Session 8:

FEEDBACK:

Stellar Feedback, AGN Feedback, Gas Accretion, Outflows

Feedback and Outflows

Norman Murray

Canadian Institute for Theoretical Astrophysics, University of Toronto,
60 St. George st., Toronto, ON, M5S 3H8, Canada
email: murray@cita.utoronto.ca

Abstract. The low stellar and gas mass fractions, low galaxy-wide star formation rates (relative to galactic dynamical times) and observations of rapid outflows from galaxies, all suggest that stars and active galactic nuclei violently alter the state of the interstellar and even inter-halo gas in galaxies. I argue that the low galaxy wide star formation rates are not the result of turbulent suppression of star formation on small scale, but rather the result of a balance between dynamical pressure and the force (or rate of momentum deposition) provided by stellar feedback, either in the form of radiation pressure or by supernovae. Galaxy scale winds can also be driven by feedback, either from stars or active galactic nuclei, although the exact mechanisms involved are still not well determined.

Keywords. galaxies: formation — stars: formation — hydrodynamics — instabilities

1. Introduction

Recent observations constrain both the abundance of dark matter galaxy halos and the luminosity function of galaxies with a fair amount of precision. The result shows that star formation efficiency, defined as the ratio of stellar mass to halo mass, has a fairly sharp peak at a halo mass slightly below $10^{12} M_\odot$ in present day galaxies (e.g., Leauthaud *et al.* 2012. Scaling to the cosmic abundance of baryons $f_{b,cos} \equiv M_{baryon}/(M_{baryon} + M_{DM}) \approx 0.17$ (Dunkley *et al.* 2009), the star formation efficiency at this halo mass is $f_{b,stars} \sim 22\%$, i.e., only 22% of the baryons associated with the dark matter halo make their way into stars.

Inventories of both stars and gas suggest that the most massive clusters contain most if not all of their cosmic abundance of baryons, i.e., $f_b \approx f_{b,cos}$ (Leauthaud *et al.* 2012, Dai *et al.* 2010). Lower mass halos appear to have $f_b < f_{b,cos}$, with f_b dropping to 0.1 or smaller for halos with $M_h < 10^{11} M_\odot$. In clusters with cooling times comparable to the current age of the universe the lack of star formation is readily explained, since the hot gas is gravitationally stable against collapse. However, the low stellar efficiency in halos with $f_b \approx 1$, combined with the relatively short gas cooling times in many massive clusters, suggests that something is preventing gas from turning into stars. One possible explanation is that the gas is heated by active galactic nuclei, which are seen in almost all clusters with cooling times significantly shorter than ~ 1 Gyr (Cavagnolo *et al.* 2008).

At lower halo masses, observations of rapidly star forming galaxies, both locally in ultra-luminous infrared galaxies (ULIRGs), and at high redshift, find that blue shifted absorption lines of ions such as NaD and MgII are ubiquitous; such lines are strong evidence that baryons are being ejected from the host galaxies. The mass loss rates appear to be of order the star formation rate ($\sim 100 M_\odot \, \mathrm{yr}^{-1}$ in the case of ULIRGs) or larger (Sturm *et al.* 2011). The outflow velocities are similar to the escape velocities from the host galaxies, suggesting that the winds are removing baryons from the host halos.

Similarly, observations of quasars embedded in local ULIRGs find molecular outflows with mass loss rates up to $700 M_\odot \, \mathrm{yr}^{-1}$ (Sturm *et al.* 2011). The gas mass currently

residing in these ULIRGs corresponds to less than 10% of $f_{b,cos}$, so that these winds are not relevant for explaining the low observed values of f_b. However, they could deplete the gas reservoir in a time less than the depletion time associated with star formation. This is an attractive feature, since massive elliptical galaxies are known to be enriched in $\alpha-$process elements relative to iron (low α/Fe ratios); this suggests that the stars in such galaxies formed from gas not enriched by Type Ia supernovae (Trager *et al.* 2000), which have low α/Fe ratios. The time delay between a burst of star formation and the subsequent explosion of type Ia SNe ranges from a few tens of millions of years to several gigayears (Gyr), with a rough scaling $\sim t^{-1}$. Thus, to avoid low α/Fe ratios, star formation must be halted on a time scale less than ~ 1 Gyr.

