*RevMexAA (Serie de Conferencias)*, **17**, 47–55 (2003)

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

# STARBURST-DRIVEN GALACTIC WINDS

Timothy M. Heckman[1]

## RESUMEN

En esta contribución resumo el conocimiento actual sobre la naturaleza de los vientos galácticos impulsados por brotes de formación estelar (supervientos). Los supervientos son flujos complejos y multifásicos de gas frío, templado y caliente, así como de polvo y plasmas relativistas magnetizados. Las manifestaciones observacionales de los supervientos son resultado de la interacción hidrodinámica entre el fluido del viento primario y el medio ambiente interestelar. Los supervientos son ubicuos en galaxias cuya tasa de formación estelar por unidad de área es mayor que unas $10^{-1}$ $M_\odot$ año$^{-1}$ kpc$^{-2}$. Este criterio lo cumplen tanto los brotes estelares locales como las galaxias Lyman Break a altos z. Varios conjuntos independientes de datos y técnicas indican que la tasa total de pérdida de masa y energía por los supervientos es comparable a la tasa de formación estelar en el brote, y a la tasa de inyección de energía mecánica respectivamente. Las velocidades del flujo de material interestelar llevado por el viento varían entre $\sim 10^2$ y $10^3$ km/s, pero el flujo primario del viento mismo puede alcanzar velocidades de $\sim$3000 km s$^{-1}$. Los datos en rayos X y UV lejano ($FUSE$) implican que las pérdidas radiativas no son importantes en los supervientos. Es posible que los supervientos hayan establecido la relación masa-metalicidad en galaxias elípticas y bulbos, que hayan contaminado el medio intergaláctico actual hasta una metalicidad de $\sim$ 10 a 30% la solar, que hayan calentado el medio intergaláctico, y que hayan expulsado suficiente polvo al medio inter- galáctico como para tener consecuencias observables.

## ABSTRACT

In this contribution I summarize our current knowledge of the nature and significance of starburst-driven galactic winds ("superwinds"). Superwinds are complex multiphase outflows of cool, warm, and hot gas, dust, and magnetized relativistic plasma. The observational manifestations of superwinds result from the hydrodynamical interaction between the primary energy-carrying wind fluid and the ambient interstellar medium. Superwinds are ubiquitous in galaxies in which the global star-formation rate per unit area exceeds roughly $10^{-1}$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$. This criterion is met by local starbursts and the high-z Lyman Break galaxies. Several independent datasets and techniques imply that the total mass and energy outflow rates in a superwind are comparable to the starburst's star-formation-rate and mechanical energy injection rate, respectively. Outflow speeds in interstellar matter entrained in the wind range from $\sim 10^2$ to $10^3$ km/s, but the primary wind fluid itself *may* reach velocities as high as $\sim$3000 km s$^{-1}$. The available X-ray and far-UV ($FUSE$) data imply that radiative losses in superwinds are not significant. Superwinds may have established the mass-metallicity relation in ellipticals and bulges, polluted the present-day inter-galactic medium to a metallicity of $\sim$ 10 to 30% solar, heated the inter-galactic medium, and ejected enough dust into the inter-galactic medium to have observable consequences.

*Key Words:* **GALAXIES: EVOLUTION — GALAXIES: INTERGALACTIC MEDIUM — GALAXIES: ISM — GALAXIES: STARBURST**

## 1. INTRODUCTION

By now, it is well-established that galactic-scale outflows of gas ("superwinds") are commonplace in the most actively star- forming galaxies in both the local universe (e.g. Lehnert & Heckman 1996; Dahlem, Weaver, & Heckman 1998; Veilleux et al. 1998) and at high redshift (e.g. Pettini et al. 2001).

In this contribution, I will review the dynamical evolution of superwinds (section 2), the nature and origin of their emission and absorption (section 3), their demographics (section 4), their estimated outflow rates (section 5), and their likely fate (section 5). Finally, I will describe their potential implications 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 (Leitherer & Heckman 1995). For typical starburst

---

[1] Department of Physics & Astronomy, Johns Hopkins University

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

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.

