Feedback Effects in Galaxy Formation

1. Basics

The discussion here follows the description found in the textbook of Cimatti, Fraternali, & Nipoti.

1.1. General Concepts in Feedback

The concept of star formation feedback in galaxy formation is generally motivated by the need to explain low global star formation efficiency within high and low mass dark matter halos. For that reason, generally feedback refers to *negative feedback* effects; that is, processes that inhibit star formation. These effects are divided into *stellar feedback*, which is literally feedback in the sense that star formation leads to stellar processes that inhibit further star formation, and *AGN feedback*, which refers to AGN processes that inhibit star formation. In both cases, some combination of radiative energy and kinetic energy flux couples to gas in the galaxy to heat it, add turbulence to it, or drive it in large scale winds to the outskirts of or entirely out of the galaxy.

In the case of winds, the distinction is made between *momentum-driven* and *energy-driven* winds. Physically, these cases are distinguished by whether the cooling time of the affected gas is short relative to the dynamical time. If the cooling time is short, then the energy quickly radiates away, but the momentum imparted is not radiated away and the wind is momentum driven. If the cooling time is not short, the thermal energy created by the feedback helps to drive the wind. The distinction is important to the dependence on galaxy potential depth of the relationship between a star formation rate ($\dot{M}_*$) or black hole accretion rate ($\dot{M}_{\rm BH}$) to a mass outflow rate.

In the case of an energy-driven wind, the energy converted to kinetic energy per unit time is proportional to the star formation or black hole accretion rate:

$$\dot{K} \propto \dot{M}. \tag{1}$$

Because in a time-invariant wind $\dot{K} = \dot{M}_{\rm w} v_{\rm w}^2$, the rate of mass driven to some velocity $v_{\rm w}$ is:

$$\dot{M}_{\rm w} \propto \dot{K} v_{\rm w}^{-2} \propto \dot{M} v_{\rm w}^{-2}. \tag{2}$$

The escape speed is proportional to the velocity dispersion of the halo σ, so if we want to know how much mass is flowing out of the galaxy (i.e. reaches $v_{\rm w} \sim \sigma$) it will scale as:

$$\dot{M}_{\rm out} \propto \dot{M} \sigma^{-2}. \tag{3}$$

In the case of a momentum-driven wind, the momentum imparted per unit time (due to mechanical energy or radiation pressure) will be proportion to the star formation or black hole

accretion rate:

$$\dot{p} \propto \dot{M}. \tag{4}$$

Because in a time-invariant wind $\dot{p} = \dot{M}_{\rm w} v_{\rm w}$, the rate of mass driven to some velocity $v_{\rm w}$ is:

$$\dot{M}_{\rm w} \propto \dot{p} v_{\rm w}^{-1} \propto \dot{M} v_{\rm w}^{-1}. \tag{5}$$

The escape speed is proportional to the velocity dispersion of the halo σ, so if we want to know how much mass is flowing out of the galaxy (i.e. reaches $v_{\rm w} \sim \sigma$) it will scale as:

$$\dot{M}_{\rm out} \propto \dot{M} \sigma^{-1}. \tag{6}$$

In the context of galaxy formation, these different scalings mean that these two types of wind shape galaxy stellar mass function differently.

1.2. Stellar Feedback

Stellar feedback comes in the form of supernovae and stellar winds, primarily from massive stars. Individual supernovae generally do not impart much of their energy to the interstellar medium as kinetic energy, only a few percent. Stellar feedback generally is thought to operate effectively through the combination of many massive stars or supernovae creating *superbubbles* from which emanate winds. These winds are usually taken to be energy driven

For either a single massive star, a group of massive stars, or a group of supernovae, we can treat the feedback as a steady, very supersonic wind acting for some period of time. We can calculate what fraction of that power is converted into kinetic energy of the interstellar medium. This calculation assumes some constant input of supersonic wind energy under spherical symmetry. The wind shocks the surrounding interstellar medium and creates a hot, expanding bubble of gas at pressure P_b, with a shocked shell of interstellar medium gas surrounding it. The bubble's thermal energy increases due to mechanical energy being converted to thermal energy, and decreases due to its expansion:

$$\frac{{\rm d}U_b}{{\rm d}t} \approx L_{\rm w} - P_b \frac{{\rm d}V}{{\rm d}t}. \tag{7}$$

For a nonrelativistic ideal gas, we can write $U_b = (3/2) P_b V$.