These observations suggest that star formation and accretion onto supermassive black-holes either prevent cooling of hot gas, producing low halo star formation efficiencies (in high mass halos), or eject baryons, producing both low star formation efficiencies and low halo baryon abundances (in low mass halos).

2. Rapid Star Formation

Kennicutt (1998) showed that, averaged over their starforming disks, i.e., over their half-light radii R_e, local sprials, starbursts, and ULIRGs converted only 1.7% of their gas into stars over the disk dynamical time, defined as R_e/v_c, where v_c is the circular velocity of the disk. Symbolically,

$$\frac{dM_*}{dt} = \eta \frac{M_g}{\tau_{\mathrm{dyn}}} \qquad (2.1)$$

where $\eta \approx 0.017$. This and similar relations are known as Kennicutt-Schmidt relations.

More recent work has modified this result at gas surface densities $\Sigma_g < 10 M_\odot \, \mathrm{pc}^{-2}$, (Bigiel *et al.* 2008), but at higher gas surface densities the results of Kennicutt (1998) hold up well.

Since all star-forming disks contain a substantial amount of gas, the age of those gas disks must exceed the disk dynamical time by a large amount, consistent with the long disk depletion time, $\tau_{dep} \equiv M_g/(dM_*/dt) \approx 10^9$ yr (the numerical value being appropriate for local spirals). This implies that the disks are in approximate vertical hydrostatic equilibrium,

$$\frac{dP}{dz} = \rho g \approx \rho \frac{v_c^2}{r} \frac{z}{r}, \qquad (2.2)$$

or $H/R \approx v_T/v_c$, where v_T is the z-component of the turbulent velocity. This shows that the local crossing time is equal to the disk dynamical time. Finally, the most massive GMCs in the Milky Way, which are known to be the location of the bulk of the star formation, have sizes comparable to the molecular disk scale height H, and virial parameters $\alpha_{\mathrm{vir}} \equiv 5\sigma^2 R_{\mathrm{GMC}}/G$ that are of order unity, (e.g., Heyer *et al.* 2009), meaning that they are self-gravitating objects. This in turn implies that the free-fall times of GMCs in spiral galaxies are similar to the local crossing time. As an example, in the Milky Way, $\tau_{dyn} = R/v_c = 35$ Myr at the solar circle, while the largest molecular clouds have $M \approx 3 \times 10^6 M_\odot$ and $R_{\mathrm{GMC}} \approx 150$ pc (Grabelsky *et al.* 1987), leading to a free fall time of 17.5 Myr.

Given that most of the molecular gas in a galaxy resides in GMCs, the bulk of the star formation takes place in GMCs, and, that the GMC free-fall time is similar to the disk dynamical time, it is plausible that the star formation rate in a GMC is proportional to

the mass of gas in the cloud, and inversely proportional to the GMC free-fall time,

$$\left(\frac{dM_*}{dt}\right)_{\rm GMC} = \epsilon_{\rm ff} M_{\rm GMC}/\tau_{\rm ff}. \tag{2.3}$$

This defines the star formation rate per free-fall time, $\epsilon_{\rm ff}$, for a GMC. It is clear that this argument can be generalized to any virial gas clump.

Krumholz & McKee (2005) have argued that $\epsilon_{\rm ff}$ is set by the properties of turbulence, and further that it is very nearly constant and equal to the value of η in equation (2.1), i.e., $\epsilon_{\rm ff} = 0.017$.

This prediction can be tested in the Milky Way. We have combined the WMAP free-free map to find free-free emission regions and the associated star forming complexes seen in Spitzer GLIMPSE images. The free-free emission of a star cluster is provided primarily by stars with $M_* \geqslant 40 M_\odot$; since these stars have lifetimes $\sim 4\,{\rm Myr}$, free-free emission traces only the most recent 4 Myr of star formation. Having found the sources of the bulk of the ionizing photons in the Milky Way, we then examined radio recombination line radial velocity catalogs to find the radial velocity of the WMAP/GLIMPSE sources, and hence their distances. This allows us to convert free-free flux into free-free luminosity, and thence to the ionizing luminosity of the association in question. This, in combination with an initial mass function (essentially the Kroupa IMF) and the lifetime of the source stars, allows us to calculate the star formation rate, averaged over the last 4 Myr, of the source. Finally, we cross-correlated the resulting SFC catalog with published catalogs of CO clouds, matching sources with the same Galactic latitude, longitude, and line of sight velocity, (b, l, v_r). This gives us both $M_{\rm GMC}$ and $\bar{\rho}$, or equivalently $\tau_{\rm ff}$ for the host GMCs. It is then straightforward to calculate $\epsilon_{\rm ff}$ (see, e.g., Murray 2011).