The dynamical evolution of a starburst-driven outflow has been extensively discussed (e.g. Chevalier & Clegg 1985; Suchkov et al. 1994; Wang 1995; Tenorio-Tagle & Munzo-Tunon 1998; Strickland & Stevens 2000). Briefly, the deposition of mechanical energy by supernovae and stellar winds results in an over-pressured cavity of hot gas inside the starburst. The temperature of this hot gas is given by:

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

for a mass (kinetic energy) deposition rate of $\dot{M}$ ($\dot{E}$). The "mass-loading" term $\mathcal{L}$ 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. $\mathcal{L} \geq 1$).

This hot gas will expand, sweep up ambient material and thus develop a bubble-like structure. The predicted expansion speed of the outer wall of such an adiabatic wind-blown superbubble is of-order $10^2$ km s$^{-1}$:

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

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).

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 Raleigh-Taylor instabilities will then lead to the fragmentation of the bubble's outer wall (e.g. MacLow, McCray, & Norman 1989). 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$^{-1}$:

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

The wind will carry entrained interstellar material out of the galactic disk and into the halo, and will also interact with ambient halo gas (e.g. Suchkov et al. 1994; Strickland & Stevens 2000). An interstellar cloud will be accelerated by the wind's ram pressure to velocities of few hundred km s$^{-1}$:

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

for a cloud with a column density $N_{cloud,21}$ (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 $\dot{p_{34}}$ (units of $10^{34}$ dynes) into a solid angle $\Omega_w$ (steradian).

## 3. THE OBSERVATIONAL MANIFESTATIONS OF SUPERWINDS

Based on the above picture, we can broadly classify the gas in a superwind into two categories. The first is the ambient interstellar medium, and the second is the the volume-filling energetic fluid created by the thermalization of the starburst's stellar eject. The thermal and kinetic energy of this fluid is the "piston" that drives the outflow and dominates its energy budget. The observed manifestations of superwinds arise when the primary wind fluid interacts hydrodynamically with relatively dense ambient interstellar gas.

This has long been known to apply to the optical emission-line gas. In the case of superbubbles, the limb-brightened morphology and the classic "Doppler ellipses" seen in long-slit spectroscopy of dwarf starburst galaxies (e.g. Meurer et al. 1992; Marlowe et al. 1995; Martin 1998) are consistent with the standard picture of emission from the shocked outer shell of a classic wind-blown bubble (e.g. Weaver et al. 1977). Typical expansion velocities are 50 to 100 km s$^{-1}$. Similarly, the morphology and kinematics of the emission-line gas in the outflows in edge-on starbursts like M 82, NGC 253, NGC 3079, and NGC 4945 imply that this material is flowing outward on the surface of a hollow bi-polar structure whose apices correspond to the starburst (e.g. Heckman, Armus, & Miley 1990; Shopbell & Bland-Hawthorn 1998; Cecil et al. 2001). The deprojected outflow speeds range from a few hundred to a thousand km s$^{-1}$. This material is presumably ambient gas that has been entrained into the boundary layers of the bipolar hot wind, or perhaps the side walls of a ruptured superbubble (e.g. Suchkov et al. 1994; Strickland & Stevens 2000). In both superbubbles and superwinds, the optical emission-line gas is excited by some combination of wind-driven shocks and photoionization by the starburst.

Prior to the deployment of the *Chandra* X-ray observatory, it was sometimes assumed that the soft X-ray emission associated with superbubbles and superwinds represented the primary wind fluid that filled the volume bounded by the emission-line gas. If so, its relatively low temperature (typically 0.5 to 1 kev) and high luminosity ($\sim 10^{-4} L_{bol}$) required that substantial mass-loading had occurred inside

