A NEW PRESCRIPTION FOR PROTOGALACTIC FEEDBACK AND OUTFLOWS: WHERE HAVE ALL THE BARYONS GONE?

Joseph Silk

Physics Department, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH

ABSTRACT

Up to half of the baryons inferred to once have been in our galaxy have not yet been detected. Ejection would seem to provide the most attractive explanation. Previous numerical studies may have underestimated the role of winds. I propose a solution involving a multiphase model of the protogalactic interstellar medium and the possibility of driving a superwind. Simulations do not yet incorporate the small-scale physics that, I argue, drives mass-loading of the cold phase gas and enhances the porosity, thereby ensuring that winds are driven at a rate that depends primarily on the star formation rate. The occurrence of hypernovae, as claimed for metal-poor and possibly also for starburst environments, and the possibility of a top-heavy primordial stellar initial mass function are likely to have played important roles in allowing winds to prevail in massive gas-rich starbursting protogalaxies as well as in dwarfs. I discuss why such outflows are generically of order the rate of star formation and may have been a common occurrence in the past.

Key words: galaxies: formation–galaxies: star formation–galaxies: baryons–galaxies: outflows.

1 INTRODUCTION

Cosmological observation and theory have now converged sufficiently that one can begin to make a reasonable census of the baryons in the universe. Four independent probes at very different epochs of the universe yield $\Omega_b \approx 0.04$. These are primordial nucleosynthesis ($z \sim 10^9$), the cosmic microwave background temperature fluctuation power spectrum ($z \sim 10^3$), modelling of the Lyman alpha forest ($z \sim 3$), and the hot gas fraction in galaxy clusters ($z \sim 0$). The latter requires knowledge of $\Omega_m$, which I take to be 0.3, as inferred from recent large-scale structure studies (e.g., Schuecker et al. 2003; Verde et al. 2002; Percival et al. 2002; Peacock et al. 2001).

Approximately 10 percent of the baryons are observed in spheroid stars, 4 percent in disk stars, and 5 percent is observed as hot gas in galaxy clusters (Fukugita, Hogan and Peebles 1998). The local Lyman alpha forest accounts for an additional 20 percent of the baryons (Penton, Shull and Stocke 2000). The dominant fraction is predicted from large-scale structure simulations to be in a diffuse warm/hot intergalactic medium at $10^5 - 10^6$K heated by gravitational clustering and accretion (Cen and Ostriker 1999, Davé et al. 2001). This WHIM gas traces the large-scale structure of the galaxy distribution, and accounts for about 30 to 40 percent of the total baryon fraction. There is some evidence in support of the existence of the WHIM, both from the diffuse x-ray background (Soltan, Freyberg and Hasinger 2002) and OVI absorption lines seen towards high redshift quasars (Simcoe, Sargent and Rauch 2002).

There appears to be an apparent shortfall of approximately 10 to 20 percent in the global intergalactic baryon fraction observed relative to that predicted initially. These baryons presumably should have cooled and fallen into galaxies, and, if still present, might be expected to be observable in halos, possibly as hot diffuse gas or as MACHO-like objects. Observationally, this possibility seems unlikely (see below), and a more compelling explanation for the "missing" baryons is that they have undergone non-gravitational heating, perhaps as a consequence of protogalactic, starburst and/or AGN-induced outflows.

There is a complementary and potentially related baryonic shortfall that is quantitatively as demanding and also rather closer to home. Indirect evidence suggests that about twice as much mass in baryons as observed today in stars was once present in halos in the form of cooled gas. Detailed modelling of disk galaxy formation and evolution that incorporates gas cooling, collapse and star formation requires

* silk@astro.ox.ac.uk
an initial gas fraction of 10 to 20 percent (Sommer-Larsen, Gotz and Fortinari 2002; Westera et al. 2002). Perhaps not wholly coincidentally, a gas fraction of 13-15 percent is observed in rich galaxy clusters (Allen, Schmidt and Fabian 2002), which may be considered to be reservoirs of primordial gas albeit contaminated by galactic outflows. This gas fraction is not observed in galaxies, however, despite the fact that it was assumed to be present within the virial radius of the protogalaxy.

