Galactic Superwinds at Low and High Redshift

Timothy M. Heckman

Department of Physics & Astronomy, Johns Hopkins University,
Baltimore, MD 21218

Abstract. In this contribution I summarize our current knowledge of the nature and significance of starburst-driven galactic superwinds. These flows are driven primarily by the kinetic energy supplied by supernovae. Superwinds are complex, multiphase phenomena requiring a panchromatic observational approach. They are ubiquitous in galaxies in which the global star-formation rate per unit area exceeds roughly $10^{-1} \text{M}_\odot \text{yr}^{-1} \text{kpc}^{-2}$ (a condition satisfied by local starbursts and high-z Lyman Break galaxies). Data on X-ray emission, optical line-emission, and optical/UV interstellar absorption-lines together imply that the mass outflow rates are comparable to the star-formation-rates and that the conversion of kinetic energy from supernovae to superwind is quite efficient ($\sim 30$ to $100\%$). Measured/inferred outflow speeds range from a few $\times 10^2$ to $10^3 \text{km/s}$ and appear to be independent of the rotation speed of the “host” galaxy. The outflows are dusty (dust/gas ratios of $\sim 1\%$ by mass). These properties imply that superwinds may have established the mass-metallicity relation in elliptical and bulges, polluted the inter-galactic medium to a metallicity of $\sim 10$ to $30\%$ solar, heated the inter-galactic medium by up to $\sim 1 \text{kev}$ per baryon, and ejected enough dust into the inter-galactic medium to have potentially observable consequences.

1. Introduction

By now, it is well-established that galactic-scale outflows of gas (sometimes called ‘superwinds’) are commonplace in the most actively star-forming galaxies in both the local universe (e.g. Heckman et al 2000; Dahlem, Weaver, & Heckman 1998; Lehnert & Heckman 1996) and at high redshift (Franx et al 1997; Pettini et al 1998). They are powered by the energy deposited in the interstellar medium by massive stars via supernovae and stellar winds. Over the history of the universe, outflows like these may have polluted the intergalactic medium with metals (e.g. Nath & Trentham 1997) and dust (Aguirre 1999), heated and polluted the intracluster medium (e.g. Ponman, Cannon, & Navarro 1999), and may have established the mass-metallicity relation and radial metallicity gradients in galactic spheroids (e.g. Carollo & Danziger 1994). However, the cosmological relevance of superwinds can not be reliably assessed without first understanding their physical, dynamical, and chemical properties.

In this contribution, I will summarize the basic theoretical ideas concerning the energetics and dynamical evolution of superwinds and describe the likely
physical origin of the emission and absorption they produce (section 2). I will
then review the observed properties of superwinds: their demographics (section
3, their estimated outflow rates (section 4), and their likely fate (section 5).
Finally, I will briefly describe the potential implications of superwinds for the
evolution of galaxies and the inter-galactic medium (section 6).

2. The Conceptual Framework

The engine that drives the observed outflows in starbursts is the mechanical
energy supplied by massive stars in the form of supernovae and stellar winds
(cf. Leitherer & Heckman 1995). For typical starburst parameters, the rate of
supply of mechanical energy is of-order 1% of the bolometric luminosity of the
starburst and typically 10 to 20% of the Lyman continuum luminosity. Some
fraction of this mechanical energy may be radiated away by dense shock-heated
material inside the starburst. However, observations of superwinds imply that
a significant fraction is available to drive the outflow (see below). Radiation
pressure acting on dust grains may also play a role in driving the observed
outflows (Aguirre 1999).

The dynamical evolution of a starburst-driven outflow has been extensively
discussed (e.g. Chevalier & Clegg 1985; Wang 1995; Strickland & Stevens 2000).
Briefly, the deposition of mechanical energy by supernovae and stellar winds re-
sults in an over-pressured cavity of hot gas inside the starburst. The temperature
of this hot gas is given by:

$$T = 0.4 \mu m_H \frac{\dot{E}}{k \dot{M}} \sim 10^8 l^{-1} K$$

for a mass (kinetic energy) deposition rate of $\dot{M}$ ($\dot{E}$). The “mass-loading” term
$l$ represents the ratio of the total mass of gas that is heated to the mass that is
directly ejected by supernovae and stellar winds (e.g. $l \geq 1$).

