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Galactic Winds: Near and Far

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Abstract. Multiwavelength data on star-forming galaxies provide strong evidence for large-scale galactic winds in both nearby and distant objects. The results from recent ground-based and space-borne programs are reviewed. The impact of these winds on the host galaxies and the surrounding environment is discussed in the context of galaxy evolution.

1. Introduction

Galactic winds that extend on a scale comparable to the host galaxies are now known to be a common feature both locally and at high redshifts. These winds are significant carriers of mass, momentum, and energies that may impact the formation and evolution of the host galaxies and the surrounding intergalactic medium. Given the scope of this conference, the present review focusses exclusively on starburst-driven winds. AGN-driven galactic winds, perhaps a very important phenomenon in the lives of galaxies with spheroids (Kormendy & Gebhardt 2001), are not discussed here (see, e.g., Veilleux et al. 2002a for a recent review of this topic). Due to space limitations, the emphasis of this review is on the recent ($\gtrsim$ 1998) literature. Readers interested in results from earlier studies may refer to the reviews by Strickland (2002) and Heckman (2002).

First, the basic physics of starburst-driven winds is described briefly in §2. An observational summary of the properties of local winds is given in the preamble to §3. The remainder of §3 describes detailed data on three well-studied cases of local starburst-driven winds, and summarizes the evidence for winds in luminous and ultraluminous infrared galaxies and distant Lyman break galaxies. This section often emphasizes the importance of using multiwavelength data to draw a complete picture of this complex multi-phase phenomenon. The impact of starburst-driven winds on the host galaxies and their environment is discussed briefly in §4. Here the focus of the discussion is on the existence and properties of the wind fluid and on the size of the "zone of influence" of these winds. A summary is given in §5.

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2. Basic Physics

The driving force behind starburst-driven winds is the mechanical energy from stellar winds and supernova events (e.g., Chevalier & Clegg 1985). This mechanical energy is quickly thermalized to produce a hot cavity with a temperature $\sim 10^8\ \Lambda^{-1}$ K, where $\Lambda = M_{\rm total}/M_{\rm ejecta} \geq 1$ is the mass-loading term. This over-pressured cavity expands through the ambient medium, sweeping this material up in the process to produce a bubble-like structure. The complex interaction between the wind and the ISM of the host galaxy has been the subject of several numerical simulations (e.g., MacLow & McCray 1988; Suchkov et al. 1994, 1996; MacLow & Ferrara 1999; D'Ercole & Brighenti 1999; Strickland & Stevens 2000; Silich & Tenorio-Tagle 2001). If radiative energy losses are negligible (probably a good assumption in some objects; e.g., Heckman et al. 2001), the bubble expands adiabatically through the galaxy ISM with a velocity $\sim 100\ n_0^{-0.2}\ \dot{E}_{42}^{0.2}\ t_7^{-0.4}$ km s^{-1}, where n_0 is the ambient nucleon density in cm^{-3}, $\dot{E}_{42}$ is the rate of deposition of mechanical energy in 10^{42} erg s^{-1}, and t_7 is the age of the bubble in 10^7 years (e.g., Weaver et al. 1977).

A powerful starburst may inject enough energy to produce a cavity of hot gas that can burst out of the disk ISM, at which point the dense walls of the bubble start accelerating outward, become Rayleigh-Taylor unstable, and break up into cloudlets and filaments. If halo drag is negligible (probably *not* a good assumption in general), the wind fluid may reach terminal velocities as high as $\sim 3000\ \Lambda^{-1}$ km s^{-1}, well in excess of the escape velocity of the host galaxy. In contrast, the terminal velocities of clouds accelerated by the wind are more modest, of order $\sim 600\ \dot{p}_{34}^{0.5}\ \Omega_w^{-0.5}\ r_{0,{\rm kpc}}\ N_{\rm cloud,21}^{-0.5}$, where $\dot{p}_{34}$ is the wind momentum flux in 10^{34} dynes, Ω_W is the solid angle of the wind in steradians, $r_{0,{\rm kpc}}$ is the initial position of the cloud in kpc, and $N_{\rm cloud,21}$ is the column density of the cloud in 10^{21} cm^{-2} (Strel'nitskii & Sunyaev 1973; Heckman et al. 2000).