The most detailed modelling to date of our own galaxy concludes that there is a well-measured stellar (and interstellar gas) baryon fraction within the virial radius of approximately 6 percent (Klypin, Zhao and Somerville 2002), whereas semi-analytic simulations of disk galaxy formation with cosmological initial conditions commonly find a mass in hot halo gas comparable to that in cooled baryons (mostly stars) and which results in x-ray emission that exceeds observational limits by an order of magnitude (Benson et al. 2000; Governato et al. 2002). In M31, there is a similar baryon shortfall. Apparently, independent arguments from x-ray emission and mass modelling, combined with galaxy formation theory, demonstrate that all of the gas was present initially, yet today there is a deficiency of unaccounted baryons that is at least 30 percent and may be as large as 50 percent or more of the stellar mass. Of course the baryons could still be present in the halo, in the form of MACHOs, for which the upper limit is about 20 percent of the halo mass (Alcock et al. 2000), old white dwarfs, for which the upper limit is about 5 percent of the dark halo (Goldman et al. 2002), or even in the form of extremely dense, compact gas globules (Pfenniger, Combes and Martinet 1994; Wardle and Walker 1999). However such schemes are contrived at best, and the most logical inference is that the missing galactic baryons were blown out in the pregalactic or protogalactic phase when the galaxy was largely gaseous. This would only make a modest contribution to the overall cosmological baryon fraction, of about 10 percent, enough to account for any “missing” baryons, but may suffice, being enriched, to contribute to the metallicity abundance in the intergalactic medium. I now argue that protogalactic gas ejection provides the most likely explanation of the galactic baryon problem.

Jets, winds and photo-ionization provide the only known means of expelling gas by input from AGN, supernovae and OB stars, respectively. I will not consider early AGN feedback here, largely because the uncertainties are so great concerning the role of AGN in galaxy formation and evolution, but I note that it is likely that AGN feedback is important for the intrachannel gas, both for understanding the entropy floor (Cavaliere, Lapi and Menci 2002) and the inhibition of cooling flows (e.g. Blanton, Sarazin and McNamara 2002).

Strong supernova feedback has been incorporated into semi-analytic treatments of disk galaxy modelling in order to expel the gas (Toft et al. 2002). However detailed simulations that incorporate some of the multiphase astrophysics show that outflows from a typical L∗ galaxy are largely quenched by the deep gravitational potential well (Springel and Hernquist 2002). If one accepts this result, then one could consider photo-ionization or supernova-driven ejection of the gas before the galaxy was assembled. Winds are known to develop more efficiently in shallow potential wells. The gas can also be ejected by photo-ionization in very low mass objects. However this type of explanation requires the bulk of star formation and heavy element enrichment to have occurred in the pregalactic environment, when the protogalaxy still consists of a collection of hierarchically merging gas-rich dwarfs, in order to achieve ejection of a mass of gas comparable to the mass in stars. Such outflows have indeed been invoked (Madau, Ferrara and Rees 2001) to account for the metallicity in the Lyman alpha forest, this hypothesis necessarily requiring enrichment via low mass objects to avoid destructive interference by massive winds. These much more modest supernova-driven pregalactic outflows invoke only of order one supernova per 10^9 M⊙, and so can account for the observed Lyman alpha forest metallicity of about half a percent of the solar value.

There are two arguments that render the drastic solution of massive pregalactic supernova-driven outflows unacceptable in the present context. Firstly, the diffuse IGM would be enriched at an early epoch to an unacceptably high level, to a factor ∼Ω_c/Ω_b of solar. One sees such enrichment in clusters but not in the high redshift IGM sampled by absorption line measurements towards remote quasars. The inferred population of pregalactic objects is necessarily common and nearly uniformly distributed, and would overpollute the entire IGM. Secondly, and even more seriously, one would have formed most of the stars before the massive galaxies were assembled, and one could not attain the observed surface brightnesses or central stellar densities.

What is needed is a mechanism that ejects gas in the protogalactic environment from massive protogalaxies, and thereby preferentially pollutes only the denser environments that are destined to form groups and clusters. There is some evidence from studies of Lyman break galaxies that massive galaxies can have winds at early stages of their evolution. With a space density and clustering scale comparable to those of local luminous galaxies, a median star formation rate of ∼90M⊙yr⁻¹, a median star formation age of ∼0.3 Gyr, and a median stellar mass of ∼3×10^10M⊙, a significant fraction of Lyman break galaxies at z ∼ 3 are surely the counterparts of L∗ galaxies (Shapley et al. 2002). Spectral studies of Lyman break galaxies, using stacked spectra (Shapley et al. 2002a), show evidence of outflows, which are also independently but indirectly inferred from an inverse correlation with nearby Lyman alpha forest hydrogen and CIV metal line system absorption that extends out to circumgalactic distances of up to ∼1 Mpc or even beyond (Adelberger et al. 2003).