This hot cavity will expand, sweep up ambient material and thus develop
a bubble-like structure. If the ambient medium is stratified (like a disk), the
‘superbubble’ will expand most rapidly in the direction of the vertical pressure
gradient. After the superbubble size reaches several disk vertical scale heights,
the expansion will accelerate, and it is believed that Raligh-Taylor instabilities
will then lead to the fragmentation of the bubble’s outer wall. This allows the
hot gas to ‘blow out’ of the disk and into the galactic halo in the form of a weakly
collimated bipolar outflow (i.e. the flow makes a transition from a superbubble
to a superwind). The terminal velocity of this hot wind is expected to be in the
range of one-to-a-few thousand km s$^{-1}$:

$$v_{wind} = (2 \dot{E}/\dot{M})^{1/2} \sim 3000 l^{-1/2} km/s$$

The observational manifestations of superbubbles and superwinds are many and
varied. The ambient gas (both the material in the outer superbubble wall and
overtaken clouds inside the superbubble or superwind) can be photoionized by
the starburst and shock-heated by the outflow. This material can produce soft
X-rays and optical/ultraviolet emission and absorption lines. The predicted
expansion speed of the outer wall of an adiabatic wind-blown superbubble is
of-order $10^2$ km s$^{-1}$:

$$v_{\text{Bubble}} \sim 100 \dot{E}_{42}^{1/5} n_0^{-1/5} t_7^{-2/5} \text{km/s}$$

for a bubble driven into an ambient medium with nucleon density $n_0$ (cm$^{-3}$) by mechanical energy deposited at a rate $\dot{E}_{42}$ (units of $10^{42}$ erg s$^{-1}$) for a time $t_7$ (units of $10^7$ years). Clouds exposed to the ram pressure of the wind will be accelerated to terminal velocities of few hundred km s$^{-1}$:

$$v_{\text{cloud}} \sim 600 p_{34}^{1/2} \Omega_w^{-1/2} r_{0,kpc}^{-1/2} N_{\text{cloud,21}}^{-1/2} \text{km/s}$$

for a cloud with a column density $N_{\text{cloud,21}}$ (units of $10^{21}$ cm$^{-2}$) that - starting at an initial radius of $r_0$ (kpc) - is accelerated by a wind that carries a total momentum flux of $p_{34}$ (units of $10^{34}$ dynes) into a solid angle $\Omega_w$ (steradian).

The hot gas that drives the expansion of the superbubble/supercwind may itself be a detectable source of X-rays, especially if a significant amount of mass-loading of the outflow occurs in or around the starburst (e.g. $l \gg 1$). Finally, cosmic ray electrons and magnetic field may be advected out of the starburst by the flow and produce a radio synchotron halo and possibly an X-ray halo via inverse Compton scattering of soft photons from the starburst (Seaquist & Odegard 1991; Moran, Lehnert, & Helfand 1999). From both a theoretical and observational perspective, it is clear that superwinds are a complex, multiphase phenomenon requiring a panchromatic observational approach.

3. Superwind Demographics

Lehnert & Heckman (1996) discussed the analysis of the optical emission-line properties of a sample of $\sim 50$ disk galaxies selected to be bright and warm in the far-infrared (active star-formers) and to be viewed within $\sim 30^\circ$ of edge-on (to facilitate detection of outflows along the galaxy minor axis). They defined several indicators of minor-axis outflows: 1) an excess of ionized gas along the minor axis (from H$\alpha$ images) 2) emission-line profiles that were broader along the galaxy minor axis than along the major axis 3) emission-line ratios that were more “shock-like” along the galaxy minor axis than the major axis (e.g. had stronger [O$I]\lambda6300$, [N$II]\lambda6584$, and [S$II]\lambda \lambda 6717,6731$ emission relative to H$\alpha$). They found that all these indicators became stronger in the galaxies with more intense star-formation (larger $L_{FIR}$, larger $L_{FIR}/L_{OPT}$, and warmer dust temperatures).

In summary, the optical emission-line evidence implies that superwinds are ubiquitous in galaxies with star-formation-rates per unit area $\Sigma_* \geq 10^{-1} M_\odot$ yr$^{-1}$ kpc$^{-2}$. Starbursts surpass this threshold, while the disks of ordinary spirals do not (Kennicutt 1998).