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

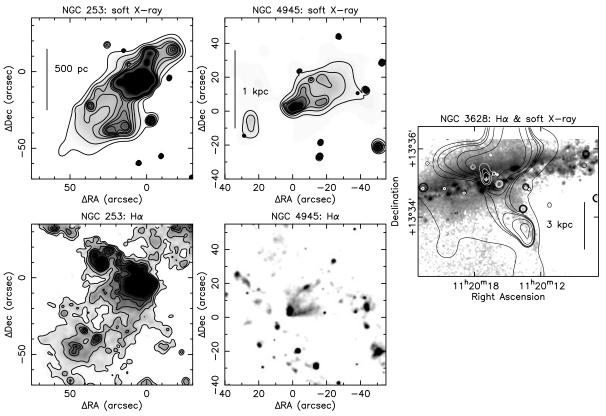

Fig. 1. Soft X-ray and Hα emission in several edge-on starburst galaxies, showing the spatial similarities between the two phases. NGC 253 & NGC 4945 have kpc-scale limb-brightened nuclear outflow cones (the opposite outflow cone is obscured in both cases) with a close match between X-ray & Hα emission. In NGC 3628 a 5 kpc-long Hα arc on the eastern limb of the wind is matched by an offset X-ray filament.

the starburst ($\mathcal{L} \sim 10$). The situation is actually more complex. The superb imaging capabilities of *Chandra* demonstrate that the X-ray-emitting material bears a very strong morphological relationship to the optical emission-line gas (Strickland et al. 2000,2002a,b; Martin, Kobulnicky, & Heckman 2002; Cecil, Bland-Hawthorn, & Veilleux 2002). The X-ray gas also shows a limb-brightened filamentary structure, and is either coincident with, or lies just to the "inside" of the emission-line filaments (Fig. 1). Thus, the soft X-rays could arise in regions in which hydrodynamical processes at the interface between the wind and interstellar medium have mixed a substantial amount of dense ambient gas into the wind fluid, greatly increasing the local X-ray emissivity. Alternatively, the filaments may represent the side walls of a ruptured superbubble left behind as the wind blows-out of a "thick-disk" component in the interstellar medium. In this case the Hα emission might trace the forward shock driven into the halo gas and the X-rays the reverse shock in the wind fluid (see Lehnert, Heckman, & Weaver 1999).

In the particular case of a wind-blown superbubble, Chu & Mac Low (1990) derive an estimate for the soft X-ray luminosity from the conductively heated interface between the outer shell of cooled swept-up material (the presumptive source of the optival line emission) and the hot thermalized wind fluid interior to the shell:

$$L_x \sim 1.8 \times 10^{40} Z \dot{E}_{42}^{33/35} n_0^{17/35} t_7^{19/35} erg/s$$

where Z is the metallicity (in solar units) of the emitting material. This predicts X-ray luminosities of-order $10^{-2}$ of $\dot{E}$, soft X-ray luminosities that are similar to the Hα emission-line luminosity from the outer radiative shock, and a close morphological connection between the X-ray and optical emission. These predictions agree with the data, although clearly a spherically symmetric expansion into a uniform medium is a gross over-simplification of the actual situation.

Ambient interstellar material accelerated by the wind can also give rise to blueshifted interstellar absorption-lines in local starbursts. Our (Heckman et al. 2000) survey of the NaI$\lambda$5893 feature in a sample of several dozen starbursts showed that the absorption-line profiles in the outflowing interstellar gas spanned the range from near the galaxy systemic velocity to a typical maximum blueshift of 400 to 600 km s$^{-1}$. Similar results were obtained for a sample of ultra-luminous galaxies observed by Rupke, Veilleux, & Sanders (2002). We argued this represented the terminal velocity reached by interstellar clouds accelerated by the wind's ram pressure. Very similar kinematics are observed in vacuum-UV absorption-lines in local starbursts (Heckman & Leitherer 1997; Kunth et al. 1998; Gonzalez-Delgado et al. 1998; Tremonti et al 2002a). This material (Figure 2) ranges from neutral gas probed by species like OI and CII to coronal-phase gas probed by OVI (Heckman et al. 2001a,b). Heckman et al. (2000) showed that there are substantial amounts of outflowing dust associated with the neutral phase of the superwind. Radiation pressure may play an important role in accelerating this material (e.g. Aguirre 1999).