The results are shown in Figure 1. This plot is similar to Figure 2 in Mooney & Solomon (1988); both show that the star formation rate per free fall time is far from constant, ranging from values ~ 0.001 up to 0.3, or 30% per free-fall time of the host GMC.

3. Feedback

3.1. *Necessity for and evidence of rapid (pre-supernova) feedback*

As we have just seen, a number of Milky Way GMCs have produced young (less than 4 Myr old) stars at a rate that would lead to $\sim 30\%$ of the GMC mass turning into stars, if the star formation went on for a GMC free-fall time. The GMC masses involved are of the order of $10^6 M_\odot$, so star formation at this rate for a dynamical time would produce a total mass of $3 \times 10^5 M_\odot$ stars or more, a factor of three larger than the largest OB associations in the Milky Way. Thus there appears to be some mechanism halting star formation.

Figure 2 is an 8 micron image taken from the Spitzer GLIMPSE survey (Benjamin *et al.* 2003) showing the region surrounding one of these $\sim 3 \times 10^4 M_\odot$ OB associations (Murray & Rahman 2010). The mass of the OB association is inferred from the free-free luminosity of the region, but infrared spectroscopy of stars in the region suggests that there is a substantial number of early O-stars in the area (Rahman *et al.* 2011). The mean radius of the bubble is $R \sim 72\,{\rm pc}$, while the rim of the bubble is expanding with a velocity $v \sim 13.5\,{\rm km\,s^{-1}}$, leading to a dynamical age of $\sim 5\,{\rm Myr}$.

The cluster and surrounding bubble is embedded in a huge molecular cloud, with $R_{\rm GMC} \sim 130\,{\rm pc}$ and $M_{\rm GMC} \sim 7 \times 10^6 M_\odot$ (Murray 2011). The swept up mass in the bubble wall is $M_{\rm wall} \sim 2 \times 10^6 M_\odot$ for a GMC run of density $\rho(r) \sim 1/r$. The momentum and energy in the wall are $P \approx 5 \times 10^{45}\,{\rm g\,cm\,s^{-1}}$ and $KE \approx 7 \times 10^{51}\,{\rm erg}$. The luminosity

of the source $L \sim 3 \times 10^{51}$ erg s^{-1}, so over a time ~ 4 Myr the light from the cluster will deposit a momentum $\sim 2 \times 10^{45}$ g cm s^{-1}, similar to that observed. The pressure of the observed ionized gas will deposit a comparable momentum into the wall of the bubble over the same time. These two forms of feedback (particularly the radiation pressure) start acting as soon as the massive stars ignite.

This very early feedback is crucial in regions where the dynamical time of the gas is shorter than the main sequence lifetime of the most massive stars. An example of such a situation is given by the local ultra-luminous infrared galaxy Arp 220; much of the star formation in Arp 220 takes place in two ~ 300 pc gas disks, which have dynamical times ~ 1 Myr.