Dahlem, Weaver, & Heckman (1998) used ROSAT and ASCA to search for X-ray evidence for outflows from a complete sample of the seven nearest edge-on starburst galaxies (selected on the basis of far-IR flux, warm far-IR colors, edge-on orientation, and low Galactic foreground HI column). Apart from the dwarf galaxy NGC55, all the galaxies showed hot gas in their halos. The gas had temperatures of a few times $10^6$ to $10^7$ K, and could be traced out to distances of-order 10 kpc from the disk plane. The overall bulk properties
of the X-ray halos (size, energy content, X-ray luminosity) were consistent with simple models of superwinds (see also Read, Ponman, & Strickland 1997).

Finally, we (Heckman et al 2000 - hereafter H2000) have completed a survey of the NaI$\lambda5893$ ("NaD") absorption-line doublet in a sample of 32 far-infrared-selected starburst galaxies. In 18 cases, the line was produced primarily by interstellar gas, and in 12 of these its centroid was blueshifted by over 100 km/s relative to the galaxy systemic velocity. The outflows occurred in galaxies systematically viewed more nearly face-on than the others. The absorption-line profiles in these outflow sources spanned the range from near the galaxy systemic velocity to a typical maximum blueshift of 400 to 600 km s$^{-1}$, which we argued represented the terminal velocity reached by ambient interstellar clouds accelerated along the minor axis of the galaxy by the hot superwind fluid.

At high-redshift, the only readily available tracers of superwinds are the interstellar absorption-lines in the rest-frame ultraviolet. Six of the seven star-forming galaxies at $z = 2.7$ to 4.9 in the combined samples of Franx et al (1997), Pettini et al (1998), and Pettini et al (2000) showed interstellar absorption-lines that were blueshifted by a few hundred to over a thousand km s$^{-1}$ relative to the estimated galaxy systemic velocity. Moreover, a "composite" spectrum formed from the sum of the spectra of 12 star-forming galaxies at $z \sim 3$ also showed interstellar absorption-lines blueshifted by several hundred km s$^{-1}$ (Franx et al 1997). The high-redshift galaxies with outflows all easily exceed the threshold in $\Sigma_*$ given above for local galaxies driving outflows (see Meurer et al 1997). Very similar kinematics are observed in UV spectra of local starbursts (Heckman & Leitherer 1997; Kunth et al 1998; Gonzalez-Delgado et al 1998). FUSE far-UV spectra recently obtained by our group shows that the outflows contain coronal-phase gas ($T \sim \text{few} \times 10^5 \text{K}$), as probed with the OVI$\lambda\lambda1032,1038$ doublet (Heckman et al and Martin et al, in preparation).

4. Estimates of Outflow Rates

4.1. X-ray Emission

While it is relatively straightforward to demonstrate qualitatively that a superwind is present, it is difficult to reliably calculate the rates at which mass, metals, and energy are being transported out by the wind. Several different types of data can be used, each with its own limitations and required set of assumptions.

X-ray imaging spectroscopy yields the superwind’s "emission integral" (the integral over the emitting volume of the square of the gas density). Presuming that the X-ray spectra are fit with the correct model for the hot gas it follows that the mass and energy of the X-ray gas scale as follows: $M_X \propto (L_X f)^{1/2}$ and $E_X \propto (L_X f)^{1/2} T_X (1 + \mathcal{M}^2)$. Here $f$ is the volume-filling-factor of the X-ray gas and $\mathcal{M}$ is its Mach number. Numerical hydrodynamical simulations of superwinds suggest that $\mathcal{M}^2 = 2$ to 3 (Strickland & Stevens 2000). The associated outflow rates ($\dot{M}_X$ and $\dot{E}_X$) can then be estimated by dividing $M_X$ and $E_X$ by the crossing time of the observed region: $t \sim (R/c_s \mathcal{M})$, where $c_s$ is the speed-of-sound.

If the X-ray-emitting gas is assumed to be volume-filling ($f \sim \text{unity}$), the resulting values for $\dot{E}_X$ are then very similar to the rate of kinetic energy depo-
sition by the starburst. This would imply that very little of this energy is lost due to radiative cooling. Similarly, the estimated values for $\dot{M}_X$ significantly exceed the rate at which massive stars directly return mass to the ISM: that is, the outflow has to be strongly “mass-loaded” with ambient interstellar gas ($l \sim 5$ to 10, typically). The implied outflow rates are then similar to the estimated star-formation rates (e.g. Martin 1999).