Extended radio-synchrotron halos around starbursts imply that there is a magnetized relativistic component of the outflow. In the well-studied case of M 82, this relativistic plasma has evidently been advected out of the starburst by the primary energy-carrying wind fluid (Seaquist & Odegard 1991). The situation in NGC 253 is less clear (Beck et al. 1994; Strickland et al. 2002a)

## 4. SUPERWIND DEMOGRAPHICS

Lehnert & Heckman (1996) discussed the analysis of the optical emission-line properties of a sample of ∼50 disk galaxies selected to be bright and warm in the far-infrared (active star-formers) and to be viewed within ∼ 30° of edge-on. They defined several indicators of minor-axis outflows: (1) an excess of ionized gas along the minor axis (from Hα images); (2) emission-line profiles that were broader along the galaxy minor axis than along the major axis;

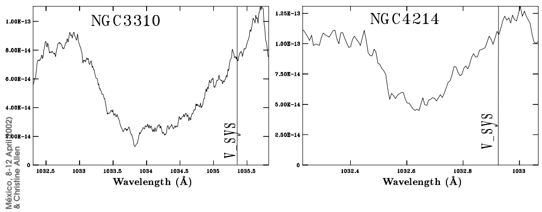

Fig. 2. *FUSE* spectra of the OVI$\lambda$1031.9 interstellar absorption-line, tracing outflowing coronal-phase gas. The absorption covers the range from $v_{sys}$ to a maximum blueshift of ~700 km s$^{-1}$ in the powerful starburst NGC 3310 (left panel) and ~140 km s$^{-1}$ in the starbursting irregular galaxy NGC 4214 (right panel).

(3) emission-line ratios that were more "shock-like" along the galaxy minor axis than the major axis. 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).

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 HI column). Apart from the dwarf galaxy NGC 55, 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 (see also Read, Ponman, & Strickland 1997). This sample has be reinvestigated using available *Chandra* data by Strickland et al (2002b), who have also included several "normal" edge-on spirals. They find that detectable soft X-ray emission in the halo is only present in the starburst galaxies (as defined by either short gas consumption times or high rates of star formation per unit area).

Heckman et al. (2000) obtained spectra of 19 starbursts in which the NaI$\lambda$5893 (NaD) absorption feature was produced primarily by interstellar gas (rather than stars). In 12 of these (63%) the NaD centroid was blueshifted by $\sim 10^2$ to $10^3$ km/s relative to the galaxy systemic velocity, and this fraction rose to 79% in galaxies viewed from within 60° of face-on. No comparably redshifted absorption was seen in any galaxies.

At high-redshift, the only readily available tracers of superwinds are the interstellar absorption-lines and the Ly$\alpha$ emission-line in the rest-frame ultraviolet. As shown by Franx et al. (1997) and Pettini et al. (2001) the Lyman Break galaxies generically show interstellar absorption-lines (Ly$\alpha$ emission-lines) that are blueshifted (redshifted) by typically several hundred relative to the estimated galaxy systemic velocity. These galaxies strongly resemble local starbursts in their high rate of star-formation per unit area (Meurer et al. 1997).

*In summary, superwinds are ubiquitous in galaxies with star-formation-rates per unit area* $\Sigma_* \geq 10^{-1}\ M_\odot\ yr^{-1}\ kpc^{-2}$. *Starbursts and the Lyman Break galaxies surpass this threshold, while the disks of ordinary present-day spiral galaxies do not (Kennicutt 1998).*

## 5. ESTIMATES OF OUTFLOW RATES

While it is relatively straightforward to demonstrate that a superwind is present, it is more difficult to robustly 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 Emission:** X-ray imaging spectroscopy yields the superwind's "emission integral". 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 ($f \sim$ unity), the resulting values for $\dot{E}_X$ and $\dot{M}_X$ are then very similar to the starburst's rates of kinetic energy deposition and star formation respectively. As described above, *Chandra* images (Fig. 1) show that the X-ray-emitting gas does not have unit volume filling factor. On morphological and physical grounds we have argued that $f$ is of-order $10^{-1}$. This would mean that previous estimates of $\dot{M}_X$ and $\dot{E}_X$ are overestimated by a factor of $\sim 3$.