Clearly, a new prescription for galactic outflows would be useful in confronting many of these issues. I propose such a prescription that operates effectively regardless of the depth of the potential well of the galaxy. The current numerical simulations lack the resolution to study the detailed interaction of the ejecta from supernovae with the interstellar medium. To model the physics, I develop a simple expression for outflows that is based on the concept of the porosity of the hot bubbles of supernova-heated ejecta in the ambient cold interstellar medium. I argue that porosity and mass loading via instabilities at the interface of the multiphase medium control the outflow efficiency. The resulting outflows depend on the potential well depth only indirectly via the star formation efficiency: the outflow rate is generi-
2 POROSITY AND THE GLOBAL STAR FORMATION RATE

I first review the porosity formulation previously developed in Silk (2001). The porosity of the interstellar medium is the product of the maximum 4-volume of a supernova remnant-driven bubble of hot gas driven by supernovae and limited by ambient pressure of the cold interstellar medium with the bubble formation rate per unit volume, that is, the supernova rate.

The filling factor \( f_{\text{hot}} \) of hot gas can be expressed in terms of the porosity \( Q \) as

\[
f_{\text{hot}} = 1 - e^{-Q}.
\]

The porosity, for an ambient two–phase medium described by a statistically uniform gas pressure \( \rho_0 \sigma_f^2 \), that includes contributions from both thermal pressure and turbulent cloud motions, can be written in the form

\[
Q = \frac{\dot{\rho}_s}{G^{1/2} \rho_0^{3/2}} \left( \frac{\sigma_f}{\sigma_g} \right)^{2.7}.
\]

Here \( \dot{\rho}_s \) is the star formation rate per unit volume, \( \rho_0 \) is the mean gas density and \( \sigma_g \) is the turbulent velocity dispersion of the interstellar medium. A fitting formula (Cioffi, McKee and Bertschinger 1988) adapted to numerical simulations of spherical supernova remnants expanding into a uniform medium and that incorporates radiative cooling, has been used in deriving this expression. I have introduced \( \sigma_f \) as a fiducial velocity dispersion that is proportional to \( E_{51}^{27} m_{SN}^{1} c_{9}^{-0.2} \) and may be taken to be 17.8 km s\(^{-1}\) for an initial supernova energy \( E_{51} = 10^{51} \) erg, where the mass in stars formed per supernova \( m_{SN} \) is set equal to 200M\(_S\) and \( c_{9} \), taken to be unity, represents the heavy element abundance relative to the solar value. Allowance for the contributions of hypernovae and in the microphysics at the interface between the hot and cold media, discussed below, as well as uncertainties in the initial mass function, that will help enhance porosity, means that this estimate of \( \sigma_f \) is a lower limit.

The global star formation rate \( \dot{M}_* \) is written as

\[
\dot{M}_* = \epsilon M_f \Omega,
\]

where \( \Omega \) is the rotation rate (or inverse dynamical time for a non-rotationally supported galaxy), \( M_f \) is the cold gas mass, and \( \epsilon \) is the star formation efficiency. In general, \( \epsilon \) is a dimensionless function that is generally taken to be constant by semi-analytical modellers, but is given a high value for spheroidal formation or starbursts and a low value for disk formation. This simply follows the common folklore that disk star formation is continuing and hence inefficient, whereas spheroids completed their star formation long ago, and hence were relatively efficient. In fact, \( \epsilon \) may be dependent on galaxy mass as well as possibly other parameters. For example the SDSS analysis of some 100000 galaxies suggests that \( \epsilon \) decreases with decreasing galaxy mass (Kauffmann et al. 2002).