The high spatial resolution data provided by *Chandra* is proving to be quite instructive in testing the assumptions described above. In particular, observations of the outflow in the prototypical starburst/superwind galaxy NGC253 (Strickland et al 2000) show that the X-ray emission in the outflow is limb-brightened and coincident with the H$\alpha$ filaments (Figure 1). We argue that the X-rays arise at the turbulent interface (mixing layer) between a very fast, hot, and tenuous wind fluid (whose X-ray emission is undetectably faint) and the walls of the hollow cavity carved by this wind. On morphological and physical grounds we argue that $f$ is of-order $10^{-1}$ for the observed X-ray-emitting gas. If this is true in general, it would mean that previous estimates of $\dot{M}_X$ and $\dot{E}_X$ are overestimated by a factor of $\sim 3$. The majority of the outflow’s energy would reside in a largely invisible fluid (shades of dark matter!).

In order to estimate a rate at which metals are transported out, we have to know the metallicity of the hot gas. It seems clear that the bulk of the mass of the X-ray emitting material is provided by ambient material that has been heated in some way by the superwind. Thus, we would expect this material to have roughly solar abundances. This is at odds with some X-ray analyses (e.g. Ptak et al 1997), but my colleagues and I would argue that the current X-ray data are indeed consistent with rather normal $\sim$solar abundances (Weaver, Heckman, & Dahlem 2000; Strickland & Stevens 2000). The superior capabilities of the *Chandra* and *XMM-Newton* X-ray observatories may be able to settle this matter.

### 4.2. Optical Emission

Optical data on the warm ($T \sim 10^4$ K) ionized gas can be used to determine the outflow rates $\dot{M}$ and $\dot{E}$ in a way that is quite analogous to the X-ray data. In this case, the outflow velocities can be directly measured kinematically from spectroscopy. They range from $\sim 10^2$ km s$^{-1}$ in starbursting dwarf galaxies (Marlowe et al 1995; Martin 1998) to a few $\times 10^2$ to $10^3$ km s$^{-1}$ in powerful starbursts (e.g. Heckman, Armus, & Miley 1990). Martin (1999) found the implied values for $\dot{M}$ are comparable to (and may even exceed) the star-formation rate.

In favorable cases, the densities and thermal pressures can be directly measured in the optical emission-line clouds using density- and temperature-sensitive ratios of emission lines. The thermal pressure in these clouds traces the ram-pressure in the faster outflowing wind that is accelerating them (hydrodynamical simulations suggest that $P_{\text{ram}} = \Psi P_{\text{cloud}}$, where $\Psi = 1$ to 10). Thus, for a wind with a mass-flux $\dot{M}$ that freely flows at a velocity $v$ into a solid angle $\Omega$, we have

$$\dot{M} = \Psi P_{\text{cloud}} \Omega r^2/v$$

$$\dot{E} = 0.5\Psi P_{\text{cloud}} \Omega r^2 v$$
Figure 1.  *Chandra* ACIS soft (0.3 to 2 keV) image of the center of NGC253 shown in white contours and a logarithmically-scaled Hα image in grey-scale. Tic marks are separated by 30 arcsec (380 pc). Note the similarity between the two images, and the strong limb-brightening in the southeast “outflow cone”. See Strickland et al (2000).
Based on observations and numerical models, the values $v \sim 10^3$ km s$^{-1}$, $\Psi \sim$ a few, and $\Omega/4\pi \sim$ a few tenths are reasonable. The radial pressure profiles $P_{\text{cloud}}(r)$ measured in superwinds by Heckman, Armus, & Miley (1990) and Lehnert & Heckman (1996) then imply that $\dot{M}$ is comparable to the star-formation rate (requiring $l = 5$ to $10$) and that $\dot{E}$ is comparable to the starburst kinetic-energy injection rate (implying that radiative losses are not severe).

Rigorously determined metallicities for the optical emission-line material are not available. However, comparisons of the observed spectra to shock or photoionization models imply that the abundances are consistent with those in the ambient ISM of the host galaxy (e.g. subsolar in dwarfs and roughly solar in the more massive galaxies).

4.3. Interstellar Absorption-Lines

The use of interstellar absorption-lines to determine outflows rates offer several distinct advantages. First, since the gas is seen in absorption against the background starlight, there is no possible ambiguity as to the sign (inwards or outwards) of any radial flow that is detected, and the outflow speed can be measured directly. Second, the strength of the absorption will be related to the column density of the gas. In contrast, the X-ray or optical surface-brightness of the emitting gas is proportional to the emission-measure. Thus, the absorption-lines more fully probe the whole range of gas densities in the outflow, rather than being strongly weighted in favor of the densest material (which may contain relatively little mass). Finally, provided that suitably bright background sources can be found, interstellar absorption-lines have been used to study outflows in high-redshift galaxies where the associated X-ray or optical emission may be undetectably faint (see above).