4. Feedback regulated galactic scale star formation rates

Equation (2.2), together with the observation that galactic disks have substantial scale heights (with $R/H \sim 40$ in local disks, extending up to $R/H \sim 4$ at $z = 2$), highlights the need for vertical support to prevent razor thin disks. Large scale gravitational instabilities such as bars or spiral waves in disks will not prevent gas from collapsing into parsec scale clumps. A source of internal "pressure" support is needed (Thompson *et al.* 2005, Ostriker & Shetty 2011). Accounting for force or pressure balance, $\rho v_T^2 = \pi G \Sigma_g^2$, together with estimates of the (vertical) momentum flux per unit time provided by stars, results in slow predicted global star formation rates, in fairly good agreement with the observed star formation rates.
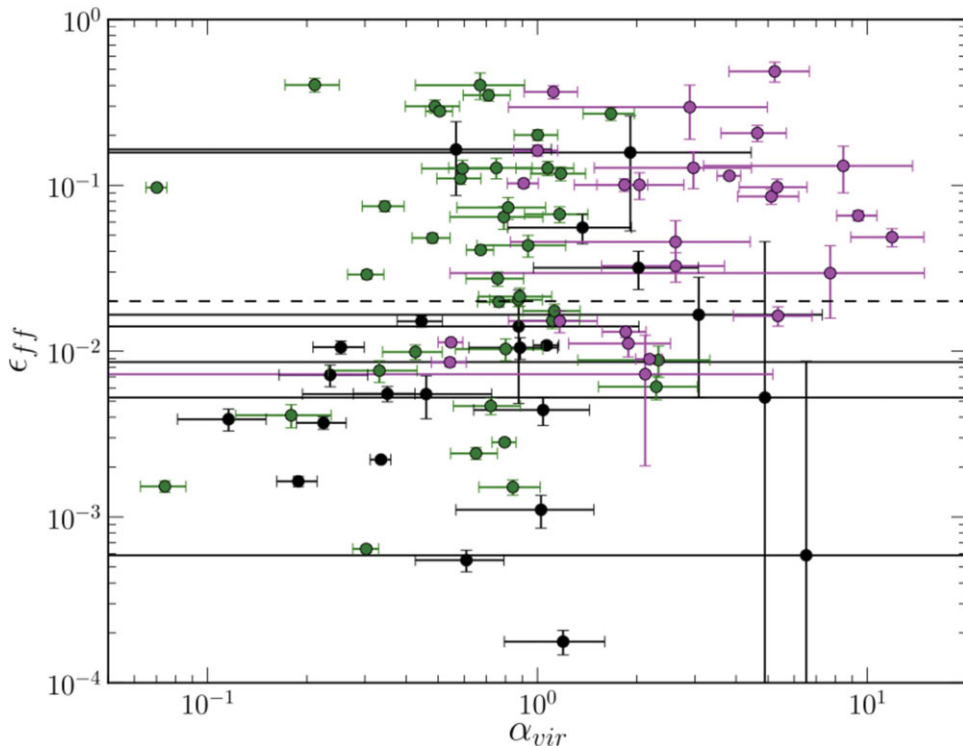

Figure 1. The star formation rate per free-fall time $\epsilon_{\rm ff}$ for Milky Way GMCs. The rate is seen to vary by more than two orders of magnitude, and reach values $\sim 30\%$, more than an order of magnitude larger than the Galaxy-averaged rate $\sim 1\%$.

The simple analytic estimates in the papers just cited are being superseded by galactic scale three dimensional hydrodynamics simulations, e.g., Hopkins *et al.* (2011), Agertz *et al.* (2012). These and similar simulations include the effects of photoionization heating, radiation pressure, shocked stellar winds, and supernovae. The gas cools radiatively and via coupling to dust grains, and, in isolated galaxy simulations, the resolution reaches $\sim$ 1 pc, so that GMCs are well resolved, while the largest star forming clumps are marginally resolved.

Figure 3 shows the star formation rate in one set of simulations, in which various forms of stellar feedback are turned off and on to determine which type is effective in each of four different galaxies: a model of a high redshift galaxy with a large gas fraction (HiZ), a moderately gas rich zero-redshift Sbc model, a Milky Way analog and a model of the Small Magellanic Cloud. In the gas rich model galaxies (HiZ and Sbc) radiation pressure is the most effective feedback, as measured by its effect on the global star formation rate, while in the Milky Way and particularly the SMC models supernovae play an important, or even dominant, role. If no feedback is supplied, the star formation rate is of order $M_g/\tau_{\rm dyn}$, i.e., turbulence (which is seen even in the absence of stellar feedback) does not limit the rate of star formation.