The shell's momentum is driven by the pressure of the hot bubble behind it, and we can write its equation of motion:

$$\frac{\rm d}{{\rm d}t} \left(M_{\rm sh} v_{\rm sh} \right) = 4\pi r_{\rm sh}^2 P_b \tag{8}$$

We can solve for P_b, and assuming the interstellar medium is of constant density ρ_0 and is all swept up in the shell, we find:

$$P_b = \rho_0 \left(\frac{1}{3} r_{\rm sh} \ddot{r}_{\rm sh} + \dot{r}_{\rm sh}^2 \right) \tag{9}$$

Solving for $r_{\rm sh}$ assuming a power law solution in time we find:

$$r_{\rm sh} = \left(\frac{125}{154\pi}\right)^{1/5} \left(\frac{L_w}{\rho_0}\right)^{1/5} t^{3/5} \tag{10}$$

We can calculate the kinetic energy of the shell's expansion:

$$K_{\rm sh} = \frac{1}{2} M_{\rm sh} v_{\rm sh}^2 = \frac{15}{77} L_w t \approx 0.2 L_w t \tag{11}$$

This calculation shows that the conversion of wind energy to kinetic energy is rather efficient for a steady, supersonic wind in a uniform medium.

Numerically, if we consider massive O-stars, they lose mass at about 10^{-6} $M_\odot$ yr^{-1}, in winds that reach thousands of km s^{-1}. Such a wind will produce a mechanical power of:

$$L_{\rm w} = \frac{1}{2} \dot{M}_{\rm w} v_{\rm w}^2 \sim 10^{36} \left(\frac{\dot{M}_{\rm w}}{10^{-6} M_\odot \ {\rm yr}^{-1}}\right) \left(\frac{v_{\rm w}}{2 \times 10^3 {\rm km \ s}^{-1}}\right) \ {\rm erg \ s}^{-1}. \tag{12}$$

Using the equations above, this results over the lifetime of a single O star (of order million years) a bubble of size ~ 100 pc.

For a given cluster of massive stars, the exercises show that a similar amount of power is produced by supernovae, but over a longer time (up to the lifetime of 8 $M_\odot$ stars, or about 30 million years), which means that the feedback is dominated by the combined effect of these supernovae producing superbubbles.

Per unit star formation the rate of core-collapse supernovae is:

$$R_{\rm SN} \approx 10^{-2} \left(\frac{\rm SFR}{M_\odot \ {\rm yr}^{-1}}\right) \ {\rm yr}^{-1} \tag{13}$$

If we relate the mass outflow rate to the kinetic energy input rate by $\dot{K} \sim \dot{M}_{\rm out} v_{\rm esc}^2/2$, and use an energy for each supernova of 10^{51} erg, then:

$$\dot{M}_{\rm out} \sim \frac{\eta}{0.1} \left(\frac{\rm SFR}{M_\odot \ {\rm yr}^{-1}}\right) \left(\frac{v_{\rm esc}}{300 \ {\rm km \ s}^{-1}}\right)^{-2} M_\odot \ {\rm yr}^{-1} \tag{14}$$

where η is the fraction conversion of wind power into kinetic energy (calculated as 0.2 above).

A momentum-driven model is also possible if the medium around the star formation is optically thick. This situation would apply mostly to starbursts. An order-of-magnitude estimate of the momentum-driven winds yields:

$$\dot{M}_{\rm out} \sim \left(\frac{\rm SFR}{M_\odot \ {\rm yr}^{-1}}\right) \left(\frac{v_{\rm esc}}{300 \ {\rm km \ s}^{-1}}\right)^{-1} M_\odot \ {\rm yr}^{-1} \tag{15}$$

which is similar to the energy-driven winds at moderate star formation rates but much more effective for star bursts (see Murray et al. 2005).

For some of the observed wind velocities in star forming galaxies, the high observed velocities (500–1000 km s^{-1}) and relatively high inferred mass-loading factors suggest a momentum driven wind.

1.3. AGN Feedback

AGN feedback is driven by accretion onto a black hole. The luminosity of an accreting black hole is limited (in the spherical case) to the Eddington luminosity $L_{\rm Edd}$. This luminosity can be related to an Eddington mass accretion rate:

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\epsilon_{\rm rad} c^2}, \tag{16}$$

where $\epsilon_{\rm rad}$ is the radiative efficiency, which in theory can be as high as 0.29 for a highly spinning black hole with very radiatively efficient accretion, but is typically thought to be ~ 0.1 even for AGN in radiatively efficient phases.

We can estimate whether AGN have sufficient energy to substantially affect the galaxy by comparing the total energy emitted in the formation of the black hole to the potential energy of the bulge:

$$\frac{E_{\rm BH}}{E_{\rm bulge}} \sim \frac{\epsilon_{\rm rad} M_{\rm BH} c^2}{M_{\rm bulge} \sigma^2} \sim 100 \frac{\epsilon_{\rm rad}}{0.1} \left(\frac{\sigma}{300 \text{ km s}^{-1}} \right)^{-2} \frac{M_{\rm BH}/M_{\rm bulge}}{0.001} \tag{17}$$

For a massive galaxy, then, there is amply energy available in principle to affect the evolution of the bulge region.