The biggest obstacle to estimating outflows rates is that the strong absorption-lines are usually saturated, so that their equivalent width is determined by the velocity dispersion and covering factor, rather than by the ionic column density. In the cases where the rest-UV region can be probed with adequate signal-to-noise (Pettini et al 2000; Heckman & Leitherer 1997), the total $HI$ column in the outflow can be measured by fitting the damping wings of the Lyman $\alpha$ interstellar line, while ionic columns may be estimated from the weaker (less saturated) interstellar lines. In the H2000 survey of the $NaD$ line, we estimated $NaI$ columns in the outflows based on the $NaD$ doublet ratio (Spitzer 1968), and we then estimated the $HI$ column assuming that the gas obeyed the same relation between $N_{HI}$ and $N_{NaI}$ as in the Milky Way. These $HI$ columns agreed with columns estimated independently from the line-of-sight color excess $E(B - V)$ toward the starburst, assuming a Galactic gas-to-dust ratio. From both the UV data and the $NaD$ data, the typical inferred values for $N_{HI}$ are of-order $10^{21}$ cm$^{-2}$.

We can then adopt a simple model of a constant-velocity, mass-conserving superwind flowing into a solid angle $\Omega_w$ at a velocity $\Delta v$ from a minimum radius ($r_*$ - taken to be the radius of the starburst within which the flow originates). This implies:

$$\dot{M} \sim 30(r_*/\text{kpc})(N_{HI}/10^{21}\text{cm}^{-2})(\Delta v/300\text{km/s})(\Omega_w/4\pi)M_\odot/\text{yr}$$
Based on this simple model, H2000 estimate that the implied outflow rates of cool atomic gas are comparable to the star-formation rates (e.g., several tens of solar masses per year in powerful starbursts). The flux of kinetic energy carried by this material is substantial (of-order $10^{-1}$ of the kinetic energy supplied by the starburst).

In the best-studied outflows it has been possible to get rough estimates of the metallicity of the cool atomic phase. In the high-redshift galaxy MS 1512-cB58, Pettini et al (2000) obtain $\sim 1/4$ solar, while Heckman & Leitherer (1997) find 20 to 50% solar in the outflow in the dwarf starburst NGC1705. These measures are consistent with the theoretical expectation that the cool component of the outflow is mostly ambient interstellar gas accelerated by the wind.

A bigger surprise is that the NaD survey of H2000 implies that a substantial amount of dust is being expelled along with the atomic gas. Figure 2 show the strong correlation between the depth of the blueshifted NaD absorption-line (a measure of the covering factor of the absorbing gas) and the line-of-sight reddening. The implied dust outflow rates are substantial (of-order $10^{-2}$ of the mass outflow rate, or typically 0.1 to 1 M\(_{\odot}\) per year in powerful starbursts).

4.4. Summary of Outflow Rates

In summary, the various techniques for estimating the outflow rates in superwinds rely on simplifying assumptions (not all of which may be warranted). On the other hand, it is gratifying that the different techniques do seem to roughly agree: the outflows carry mass out of the starburst at a rate comparable to the star-formation rate and kinetic/thermal energy out at a rate comparable to the rate supplied by the starburst.

Estimates of the rates at which metals and dust are carried out are more uncertain. It appears that the metallicity of a typical outflow is roughly solar, and that the dust-to-gas ratio in the cool atomic component of the outflow is similar to the Galactic value (e.g. dust $\sim 1\%$ by mass).

5. The Fate of Superwinds

The outflow rates in superwinds should not be taken directly as the rates at which mass, metals, and energy escape from galaxies and are transported into the intergalactic medium. After all, the observable manifestations of the outflow are produced by material still relatively deep within the gravitational potential of the galaxy’s dark matter halo.