I have previously proposed an expression for \( \epsilon \) that depends explicitly on both porosity and turbulent velocity dispersion (Silk 2001). Specifically, on combining the expression for the star formation rate with that for porosity, one finds that the porosity is given by

\[
Q = \epsilon \left( \frac{\rho}{\rho_0} \right)^{1/2} \left( \frac{\sigma_f}{\sigma_g} \right)^{2.7}.
\]

It is useful to define a fiducial star formation rate and efficiency when \( Q = 1 \):

\[
\epsilon_{\text{cr}} = \left( \frac{\rho_s}{\rho} \right)^{1/2} \left( \frac{\sigma_f}{\sigma_g} \right)^{2.7}.
\]

We expect \( \sigma_g \) to be of order 100 km/s for typical protospherical systems. This should be similar in magnitude to the fiducial scale \( \sigma_f \) in the protogalactic environment, if \( \sigma_f \) were somewhat larger than the value cited above, which was obtained from adopting a canonical local initial mass function and modelling supernova remnants as expanding spherical shells. There are three, probably coexisting, ways by which \( \sigma_f \) should be boosted to of order \( \sigma_g \) even for massive protogalaxies.

Suppose firstly that there was, for example, one hypernova with \( E_{SN} \sim 10^{53} \) erg for every 10 Type II supernovae. Hypernovae are possibly the dominant type of supernovae in metal-poor environments and in starbursts in terms of their overall contribution to both metallicity and to energy input into the interstellar medium. A contribution of this order is suggested both for extremely metal-poor environments and in the case of starbursts such as M82 by observed chemical abundances and computed yields (Nomoto et al. 2002), despite theoretical models which may prefer a lower rate (Woosley, Zhang and Heger 2002). The preceding expression is useful in suggesting that when \( \epsilon \sim \epsilon_{\text{cr}} \), a wind should develop, if \( Q \sim 1 \) is indeed the relevant criterion, even in massive galaxies if the hypernova energy input once was dominant. Star formation is generally assumed to have been efficient in massive early-type galaxies, and the protogalactic porosity would plausibly have been large. Secondly, one can plausibly imagine that the initial mass function in the early stages of galaxy evolution was top-heavy, as suggested by discussions of primordial star formation. This could reduce \( m_{SN} \) by up to an order of magnitude. Finally, it is also likely that the naive analytic calculation of porosity given above based on spherical shell modelling significantly underestimates the efficiency of driving winds because of the omission of such critical high resolution microphysics as Rayleigh-Taylor instabilities in the stalling supernova-driven shells. The limited resolution of the simulations suggests that microscopic instabilities are being neglected that may have an important effect on the macroscopic flow. In particular, a combination of Rayleigh-Taylor instabilities as the dense cool gas decelerates in response to its interaction with the hot supernova-driven outflows, and Kelvin-Helmholtz instabilities as the wind streams by the cold gas, makes the interstellar medium highly porous to the wind and entrains cold gas into the wind.

Two important effects of the Rayleigh-Taylor instabilities are to punch holes through the cold dense shell and to mix the cold and hot phases. The mixing will be enhanced by the Kelvin-Helmholtz instabilities at the interfaces where the hot gas flows by the cold interstellar clouds. Both the Rayleigh-Taylor and Kelvin-Helmholtz instabilities
will drive the porosity, entrainment and mixing of cold and hot gas at rates that are outside the domain accessible to current galactic-scale simulations. Individual cloud simulations, albeit in 2-D (Klein, McKee and Colella 1994), suggest that wind interactions drive cloud destruction by the combined action of Rayleigh-Taylor and Kelvin-Helmholtz instabilities, and mass loading of the wind is a consequence of ensuing conductive and ablative cloud destruction (Hartquist et al. 1997).

3 OUTFLOW MODEL

I now develop the hypothesis that high porosity, inevitably associated with a high star formation efficiency, should suffice to drive a wind. For dwarf galaxies, winds are inevitable as a consequence of a starburst, since $\sigma_g \sim \alpha f$. For massive galaxies, the situation is less clear since $\sigma_g \gtrsim \alpha f$. In general, winds are not important today from massive disks since $\epsilon$ is small. The situation may have been completely different in the protogalactic phase when $\sigma_g$ was larger and so most likely was $\epsilon$. For massive spheroids, $\sigma_g$ is large, and one may well need recourse to strong feedback from supernovae, a top-heavy IMF and correspondingly enhanced supernova rate, and/or appeal to deficiencies in the preceding spherically symmetric analysis that surely underestimates the effects of porosity in order to justify the generation of a protogalactic wind. Since spheroids are the dominant stellar reservoir, this argument suggests that winds played an important chemical evolution role at the epoch of spheroid formation. Strong feedback is required in recent discussions of disk angular momenta and sizes (Sommer-Larsen, Gotz and Portinari 2002) and the heating of the intragroup medium (Kay, Thomas and Theuns 2002).