**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. Martin (1999) found the implied values for $\dot{M}$ are comparable to (and may even exceed) the star-formation rate.

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

In favorable cases, the densities and thermal pressures can be directly measured in the optical emission-line clouds using the appropriate 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 $P_{ram} = \Psi P_{cloud}$, 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

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

$$\dot{E} = 0.5 \Psi P_{cloud} \Omega r^2 v$$

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 $P_{cloud}(r)$ measured in superwinds by Heckman, Armus, & Miley (1990) and Lehnert & Heckman (1996) then imply that $\dot{M}$ is comparable to the star-formation rate and that $\dot{E}$ is comparable to the starburst kinetic-energy injection rate (implying that radiative losses are not severe).

**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 (e.g. Fig. 2). 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).

The biggest obstacle to estimating outflows rates is that the strong absorption-lines are usually saturated, so that their equivalent width is determined primarily 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 Ly$\alpha$ interstellar line, while ionic columns may be estimated from the weaker (less saturated) interstellar lines. In the Heckman et al. (2000) 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 superwind flowing into a solid angle $\Omega_w$ at a velocity $v$ from a minimum radius $r_*$ (taken to be the radius of the starburst within which the flow originates). This implies:

$$\dot{M} \sim 30 r_{*,kpc} (N_H/10^{21})(v/300km/s)(\Omega_w/4\pi) M_\odot/yr$$

$$\dot{E} \sim 10^{42} r_{*,kpc} (N_H/10^{21})(v/300km/s)^3 (\Omega_w/4\pi) erg/s$$

Based on this simple model, Heckman et al. (2000) estimated 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). We also estimated that ∼1% of the mass in the outflow is the form of dust grains. Rupke, Veilluex, & Sanders (2002) obtained similar estimates for the outflows in ultra-luminous infrared galaxies.

**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.*

## 6. 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. We know very little about the gaseous halos of galaxies, and it is possible that this halo gas could confine a wind that has blown-out of a galactic disk (Silich & Tenorio-Tagle 2001).

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

A necessary condition for wind escape is that radiative losses are not severe enough to drain energy from the wind, causing it to stall (e.g. Wang 1995). The X-ray luminosity of the wind is typically of-order 1% of the rate at which the starburst supplies kinetic energy. Thus, radiative losses from hot ($T \geq 10^6$ K) gas will not be dynamically significant. The radiative cooling curve peaks in the so-called "coronal" regime ($T \sim 10^5$ to $10^6$ K). The *FUSE* mission has now provided the first probe of coronal-phase gas in starbursts and their winds via the OVI$\lambda$1032,1038 doublet (Figure 2). Our analysis of these data imply that in no case is radiative cooling by the coronal gas sufficient to quench the outflow (Heckman et al. 2001a).

In the absence of severe radiative cooling, one instructive 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. For an isothermal gravitational potential that extends to a maximum radius $r_{max}$, and has a circular rotation velocity $v_{rot}$, the escape velocity at a radius $r$ is given by:

$$v_{esc} = v_{rot}[2(1 + ln(r_{max}/r))]^{1/2}$$

In the case of the interstellar absorption-lines, Heckman et al. (2000) argued that the observed profiles were produced by material ablated off ambient clouds 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 $\mu$ (Chevalier & Clegg 1985):

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

This is a conservative assumption 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). Based on this approach, Heckman et al. (2000) and Martin (1999) found that the observed outflow speeds are independent of the galaxy rotation speed and have typical values of 400 to 800 km s$^{-1}$. This suggests that the outflows can readily escape from dwarf galaxies, but possibly not from the more massive systems.