One way of assessing the likely fate of the superwind material is to compare the observed or estimated outflow velocity to the estimated escape velocity from the galaxy (see Martin 1999; H2000). For an isothermal gravitational potential that extends to a maximum radius \( r_{\text{max}} \), and has a circular rotation velocity \( v_{\text{rot}} \), the escape velocity at a radius \( r \) is given by:

\[
\nu_{\text{esc}} = \left[ 2v_{\text{rot}}(1 + \ln(r_{\text{max}}/r)) \right]^{1/2}
\]
Figure 2. Plot of the normalized residual intensity at the center of the interstellar NaD λ5890 absorption-line ($I_{5890}$) vs. the log of the color of the optical continuum (the ratio of $F_\lambda$ at rest wavelengths of 6560 and 4860 Å). Points plotted as solid dots are the nuclei of infrared-bright starbursts and the other points are off-nuclear locations. See H2000 for details. The deeper the NaD line (higher covering factor), the more-reddened the background starlight. The correlation is obeyed by both the nuclear and off-nuclear regions. An unreddened starburst population should have $\log(C_{65}/C_{48}) = -0.3$. For a standard Galactic reddening curve, the implied $A_V$ ranges up to roughly 4 magnitudes for the most-reddened sight-lines. Typical uncertainties for the nuclear (extra-nuclear) data are indicated by the error-bar in the lower-left (upper-right) of the plot.
In the case of the interstellar absorption-lines, H2000 argued that the observed profiles were produced by material ablated off of ambient clouds at the systemic velocity and accelerated by the wind up to a terminal velocity represented by the most-blueshifted part of the profile. In the case of the X-ray data, we do not measure a Doppler shift directly, but we can define a characteristic outflow speed $v_X$ corresponding to the observed temperature $T_X$, assuming an adiabatic wind with a mean mass per particle $\mu$ (see Chevalier & Clegg 1985):

$$v_X \sim (5kT_{X}/\mu)^{1/2}$$

This is a conservative approach as it ignores the kinetic energy the X-ray-emitting gas already has (probably a factor typically 2 to 3 times its thermal energy - Strickland & Stevens 2000).

The results of comparing the outflow and escape velocities are shown in Figure 3 (see H2000), which suggests that the outflows can readily escape from dwarf galaxies, but possibly not from the more massive systems.

How far out from the starburst can the effects of superwinds be observed? In general, such tenuous material will be better traced via absorption-lines against background QSOs than by its emission (since the emission-measure will drop much more rapidly with radius than will the column density). To date, the only such experiment that has been conducted is by Norman et al (1996) who examined two sight-lines through the halo of the merger/starburst system NGC520 using HST to observe the MgII2800 doublet. Absorption was definitely detected towards a QSO with an impact parameter of $35h^{-1}_{70}$ kpc and possibly towards a second QSO with an impact parameter of $75h^{-1}_{70}$ kpc. Since NGC520 is immersed in tidal debris (as mapped in the HI 21cm line), it is unclear whether the MgII absorption is due to tidally-liberated or wind-ejected gas. We can expect the situation to improve in the next few years, as the Galex mission and the Sloan Digital Sky Survey provide us with $10^5$ new QSOs and starburst galaxies, and the Cosmic Origins Spectrograph significantly improves the UV spectroscopic capabilities of HST.

While a wind’s X-ray surface brightness drops rapidly with radius due to expansion and adiabatic cooling, its presence at large radii can be inferred if it collides with an obstacle. In the case of M82, Lehnert, Heckman, & Weaver (1999) show that a ridge of diffuse X-ray and Hα emission at a projected distance of 12 kpc from the starburst is most likely due to a wind/cloud collision in the galaxy halo. An even more spectacular example (Irwin et al 1987) is the peculiar tail of HI associated with the galaxy NGC3073 which points directly away from the nucleus of its companion: the prototypical superwind galaxy NGC3079 (60 $h^{-1}_{70}$ kpc away from NGC3073 in projection). Irwin et al (1987) proposed that the HI tail is being swept out of NGC3073 by the ram pressure of NGC3079’s superwind.

6. Implications of Superwinds

As discussed above, we now know that superwinds are ubiquitous in actively-star-forming galaxies in both the local universe, and at high-redshift. The outflows detected in the high-z Lyman Break galaxies are particularly significant,
Figure 3. Plot of the galaxy rotation speed vs. the inferred terminal velocity of the outflows (see H2000). The solid points are based on the NaD absorption-line profiles. The hollow points are estimated from the observed temperature of the hot X-ray-emitting gas (see text). Note that the two data sets are consistent with each other, imply that the outflow speed is independent of the host galaxy potential well depth, and thus suggest that outflows will preferentially escape from the least massive galaxies. The two diagonal lines indicate the galaxy escape velocity under the assumption that $v_{esc} = 2 v_{rot}$ and $v_{esc} = 3 v_{rot}$ respectively. Typical uncertainties in the X-ray (NaD) estimates of $v_{term}$ are shown by the error-bar on the bottom right (upper center).
since these objects may plausibly represent the sites where the majority of the stars and metals have been produced over the history of the universe (e.g. Adelberger & Steidel 2000). Even if the sub-mm SCUBA sources turn out to be a distinct population at high-z, their apparent similarity to local “ultraluminous galaxies” suggests that they too will drive powerful outflows (cf. Heckman et al 1996). With this in mind, let me briefly describe the implications of superwinds for the evolution of galaxies and the inter-galactic medium.