A critical quantity in all of these calculations is the thermalization efficiency, or the percentage of the mechanical energy from the starburst that goes into heating the gas. Unfortunately, this quantity is poorly constrained observationally. Most simulations assume a thermalization efficiency of 100%, i.e. none of the energy injected by the starburst is radiated away. In reality, this efficiency depends critically on the environment, and is likely to be significantly less than 100% in the high-density environment of powerful nuclear starbursts (e.g., Thornton et al. 1998; Strickland & Stevens 2000; Silich, Tenorio-Tagle, & Muñoz-Tuñón 2003). Galactic magnetic fields may also "cushion" the effects of the starburst on the ISM, and reduce the impact of the galactic wind on the host galaxy and its environment (e.g., Tomisaka 1990; Ferrière et al. 1991; Slavin & Cox 1992; Mineshinge et al. 1993; Ferrière 1998).

3. Observed Properties of Galactic Winds

A great number of surveys have provided important statistical information on galactic winds in the local universe (e.g., Heckman, Armus, & Miley 1990; Veilleux et al. 1995; Lehnert & Heckman 1995, 1996; Gonzalez Delgado et al. 1998; Heckman et al. 2000, Rupke, Veilleux, & Sanders 2002, 2003, in prep.). Galaxy-scale winds are common among galaxies with global star formation rates per unit area $\Sigma_* \equiv SFR/\pi R_{\rm opt}^2 \gtrsim 0.1$ M$_\odot$ yr^{-1} kpc^{-2}, where $R_{\rm opt}$ is the optical radius. This general rule-of-thumb also appears to apply to ultra/luminous infrared galaxies (see §3.3) and distant Lyman break galaxies (see §3.4). "Quiescent" galaxies with global star formation rates per unit area below this threshold often show signs of galactic fountaining in the forms of warm, ionized extraplanar material a few kpc above or below the galactic disks (e.g., Miller & Veilleux 2003a, 2003b and references therein). The energy input from stellar winds and supernovae in these objects elevates some of the ISM above the disk plane, but is not sufficient to produce large-scale winds.

This rule-of-thumb is conservative since a number of known wind galaxies, including our own Galaxy (§3.1) and several dwarf galaxies, have $\Sigma_* << 0.1$ M$_\odot$ yr^{-1} kpc^{-2} (e.g., Hunter & Gallagher 1990, 1997; Meurer et al. 1992; Marlowe et al. 1995; Kunth et al. 1998; Martin 1998, 1999; see Kunth's and Martin's contributions at this conference). The production of detectable winds probably depends not only on the characteristics of the starburst (global *and* local Σ_*, starburst age), but also on the detailed properties of the ISM in the host galaxies (e.g., see the theoretical blowout criterion of MacLow & McCray 1988).

The winds in actively star-forming galaxies in the local universe show a very broad range of properties, with opening angles of $\sim 0.1 - 0.5 \times (4\pi$ sr), radii ranging from < 1 kpc to several 10s of kpc, outflow velocities of a few 10s of km s^{-1} to more than 1000 km s^{-1} (with clear evidence for a positive correlation with the temperature of the gas phase), total (kinetic and thermal) outflow energies of $\sim 10^{53} - 10^{57}$ ergs or 5 – 20% of the total mechanical energy returned to the ISM by the starburst, and mass outflow rates ranging from < 1 M$_\odot$ yr^{-1} to $>$ 100 M$_\odot$ and scaling roughly with the star formation rates (see §3.3 below).

In the remainder of this section, we discuss a few well-studied cases of galactic winds in the local universe and summarize the evidence for winds in luminous and ultraluminous infrared galaxies at low and moderate redshifts as well as in distant Lyman break galaxies.

3.1. The Milky Way

By far the closest case of a large-scale outflow is the wind in our own Galaxy. Evidence for a dusty bipolar wind extending ~ 350 pc ($\sim 1^\circ$) above and below the disk of our Galaxy has recently been reported by Bland-Hawthorn & Cohen (2003) based on data from the Midcourse Space Experiment (MSX). The position of the warm dust structure coincides closely with the well-known Galactic Center Lobe detected at radio wavelengths (e.g., Sofue 2000 and references therein). Simple arguments suggest that the energy requirement for this structure is of order $\sim 10^{55}$ ergs with a dynamical time scale of ~ 1 Myr.