While turbulence is seen in these and similar simulations lacking stellar feedback, the character of the resulting ISM is very different than that in real galaxies, or in simulations which include stellar feedback: in the absence of feedback, the gas collapses into very dense clumps (with a maximum density set by the resolution of the simulation), e.g., Bournaud
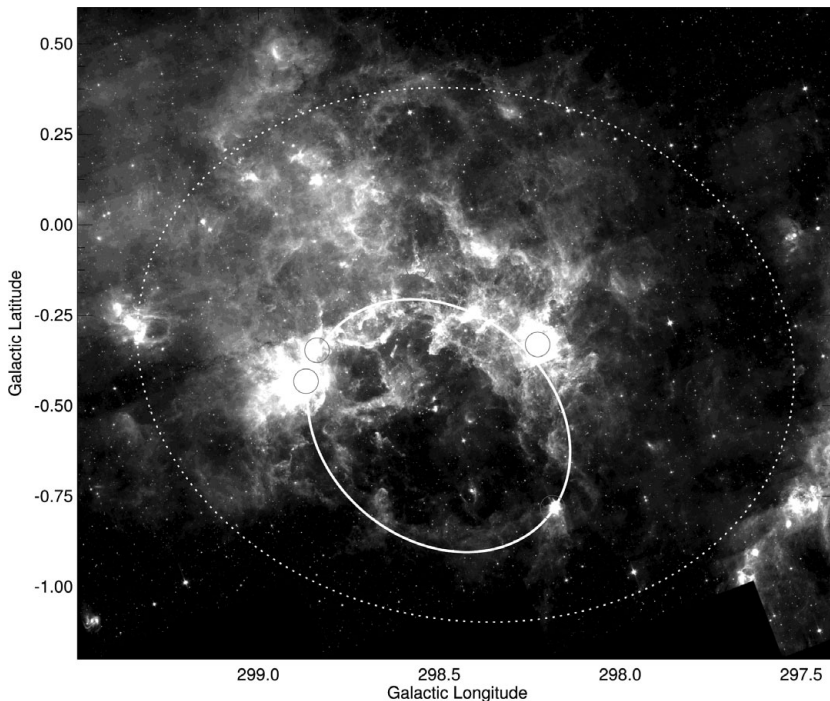

Figure 2. GLIMPSE 8 μm image of the WMAP free-free source G298.4-0.4. The solid white ellipse outlines a bubble with a mean radius of $\sim$ 60 parsec, at a distance from the sun of 11.7 kpc , the distance to the associated HII regions (delineated by the red circles). This is one of the most luminous free-free sources in the Milky Way, with little associated synchrotron emission, indicating that few if any supernovae have exploded in the region. A large OB association, with an estimated mass $\sim 10^5 M_\odot$, has been found at this location on the sky (Rahman *et al.* 2011).

et al. (2010), illustrating yet again that rapid stellar feedback is required, in this case to explain the rather low fraction of very dense gas ($n > 10^5\,\mathrm{cm}^{-3}$) seen in galaxies.

5. Stellar feedback driven winds

When the gas surface density in a galaxy is large, the high pressure ($\propto \Sigma_g^2$) calls forth very high rates of momentum deposition from stars, i.e., very large star clusters form. If Σ_g is high enough, the escape velocity from the stellar clusters approaches the escape velocity of the galaxy. Thus in order for the star clusters to disrupt their host GMCs, they must generate bulk gas velocities high enough that they are likely to drive large (kpc) scale winds. Analytic calculations, 1D radiation-hydrodynamics (Murray *et al.* 2011), and, very recently, 3D radiation-hydrodynamic calculations (Hopkins *et al.* 2012) all predict this behavior.

Supernovae produce high velocity ($\sim 2000\,\mathrm{km\,s^{-1}}$) high temperature winds, but observed winds have much higher mass loss rates than those that would be produced by SNe alone. In addition, observed winds have the bulk of their gas in a high density, low T, and relatively low velocity ($300 - 1000\,\mathrm{km\,s^{-1}}$) component. This is often explained by appealing to mass loading of hot gas outflows, e.g., Heckman *et al.* (1990). However, it can also be the result of ram pressure driving, by hot gas, of pre-existing atomic or molecular (cold) gas. The details of the driving, and the total mass loss rate, are currently not well understood either theoretically or observationally.
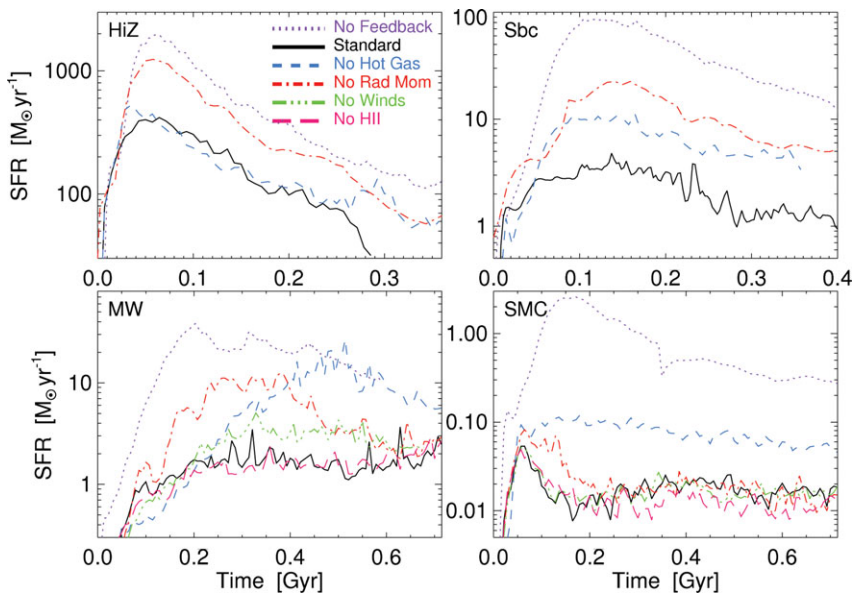
Figure 3. Star formation rate dM_*/dt versus time for four different galaxy models. Each of the four types of galaxy models was used in simulations with a variety of stellar feedback models, including models with no feedback (the dotted purple line). In the gas rich models (the model for $z \sim 2$ galaxies, and Sbc, for a local Sbc galaxy) the star formation rates are overpredicted relative to the Kennicutt-Schmidt relation, unless radiation pressure feedback is included. In the gas poor galaxies, in particular the SMC model, the effects of supernovae are sufficient to reproduce the Kennicutt-Schmidt relation (Hopkins *et al.* 2011).

