The hot component is susceptible to thermal feedback (b/c it is of low density and high temperature), and so SN feedback can be effective at reducing the growth of the cold component
SN feedback in simulations: current attempts

- Effective yield is reduced with SN feedback because metal-rich gas is blown out of the galaxy.
- SN feedback also regulates SF efficiency, which is responsible for the mass-metallicity relation.
• **Runaway stars** are stars that have acquired velocities large enough to escape their natal molecular cloud
  – \( \sim 10\text{-}30\% \) of OB stars are runaways (e.g. Hoogerwerf et al. 2000)
• Runaway stars may be very important for the efficient transfer of SN energy into the surrounding ISM
  – When they explode, they are not in the very dense gaseous regions, and so deposited thermal energy will not radiate away very quickly
Insights from semi-analytic models

- Semi-analytic models aim to describe the baryonic evolution of galaxies via a number of simple analytic prescriptions for gas cooling, heating, star formation, feedback, etc.
  - Recall: $E_{\text{bind}} \sim M^{5/3}$

1. SN feedback can modulate the faint end of the LF
2. The exponential cutoff is controlled by a much more energetic feedback process (AGN?)

K-band luminosity function

“super winds” feedback

“standard” SN feedback
1. How to model runaway stars?
   - Runaways were probably members of binaries
   - We don’t know the binarity fraction!
     • Must be modeled with subgrid recipes
2. The net effect of SN feedback is sensitive to other feedback processes, such as photoheating
   - Heated gas is more susceptible to further heating
   - This means that we have to understand the panoply of relevant heating mechanisms in order to understand one mechanism!
3. Are the UV photons produced by massive stars important?
   - Coupling of UV photons to gas is mediated by radiation pressure on dust grains
     • This means we have to understand dust production/destruction in harsh environments!
There is ample evidence that some sort of energetic feedback takes place

- Galaxy formation is “inefficient” at both low and high masses
- Enriched IGM at 2<z<5 indicates that feedback is occurring over a range of epochs
- There are probably several forms of feedback operating over the full range of galaxy properties

There is plenty of energy available in SN to significantly impede galaxy formation at low masses (M<10^{11} M_{\odot})

- Direct evidence for SN feedback comes from the MW
- SN feedback still important at regulating SF in more massive systems

Many important aspects of this problem remain unsolved

- “subgrid” recipes will continue to be a necessary aspect of modeling SN feedback
  - Brute-force simulations will not be able to solve this problem, although they will help