In all these discussions it is important to keep in mind the multiphase nature of galactic winds. It is possible (even likely) that the question of "escape" will have a phase-dependent answer. The relatively dense ambient interstellar material seen in absorption-lines, in optical line emission, and perhaps soft X-rays may be propelled only as far as the halo and then return to the disk. In contrast, the primary energy-carrying wind fluid (which could be flowing out at velocities of up to 3000 km s$^{-1}$) could escape even the deepest galactic potentials and carry away much of the kinetic energy and metals supplied by the starburst. Moreover, for a realistic geometry, it is clearly much easier for a wind to blow-out of a galaxy's interstellar medium than than to blow it away (e.g. De Young & Heckman 1994; MacLow & Ferrara 1999).

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 NGC 520 using HST to observe the MgII$\lambda$2800 doublet. Absorption was definitely detected towards a QSO with an impact parameter of 35 $h_{70}^{-1}$ kpc and possibly towards a second QSO with an impact parameter of 75 $h_{70}^{-1}$ kpc. Since NGC 520 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 M 82, Lehnert, Heckman, & Weaver (1999) show that a ridge of diffuse X-ray and H$\alpha$ 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 NGC 3073 which points directly away from the nucleus of its companion: the superwind galaxy NGC 3079 (50 $h_{70}^{-1}$ kpc away from NGC 3073 in projection). Irwin et al. (1987) proposed that the HI tail is swept out of NGC 3073 by the ram pressure of NGC 3079's superwind.

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

## 7. 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, since these objects may plausibly represent the production sites of much of the stars and metals in today's universe (Steidel el al. 1999). 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 (Heckman et al. 1996,2000; Rupke, Veilluex, & Sanders 2002). With this in mind, let me briefly describe the implications of superwinds for the evolution of galaxies and the inter-galactic medium.

Martin (1999) and Heckman et al. (2000) estimated outflow speeds of the observed neutral, warm, and hot phases in superwinds of $\sim$ 400 to 800 km s$^{-1}$, independent of the rotation speed of the "host galaxy" over the range $v_{rot}$ = 30 to 300 km s$^{-1}$. This strongly suggests that the outflows selectively escape the potential wells of the less massive galaxies. This would provide a natural explanation for the strong mass-metallicity relation in present-day galaxies (e.g. Lynden-Bell 1992; Tremonti et al. 2002b; Garnett 2002).

As summarized above, the mass-outflow rate in entrained interstellar matter in a superwind is similar to the star-formation rate in the starburst. 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. Kauffmann, White, & Guiderdoni 1993; 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 (Kauffmann et al. 2002).

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 NGC 3073/3079 interaction (Irwin et al. 1987) may represent a local example.

A direct consequence of a galactic-wind origin for the mass-metallicity relation in galactic spheroids is that a substantial fraction of the metals today should reside in the inter-galactic medium. This has been confirmed by X-ray spectroscopy of the intra-cluster medium (e.g. Finoguenov, Arnaud, & David 2001). The mean metallicity of the present-day inter-galactic medium is not known, but the presence of warm/hot metal-enriched intergalactic gas is demonstrated by the abundant population of OVI absorption-line clouds (Tripp, Savage, & Jenkins 2000). If the ratio of ejected metals to stellar spheroid mass is the same globally as in clusters of galaxies, then the present-day mass-weighted metallicity of a general intergalactic medium will be of-order $10^{-1}$ solar (e.g. Renzini 1997; Heckman et al. 2000). Early galactic winds have been invoked to account for the wide-spread presence of metals in the Ly$\alpha$ forest at high-redshift (e.g. Madau, Ferrara, & Rees 2001).

There is now a vigorous debate as to whether and by what means the inter-galactic medium might have been heated by non-gravitational sources at relatively early epochs (e.g. Ponman, Cannon, & Navarro 1999; Pen 1999; Tozzi & Norman 2001; Voit & Bryan 2001; Voit et al. 2002; Croft et al. 2001). As a benchmark, consider the maximum amount of energy per inter-galactic baryon that can be supplied by galactic winds. Star-formation with the local initial mass function (Kroupa 2001) produces about $10^{51}$ ergs of kinetic energy from supernovae per 30 $M_\odot$ 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 180 $M_\odot$, or $\sim$3 keV per baryon. A similar value would apply globally. While this upper bound is based on an assumption of unit efficiency for the delivery of supernova energy, I have emphasized above that the observed properties of superwinds demand high efficiency.