6. AGN feedback driven winds

The sharp fall off in the number counts of high stellar mass galaxies above $M_* \sim 10^{11} M_\odot$, or alternately the drop in halo star formation efficiency above a (total) halo mass of $10^{12} M_\odot$, suggests the possibility that a very distinct form of feedback operates in such massive objects. It should be kept in mind, of course, that the cooling times in such large halos are long, and that star formation can therefore be suppressed even without feedback.

However, there is fairly strong evidence that active galactic nuclei can both suppress star formation, particularly in massive cluster halos, and that quasars can drive outflows, e.g., Sturm *et al.* (2011). The latter reference provides evidence that the mass loss rate in the observed wind is equal to or exceeds the star formation rate in the host galaxies, in some cases by a factor of nearly ten. If the mass loss rates are as high as suggested, it would appear that the rate at which the wind carries away momentum exceeds, by a similar factor, the rate of momentum loss in photons, i.e., $\dot{M}_w v_w > L/c$.

Such large rates of momentum transfer can occur if light from the quasar is trapped, in the form of far infrared radiation, near the quasar (Murray *et al.* 2005), or if the broad absorption line winds from the quasar are similarly trapped (Faucher-Giguère & Quataert 2012). Three dimensional hydrodynamics simulations with sufficient resolution and realistic physics to model such winds are just now becoming available.

The largest halos, those associated with galaxy clusters, appear to possess their cosmic allotment of baryons, mostly in the form of hot gas. Thus any starburst or AGN winds experienced by the galaxies in these halos were not sufficiently powerful to remove the baryons from the final massive halo. The low star formation efficiency in such clusters still requires some form of feedback, at least for those clusters with 'cool cores', since the cooling time in these objects is shorter than the Hubble time, but this is a subject for a different talk.

7. Conclusions

I have argued that star formation on the scale of giant molecular clouds is rapid, approaching a rate that, if continued, would consume $20 - 30\%$ of the GMC mass in a single free-fall time. I have presented evidence that such rates are seen in the Milky Way. The fact that galaxy wide star formation rates are a factor of 20 smaller is due, as has been argued by a number of authors, to stellar feedback halting the star formation once a large enough star cluster has formed. This same feedback, or possibly some later stellar feedback, then regulates the state of the interstellar medium so as to maintain vertical pressure equilibrium.

In galaxies with high gas surface densities, the high required rate of momentum deposition, which scales as Σ_g^2, means that massive star clusters will form. Since the escape velocity from such clusters approaches the escape velocity of the host galaxy, such clusters are capable of launching winds that will eventually escape the galaxy. This process has been invoked to explain the low stellar and baryon fractions seen in galaxies with stellar masses below $\sim 10^{11} M_\odot$.

The low star formation efficiency at large halo mass has also been attributed to feedback, but in that case the preferred form of feedback arises from the central black hole. The feedback can be either preventive, e.g., heating of gas in the halo can prevent that gas from cooling and falling into galaxies, or it can be active, ejecting gas from the central regions of galaxies.

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