Figure 3 shows that the estimated outflow speeds in superwinds are \( v_{\text{wind}} \sim 300 \text{ to } 800 \text{ km s}^{-1} \), and are independent of the rotation speed of the “host galaxy” over the range \( v_{\text{rot}} = 30 \text{ to } 300 \text{ km s}^{-1} \). This strongly suggests that the outflows selectively escape the potential wells of the less massive galaxies. H2000 considered the simple model based on Lynden-Bell (1992) in which the fraction of starburst-produced metals that are retained by a galaxy experiencing an outflow is proportional to the galaxy potential-well depth for galaxies with escape velocities \( v_{\text{esc}} < v_{\text{wind}} \), and asymptotes to full retention for the most massive galaxies \( (v_{\text{esc}} > v_{\text{wind}}) \). For \( v_{\text{wind}} \) in the above range, such a simple prescription can reproduce the observed mass-metallicity relation for elliptical galaxies.

The selective loss of gas-phase baryons from low-mass galaxies via supernova-driven winds is an important ingredient in semi-analytic models of galaxy formation (e.g. Somerville & Primack 1999). It is usually invoked to enable the models to reproduce the observed faint-end slope of the galaxy luminosity function by selectively suppressing star-formation in low-mass dark-matter halos. A different approach is taken by Scannapieco, Ferrara, & Broadhurst (2000), who have argued that starburst-driven outflows can suppress the formation of dwarf galaxies by ram-pressure-stripping the gaseous baryons from out of the dark-matter halos of low-mass companion galaxies. The NGC3073/3079 interaction (Irwin et al 1987) may represent a local example.

H2000 also show that the simple Lynden-Bell (1992) model for a mass-dependent wind-driven loss of metals can (if applied to the population of elliptical galaxies and bulges in a cluster) deposit the required amount of observed metals in the intra-cluster medium. If the ratio of ejected metals to stellar spheroid mass is the same globally as in clusters of galaxies, we predicted that the present-day mass-weighted metallicity of a general intergalactic medium with \( \Omega_{\text{igm}} = 0.015 \) will be \( \sim 1/6 \) solar (see also Renzini 1997).

There is now a consensus that the inter-galactic medium has been significantly heated by a non-gravitational source (probably at rather early epochs). This “pre-heating” is required to explain the steep luminosity-temperature relation for the X-ray gas in galaxy clusters (e.g. Tozzi & Norman 2000), the existence of an entropy excess in the gas in the central regions of small clusters (Ponman, Cannon, & Navarro 1999), and the relative faintness of any contribution by the inter-galactic medium to the cosmic X-ray background (e.g. Pen 1999). The required amount of heating depends somewhat on the details and history of the heating process, but amounts to of-order 1 keV per baryon. It is interesting that this is just the amount produced by superwinds (assuming 100% heating efficiency!). A standard Salpeter IMF extending from 0.1 to 100 \( M_\odot \) produces about \( 10^{51} \) ergs of kinetic energy from supernovae per 80 \( M_\odot \) of low-mass stars (\( \leq 1 M_\odot \)). The present ratio of baryons in the intra-cluster medium
to baryons in low-mass stars is $\sim 6$ in clusters, so the amount of kinetic energy available in principle to heat the intra-cluster medium is then $10^{51}$ ergs per 480 $M_\odot$, or $\sim 1$ keV per baryon.

H2000 have summarized the evidence that starbursts are ejecting significant quantities of dust. If this dust can survive a trip into the intergalactic medium and remain intact for a Hubble time, they estimated that the upper bound on the global amount of intergalactic dust is $\Omega_{dust} \sim 10^{-4}$. While this is clearly an upper limit, it is a cosmologically interesting one: Aguirre (1999) argues that dust this abundant could in principle obviate the need for a positive cosmological constant, based on the Type Ia supernova Hubble diagram.