It is believed that AGN feedback occurs in both radiatively efficient and radiatively inefficient AGN phases. The *radiative* or *quasar* mode feedback is associated with Eddington ratios of $L/L_{\rm Edd} > 10^{-2}$. Feedback occurs through photoionization heating and radiation pressure. The dominant effect on the galaxy as a whole is thought to be through the radiation pressure, which can create a galactic wind. The radiation pressure is proportional to the luminosity and the momentum imparted per unit time to the wind is dimensionally:

$$p_w \propto \dot{M}_{\rm BH} v_w \tag{18}$$

with the constant of proportionality estimated theoretically at about 0.5. This effect drives a momentum-driven wind. In theoretical models the mechanical efficiency is:

$$\epsilon_w = \frac{L_w}{\dot{M}_{\rm BH} c^2} \sim 10^{-3}. \tag{19}$$

The *jet* or *radio* mode feedback occurs primarily in the radiatively inefficient regime (Eddington ratios $< 10^{-2}$). The jets of the AGN interact with the hot gas in the galaxy or surrounding cluster mechanically. In a few systems, the effects of these interactions can be seen as X-ray bubbles or cavities. The gas outside the cavity is at the virial temperature and emits in the X-rays. The gas inside the cavity is moving relativistically and its primary emission is radio synchtron. The surrounding pressure can be estimated from the X-ray data, and the total energy in the bubble is:

$$E = U + W = \frac{1}{\gamma - 1} PV + PV = \frac{\gamma}{\gamma - 1} PV, \tag{20}$$

where $\gamma = 4/3$ for a relativistic gas. The kinetic power can be estimated as E/t where t is some estimate of the age of the bubble, for example based on its size and the sound speed (**?**). This power is comparable in magnitude and tends to scale with the X-ray luminosity, indicating that it can balance cooling. In fact, the kinetic power associated with these bubbles is thought to couple very efficiently to the interstellar or intergalactic gas.

One of the reasons that AGN feedback began to be considered seriously is that it is possible to construct a scaling relation based on the Eddington limit that looks like $M_{\rm BH}$-σ relation of galaxies. In particular, if you set the total outward force due to radiation pressure at the Eddington limit, $L_{\rm Edd}/c$, equal to the total inward force due to gravity on some amount of gas $M_{\rm gas} = fM_{\rm gal}$:

$$\frac{L_{\rm Edd}}{c} = \frac{4\pi G_{\rm BH} m_p}{\sigma_T} = \frac{GM_{\rm gal}M_{\rm gas}}{r} = \frac{fG}{r^2}\left(\frac{2\sigma^2 r}{G}\right)^2 = \frac{4f\sigma^2}{G} \tag{21}$$

which implies that $M_{\rm BH} \propto \sigma^4$, relatively similar to the relation observed. Thus, if the fraction of gas loss f is constant across galaxy mass, and the typical Eddington ratios are constant across galaxy mass (or at least that the momentum imparted by feedback processes scales linear with black hole mass), then the $M_{\rm BH}$-σ relation will follow.

The argument can be made more specific by supposing that the growth of the surrounding galaxy is in fact Eddington limited by the action of the quasar. This requires that the quasar radiation couple with the interstellar gas much better than the Thomson cross-section with the electrons. In fact, for galaxies with Milky Way-like dust to gas ratios, the cross-section of dust per proton is about $\sigma_d \sim 1000\sigma_T$. Thus for dusty neutral gas, the Eddington limit is about 1000 times larger. Over the course of the lifetime of the galaxy and black hole, if both grow at their respective Eddington limits (or some equal fraction thereof) they will end up with $M_{\rm BH}/M_{\rm gal} \sim \sigma_T/\sigma_d \sim 10^{-3}$ (**?**). This same argument also would lead to $M_{\rm gal} \propto \sigma^4$, as seen for elliptical galaxies in the Faber-Jackson relation.

2. Commentary

Much of the literature on feedback is motivated by the desire to get the theoretical predictions of galaxy formation simulations to agree with observations. Although some of the arguments are suggestive regarding AGN feedback and the $M_{\rm BH}$-σ relation, it is still fairly speculative that these processes are related and not a numerical and dimensional coincidence.

3. Key References

- Cimatti
- *Physical Models of Galaxy Formation in a Cosmological Framework* (Somerville & Davé 2015)

4. Order-of-magnitude Exercises

1. Estimate proportionality between the supernova rate and the star formation rate.
2. For an O/B association with 100 O and B stars (down to 8 $M_\odot$), what is the typical power output of supernovae?
3. For a single massive with a wind like that described above, in a typical region of the interstellar medium, after about 100,000 years what sized region will it have created around it?
4. Estimate of energy driven stellar feedback wind outflow rates
5. Estimate of momentum driven stellar feedback wind outflow rates

5. Analytic Exercises

1. Sedov
2. Derive Equation 9 from 8. Using this relationship along with Equation 7 show that Equation 10 holds. Finally, show that the kinetic energy of the shell obeys Equation 11.
3. Show that about 20% of the power input into an expanding bubble this relationship along with Equation 7 show that Equation 10 holds.
4. Energy from SNe (Cimatti S8.7.1)

REFERENCES

Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569

Somerville, R. S., & Davé, R. 2015, ARA&A, 53, 51

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