It is known from simulations of low mass galaxies that the hot SN-enriched medium excavates cavities in the interstellar medium and blows out in a wind. In massive galaxies, the wind loses energy as it runs into ambient interstellar material and is quenched by cooling losses. If in fact the arguments in the previous section have some validity, the effects of entrainment and porosity are considerably underestimated in current simulations. This means that a plausible outcome is the occurrence of quasi-adiabatic, mass-loaded outflows once the porosity $Q$ is large. As long as the hot volume fraction and the resulting porosity are high, mass outflows entrain interstellar gas at a rate that is comparable to the star formation rate. I will show that the outflows are partially suppressed if the porosity of the hot phase is low, and the outflow rate is then much less than the star formation rate.

Consider a multiphase interstellar medium. Supernovae drive bubbles of hot gas that are halted by ambient thermal and turbulent pressure of the interstellar medium, including both hot and cold phases. I do not explicitly consider spatial and temporal correlations of the supernovae: the outflows will be enhanced by such correlations.

I hypothesize that the outflow rate is

$$M_{\text{outflow}} = \beta \dot{M}_* f_{\text{hot}},$$

and is controlled by entrainment via the wind mass-loading factor $L$ and by porosity via the filling factor of the hot phase $f_{\text{hot}}$. The effective load factor $\beta$ can be written as

$$\beta = (1 + L) \frac{\Delta m_{\text{SN}}}{m_{\text{SN}}},$$

where $\Delta m_{\text{SN}}$ is the IMF-weighted mass ejected per supernova of Type II and the amount of mass loading can be estimated from the X-ray properties of the supernovae (Suchkov et al. 1996). In particular, the metal content of winds is an especially powerful tool, and it is argued that the wind consists predominantly of interstellar gas entrained in the wind. Most of the oxygen in the outflows comes from the stellar ejecta in the wind. The enrichment observed in Chandra observations of, for example, the dwarf starburst galaxy NGC 1569 suggests that the mass of entrained interstellar gas is approximately 9 times the mass of stellar ejecta in the wind ($L \sim 9$) (Martin, Kobulnicky and Heckman 2002).

The preceding prescription for an outflow that is not explicitly dependent on galactic potential well is an ansatz that can be justified, although certainly not rigorously. It lies between extreme viewpoints to be found in the literature. For example, Silich and Tenorio-Tagle (1998) argue that HI halos inhibit winds even from dwarf galaxies, and Strickland and Stevens (1999) find that multiple superbubbles precondition the interstellar medium and help to quench winds. However the simulations of MacLow and Ferrara (1999) find that winds can be driven from dwarf galaxies, but may under-estimate the role of winds in more massive galaxies because of their thin disk assumption. Indeed, chemical evolution models suggest that even massive ellipticals must have driven strong early winds to account for the trend in [$\alpha/Fe$] increasing with mass (e.g. Matteucci 1994). It is clear that winds must involve SN input over a wide range of galaxy masses simply in order to account for the near solar iron abundance in galaxy clusters (Renzini 2002).

Consider first the limiting case of large porosity:

$$M_{\text{outflow}} \approx \beta \dot{M}_*$$

if $f_{\text{hot}} \sim 1$. Since $\beta \sim 1$, we infer that the outflow rate is generically of order the star formation rate, as indeed is observed for many starburst galaxies where evidence for winds has been obtained (Heckman 2002). The outflow rate is observed to be approximately equal to the star formation rate in superwinds associated with starbursts. This is a natural consequence of a typical IMF for which $\Delta m_{\text{SN}} \sim 10 M_\odot$ and $m_{\text{SN}} \sim 200 M_\odot$, so that $\beta \sim 0.5$ for $L \sim 10$. For the cases of a Salpeter, Scalo and Kennicutt IMF, respectively, $m_{\text{SN}} = 135, 256, 107 M_\odot$. These estimates are only for SNIa, as appropriate to a starburst of typical duration $4 \times 10^7$ yr. In primordial situations with $Z \lesssim 10^{-4} Z_\odot$, or even $10^{-2} Z_\odot$, the IMF is likely to be top-heavy, favouring massive stars. In this situation, $m_{\text{SN}}$ could be somewhat lower, and this would help enhance the wind efficiency.