It seems clear that superwinds play a fundamental role in the evolution of galaxies and the inter-galactic medium.

Acknowledgments. I would like to thank my principal collaborators on the work described in this contribution: L. Armus, M. Dahlem, R. Gonzalez-Delgado, M. Lehnert, C. Leitherer, A. Marlowe, C. Martin, G. Meurer, C. Norman, K. Sembach, D. Strickland, and K. Weaver. This work has been supported in part by grants from the NASA LTSA program and the HST, ROSAT, ASCA, and Chandra GO programs.

References

Adelberger, C. & Steidel, C. 2000, ApJ, in press [astro-ph/0001126]
Aguirre, A. 1999, ApJ, 525, 58
Carollo, M. & Danziger, I.J. 1994, MNRAS, 270, 523
Chevalier, R. & Clegg A. 1985, Nature, 317, 44
Dahlem, M., Weaver, K., & Heckman, T. 1998, ApJS, 118, 401
Franx, M., Illingworth, G., Kelson, D., van Dokkum, P., & Tran, K.-V. 1997, ApJL, 486, L75
Gonzalez-Delgado, R., Leitherer, C., Heckman, T., Lowenthal, J., Ferguson, H., & Robert, C. 1998, ApJ, 495, 698
Heckman, T., Armus, L., & Miley, G. 1990, ApJS, 74, 833
Heckman, T., Dahlem, M., Eales, S., Fabbiano, G., & Weaver, K. 1996, ApJ, 457, 616
Heckman, T., & Leitherer, C. 1997, AJ, 114, 69
Heckman, T., Lehner, M., Strickland, D., & Armus, L. 2000, ApJ, in press [astro-ph/0002526]
Irwin, J., Seaquist, E., Taylor, A., & Duric, N. 1987, ApJL, 313, L91
Kennicutt, R. 1998, ApJ, 498, 541
Kunth, D., Mas-Hesse, J., Terlevich, E., Terlevich, R., Lequeux, J., & Fall, S.M. 1998, A&A, 334, 11
Lehnert, M. D., & Heckman, T. M. 1996, ApJ, 462, 651
Lehnert, M., Heckman, T., & Weaver, K. 1999, ApJ, 523, 575
Lynden-Bell, D. 1992, in “Elements and the Cosmos”, ed. M. Edmunds & R. Terlevich (Cambridge University Press: New York), p. 270
Marlowe, A., Heckman, T., Wyse, R., & Schommer, R. 1995, ApJ, 438, 563
Martin, C. 1998, ApJ, 506, 222
Martin, C. 1999, ApJ, 513, 156
Heckman

Meurer, G., Heckman, T., Leitherer, C., Lowenthal, J., & Lehnert, M. 1997, AJ, 114, 54
Moran, E., Lehnert, M., & Helfand, D. 1999, ApJ, 526, 649
Nath, B., & Trentham, N. 1997, MNRAS, 291, 505
Norman, C., Bowen, D., Heckman, T., Blades, J.C., & Danly, L. 1996, ApJ, 472, 73
Pen, U. 1999, ApJL, 510, L1
Pettini, M., Kellogg, M., Steidel, C., Dickinson, M., Adelberger, K., & Giavalisco, M. 1998, ApJ, 508, 539
Pettini, M., Steidel, C., Adelberger, C., Dickinson, M., & Giavalisco, M. 2000, ApJ, 528, 96
Ponman, T., Cannon, D., & Navarro, J. 1999, Nature, 397, 135
Ptak, A., Serlemitsos, P., Yaqoob, T., Mushotzky, R., & Tsuru, T. 1997, AJ, 113, 1286
Read, A., Ponman, T., & Strickland, D. 1997, MNRAS, 286, 626
Renzini, A. 1997, ApJ, 488, 35
Scannapieco, E., Ferrara, A., & Broadhurst, T. 2000, ApJL, 536, L11
Seaquist, E., & Odegard, N. 1991, 369, 320
Somerville, R., & Primack, J. 1999, MNRAS, 310, 1087
Spitzer, L. 1968, “Diffuse Matter in Space”, (Interscience: New York)
Strickland, D., & Stevens, I. 2000, MNRAS, 314, 511
Tozzi, P. & Norman, C. 2000, ApJ, in press (astro-ph/0008182)
Wang, B. 1995, ApJ, 444, 590
Weaver, K., Heckman, T., & Dahlem, M. 2000, ApJ, 534, 684