The physical state of much of the inter-galactic medium is regulated by the meta-galactic ionizing background. QSOs alone appear inadequate to produce the inferred background at the highest redshifts (e.g, Madau, Haardt, & Rees 1999). In principle, star-forming galaxies could make a significant contribution to the background, provided that a significant fraction of the ionizing radiation can escape the galaxy ISM. Steidel, Pettini, & Adelberger (2001) have have reported the detection of substantial amounts of escaping ionizing radiation in Lyman Break galaxies and have speculated that galactic superwinds clear out channels through which this radiation can escape. We (Heckman et al. 2001b) have considered the extant relevant data on present-day starbursts, and have concluded that galactic winds

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

may be necessary but not sufficient for creating a globally porous interstellar medium.

Heckman et al. (2000) 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). Dust this abundant is probably ruled out by the recent results by Riess et al. (2001), but intergalactic dust could well complicate the interpretation of the Type Ia supernova Hubble diagram.

I would like to thank my principal collaborators on the work described in this contribution: L. Armus, D. Calzetti, M. Dahlem, R. Gonzalez-Delgado, G. Kauffmann, 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 $HST$, $ROSAT$, $ASCA$, $Chandra$, $XMM-Newton$, and $FUSE$ GO programs.

## REFERENCES

Aguirre, A. 1999, ApJ, 525, 58
Beck, R., Carilli, C., Holdaway, M., & Klein, U. 1994, A&A, 292, 409
Cecil, G., Bland-Hawthorn, J., Veilleux, S., & Filippenko, A. 2001, ApJ, 555, 338
Cecil, G., Bland-Hawthorn, J., & Veilleux, S. 2002, ApJ, 576, 745
Chevalier, R. & Clegg A. 1985, Nature, 317, 44
Chu, Y.-H., & MacLow, M.-M. 1990, ApJ, 365, 510
Croft, R., Matteo, T., Dave, R., Hernquist, L., Katz, N., Fardal, M., & Weinberg, D. 2001, astro-ph/0010345
Dahlem, M., Weaver, K., & Heckman, T. 1998, ApJS, 118, 401
De Young, D., & Heckman, T. 1994, ApJ, 431, 598
Finoguenov, A., Arnaud, M., & David, L. 2001, ApJ, 555, 191
Franx, M., Illingworth, G., Kelson, D., van Dokkum, P., & Tran, K.-V. 1997, ApJ, 486, L75
Garnett, D. 2002, astro-ph/0209012
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., Lehnert, M., Strickland, D., & Armus, L. 2000, ApJS, 129, 493
Heckman, T., Sembach, K., Meurer, G., Strickland, D., Martin, C., Calzetti, D., & Leitherer, C. 2001a, ApJ, 554, 1021
Heckman, T., Sembach, K., Meurer, G., Leitherer, C., Calzetti, D., & Martin, C. 2001b, ApJ, 558, 56
Irwin, J., Seaquist, E., Taylor, A., & Duric, N. 1987, ApJ, 313, L91
Kauffmann, G., White, S., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kauffmann, G., Heckman, T., White, S., Charlot, S., Tremonti, C., Peng, E., Seibert, M., Brinkmann, J., Nichol, R., SubbaRao, M., & York, D. 2002, astro-ph/0205070
Kennicutt, R. 1998, ApJ, 498, 541
Kroupa, 2001, MNRAS, 322, 231
Kunth, D., Mas-Hesse, J., Terlevich, E., Terlevich, R., Lequeux, J., & Fall, S.M. 1998, A&A, 334, 11
Lehnert, M., & Heckman, T. 1996, ApJ, 462, 651
Lehnert, M., Heckman, T., & Weaver, K. 1999, ApJ, 523, 575
Leitherer, C., & Heckman, T. 1995, ApJS, 99, 173
Lynden-Bell, D. 1992, in Elements and the Cosmos, ed. M. Edmunds & R. Terlevich (Cambridge University Press: New York), 270
MacLow, M. & Ferrara, A. 1999, ApJ, 513, 142
MacLow, M., McCray, R., & Norman, M. 1989, ApJ, 337, 141
Madau, P., Ferrara, A., & Rees, M. 2001, ApJ, 555, 192
Madau, P., Haardt, F., & Rees, M. 1999, ApJ, 514, 648
Marlowe, A., Heckman, T., Wyse, R., & Schommer, R. 1995, ApJ, 438, 563
Martin, C.L. 1998, ApJ, 506, 222
Martin, C.L. 1999, ApJ, 513, 156
Martin, C.L., Kobulnicky, H., & Heckman, T., 2002, ApJ, 574, 663
Meurer, G., Freeman, K., Dopita, M., & Cacciari, C. 1992, AJ, 103, 60
Meurer, G., Heckman, T., Leitherer, C., Lowenthal, J., & Lehnert, M. 1997, AJ, 114, 54
Norman, C., Bowen, D., Heckman, T., Blades, J.C., & Danly, L. 1996, ApJ, 472, 73
Pen, U. 1999, ApJ, 510, L1
Pettini, M., Steidel, C., Adelberger, C., Dickinson, M., & Giavalisco, M. 2000, ApJ, 528, 96
Pettini, M., Shapley, A., Steidel, C., Cuby, J.-G., Dickinson, M., Moorwood, A., Adelberger, K., & Giavalisco, M. 2001, ApJ, 554, 981
Ponman, T., Cannon, D., & Navarro, J. 1999, Nature, 397, 135
Read, A., Ponman, T., & Strickland, D. 1997, MNRAS, 286, 626
Renzini, A. 1997, ApJ, 488, 35
Riess, A., et al. 2001, ApJ, 560, 49
Rupke, D., Veilleux, S., & Sanders, D. 2002, ApJ, 570, 588
Scannapieco, E., Ferrara, A., & Broadhurst, T. 2000, ApJ, 536, L11
Seaquist, E., & Odegard, N. 1991, ApJ, 369, 320