Suppose that the wind outflow energy amounts to a fraction $f_w$ of the supernova input energy to the interstellar medium. The inefficiency occurs in large part because of radiative losses. Energy balance gives

$$M_{\text{outflow}} = \dot{M}_* \frac{2E_{\text{SN}} f_w}{m_{\text{SN}} V_{\text{esc}}^2}$$

where $V_{\text{esc}}$ is the escape velocity from the galaxy and $f_w$ is the wind efficiency, the fraction of supernova energy tapped by the outflow. Now define the ejection velocity of supernova-enriched matter by $V_{\text{ej}}^2 = 2E_{\text{SN}} / \Delta m_{\text{SN}}$. The
load factor is then estimated by
\[ L = f_w \left( \frac{V_{ej}}{V_{esc}} \right)^2 \frac{1}{1 - e^{-Q}}. \] (10)
If \( Q \gtrsim 1 \), this reduces to the usual expression for starbursts:
\[ L = f_w \left( \frac{V_{ej}}{V_{esc}} \right)^2, \] (11)
and the wind efficiency is
\[ f_w \propto LV_{esc}^2. \] (12)

The preceding discussion is almost certainly far too simplistic. Mass loading will also decelerate the outflow, and the net effect on the mass outflow rate is likely to be more complicated than the simple linear proportionality suggested by equation (10).

If the porosity is low, the wind is reduced relative to the star formation rate according to
\[ \dot{M}_{\text{outflow}} \approx \beta Q M_*, \] (13)
if \( f_{\text{hot}} \ll 1 \). In this case there is no outflow, but there will be feedback that however is suppressed by a factor roughly proportional to \( \sigma_g^{-0.7} \):
\[ f_w \propto L \sigma_g^{-0.7} \left( \frac{V_{esc}}{\sigma_g} \right)^2. \] (14)

In general, the outflow rate is comparable to the star formation rate in starbursts: \( \dot{M}_{\text{outflow}} \approx \beta M_* \). This would imply that the ejected mass is expected to be on the order of the stellar mass for all stars formed via the starburst mode. Substantial enrichment of the intergalactic medium therefore occurs, and can be estimated for the intracluster medium from the corresponding dilution factor:
\[ \frac{M_{ij}}{M_{ij} + M_{\text{prim}}} \approx \frac{M_*}{M_{ICM}} \approx 1/3, \] (15)
where \( M_{ij} \) is the ejected gas in early winds, \( M_* \) is the stellar mass, \( M_{\text{prim}} \) is the initial (unenriched) intracluster gas mass, and \( M_{ICM} \) is the present mass of intracluster gas. In deriving this estimate I have assumed that the gas fraction in a rich cluster is approximately 15%. I have also assumed that the ejecta from Type Ia supernovae is mostly ejected in the winds.

4 IMPLICATIONS

Semi-analytic galaxy formation modelling is plagued by the problem, common to all discussions, that low mass galaxies have strong winds but massive systems cool strongly and do not. This is a consequence of the ansatz (Dekel and Silk 1986) for cold dark matter-dominated halos which provides the basis for feedback in all semi-analytical galaxy formation modelling until now. The porosity expression proposed here is identical for all masses: the outflow rate is of the order of the star formation rate. Only the star formation efficiency depends on potential well depth \( (\epsilon_{cr} \sim \sigma_g^{0.7}) \). The wind efficiency depends only weakly on \( \sigma_g \). One now has the prospect, yet to be implemented in actual simulations, that both massive galaxies including (some of) the Lyman break galaxies and dwarf galaxies at high redshift can undergo strong winds. This would simultaneously alleviate both the dwarf excess predicted and not seen at low redshift (Moore et al. 1999) and the cooling catastrophe at high redshift that results in the overproduction of massive luminous galaxies that are not seen in the nearby galaxy luminosity function (Cole et al. 2000). What is more, since the winds occur early and efficiently in massive galaxies, and the star formation rate in lower mass galaxies is predicted to be inefficient, one has the prospect of obtaining consistent colour-magnitude relations for disk and elliptical galaxies and \([\alpha/Fe]\) ratios for early-type galaxies. These represent important difficulties with current models (van den Bosch 2002; Thomas, Maraston and Bender 2002), and it is clear that a change in the feedback prescription along the lines of what is suggested here would be desirable.