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

Shopbell, P., & Bland Hawthorn, J. 1998, ApJ, 493, 129
Silich, S., & Tenorio-Tagle, G. 2001, ApJ, 552, 91
Somerville, R., & Primack, J. 1999, MNRAS,, 310, 1087
Spitzer, L. 1968, Diffuse Matter in Space, (Interscience: New York)
Steidel, C., Pettini, M., & Adelberger, K. 2001, ApJ, 546, 665
Steidel, C., Adelberger, K., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Strickland, D., & Stevens, I. 2000, MNRAS, 314, 511
Strickland, D., Heckman, T., Weaver, K., & Dahlem, M. 2000, AJ, 120, 2965
Strickland, D., Heckman, T., Weaver, K., Dahlem, M., & Hoopes, C. 2002a, ApJ, 568, 689
Strickland, D., Heckman, T., Colbert, E., Hoopes, C., & Weaver, K. 2002b, in preparation
Suchkov, A., Balsara, D., Heckman, T., & Leitherer, C. 1994, ApJ, 430, 511
Tenorio-Tagle, G., & Munoz-Tunon, C. 1998, MNRAS, 293, 299
Tozzi, P. & Norman, C. 2001, ApJ, 546, 63
Tremonti, C., Leitherer, C., Heckman, T., & Calzetti, D. 2002a, in preparation
Tremonti, C., Heckman, T., Kauffmann, G., Charlot, S., and the SDSS collaboration, 2002b, in preparation
Tripp, T., Savage, B., & Jenkins, E. 2000, ApJ, 534, L1
Veilleux, S., Bland-Hawthorn, J., Cecil, G., & Shopbell, P. 1998, in IAU Symp. 184, ed. Y. Sofue (Kluwer: Dordrecht), 417
Voit, G.M., & Bryan, G. 2001, Nature, 414, 425
Voit, G.M., Bryan, G., Balogh, M., & Bower, R. 2002, ApJ, 576, 601
Wang, B. 1995, ApJ, 444, 590
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377

Timothy M. Heckman: Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA (heckman@pha.jhu.edu).