In summary, outflows can occur even from massive galaxies since star formation efficiency is greatest in these systems: \( \epsilon_{cr} \propto \sigma_g^{0.7} \), provided that \( Q \sim 1 \). It may be necessary however to appeal to hypernovae, a top-heavy IMF, possible AGN heating, or a more refined treatment of porosity than that presented here, in order for \( \sigma_g \) to be large enough so that \( Q \sim 1 \) in massive galaxies. The outflow velocity is expected to be independent of escape or rotation velocity, as observed for starbursts. The proposed analytic prescription for outflows no longer systematically sacrifices dwarf galaxies at the expense of more massive galaxies. All galaxies have outflows \( \dot{M}_{\text{outflow}} \approx \beta M_* \), for interstellar turbulence velocities up to \( \sigma_g \sim \sigma_f \), and at least in the proto-galactic environment, this plausibly applies to all galaxies.

The observed enrichment of outflows suggests the entrainment load factor is around 10. The best case is based on Chandra observations of the dwarf starburst galaxy NGC 1569. One would expect both the interaction of the supernova-driven hot gas with clumps of ambient cold gas and Kelvin-Helmholtz instabilities at the interface with the diffuse cold interstellar medium, once the porosity becomes large, to enhance the entrainment of cold gas. The colder, denser clumps of gas should have kinematics that reflects their dynamical entrainment. The maximum velocity of the entrained clouds is at most 10 percent of the global shock velocity (Poludnenko, Frank and Blackman 2002). Different velocity outflows are observed for different states of the interstellar gas. For H\( \alpha \) emitting gas, lower velocity flows are found than for the x-ray emitting gas. The lowest outflow velocities occur for the neutral gas seen in HI. This velocity structure is expected if entrainment of the cold interstellar medium is occurring.

Another consequence is enrichment and heating of the intergalactic, and in particular the intracluster, medium. The outflow model predicts that \( \dot{V}_w \approx \dot{V}_{SN} L^{-1/2} \), where \( \dot{V}_{SN} \) is somewhere between the supernova ejection velocity per unit mass of gas consumed to form a supernova either with cooling \( E_{SN}/V_{msn} \), where \( V_{c} \) is the remnant velocity that marks the transition from adiabatic to cooling-dominated expansion, or without cooling \( (E_{SN}/m_{SN})^{1/2} \). This gives \( \dot{V}_w \approx 300 \text{km/s} \) or 1 keV per particle, similar to what is required to break cluster self-similarity (Lloyd-Davies, Ponman and Cannon 2000; Borgani et al. 2002).

The model presented here is highly simplified. In effect, I suggest a quantitative way of empirically incorporating crucial pieces of microphysics that are not present in current galaxy outflow simulations. An amount of baryons that is comparable to the stellar mass currently observed in
galaxies may have been ejected in early outflows. Such massive early outflows could modify the dark matter halo core profiles (Binney, Gerhard and Silk 2001), and consequently reduce the dark mass concentrations in massive galaxies as suggested by modeling of gravitational lensing time delays (Kochanek 2003) as well as in low surface brightness galaxies as inferred from rotation curves (de Blok and Bosma 2002). Early massive winds might also result in selective ejection of low angular momentum gas, thereby helping to alleviate the angular momentum problems of galactic disks (Steinmetz and Navarro 1999; Bullock et al. 2001).

The present model considers only a steady state, and should be generalized to study the time-development of the load factor and the porosity. The evolving role of supernovae will contribute to the evolution of feedback. Winds are not the only outcome, as one could equally consider the dispersion in porosity and the effects of ge-ometry, which will result in a minimum mass in stars needed before feedback becomes important, and help account for the fact that there is a range of metallicity, gas content, and surface brightness in dwarfs but far more uniformity in more massive galaxies.

5 ACKNOWLEDGEMENTS

I acknowledge helpful discussions with G. Bryan, J. De-vriendt, C. Martin, P. Podsiadlowski, A. Slyz and J. Taylor, and the hospitality of the KITP where this work was begun. I also thank the referee for useful comments.

REFERENCES