Bland-Hawthorn & Cohen (2003) also argue that the North Polar Spur, a thermal X-ray/radio loop that extends from the Galactic plane to $b = +80^\circ$ (e.g., Sofue 2000), can naturally be explained as an open-ended bipolar wind, when viewed in projection in the near field. This structure extends on a scale of 10 – 20 kpc and implies an energy requirement of $\sim (1 - 30) \times 10^{55}$ ergs and a dynamical timescale of ~ 15 Myr, i.e. considerably longer than that of the smaller structure seen in the MSX maps. If confirmed, this may indicate that the Milky Way Galaxy has gone through multiple galactic wind episodes. Bland-Hawthorn & Cohen (2003) point out that the North Polar Spur would escape detection in external galaxies; it is therefore possible that the number of galaxies with large-scale winds has been (severely?) underestimated.

3.2. Nearby Starburst Galaxies

Two classic examples of starburst-driven outflows are described in this section to illustrate the wide variety of processes taking place in these objects.

M 82. This archetype starburst galaxy hosts arguably the best studied galactic wind. Some of the strongest evidence for the wind is found at optical wavelengths, where long-slit and Fabry-Perot spectroscopy of the warm ionized filaments above and below the disk shows line splittings of up to ~ 250 km s^{-1}, corresponding to deprojected velocities of order 525 – 655 km s^{-1} (e.g., McKeith et al. 1995; Shopbell & Bland-Hawthorn 1998). Combining these velocities with estimates for the ionized masses of the outflowing filamentary complex, the kinetic energy involved in the warm ionized outflow is of order $\sim 2 \times 10^{55}$ ergs or $\sim 1\%$ of the total mechanical energy input from the starburst. The ionized filaments are found to lie on the surface of cones with relatively narrow opening angles ($\sim 5 - 25°$) slightly tilted ($\sim 5 - 15°$) with respect to the spin axis of the galaxy. Deep narrow-band images of M82 have shown that the outflow extends out to at least 12 kpc on one side (e.g., Devine & Bally 1999), coincident with X-ray emitting material seen by *ROSAT* (Lehnert, Heckman, & Weaver 1999) and *XMM*-Newton (Stevens, Read, & Bravo-Guerrero 2003). The wind fluid in this object has apparently been detected by both *CXO* (Griffiths et al. 2000) and *XMM*-Newton (Stevens et al. 2003). The well-known H I complex around this system (e.g., Yun et al. 1994) may be taking part, and perhaps even focussing, the outflow on scales of a few kpc (Stevens et al. 2003). Recently published high-quality CO maps of this object now indicate that some of the molecular material in this system is also involved in the large-scale outflow (Walter, Weiss, & Scoville 2002; see also Garcia-Burillo et al. 2001). The outflow velocities derived from the CO data (~ 100 km s^{-1} on average) are considerably lower than the velocities of the warm ionized gas, but the mass involved in the molecular outflow is substantially larger (~ 3 x 10^8 M$_\odot$), implying a kinetic energy ($\sim 3 \times 10^{55}$ ergs) that is comparable if not larger than that involved in the warm ionized filaments. The molecular gas is clearly a very important dynamical component of this outflow.

NGC 3079. An outstanding example of starburst-driven superbubble is present in the edge-on disk galaxy, NGC 3079. High-resolution *HST* Hα maps of this object show that the bubble is made of four separate bundles of ionized filaments (Cecil et al. 2001). The two-dimensional velocity field of the ionized bubble material derived from Fabry-Perot data (Veilleux et al. 1994) indicates that the ionized bubble material is entrained in a mushroom vortex above the disk with velocities of up to ~ 1500 km s^{-1} (Cecil et al. 2001). A recently published X-ray map obtained with the *CXO* (Cecil, Bland-Hawthorn, & Veilleux 2002) reveals excellent spatial correlation between the hot X-ray emitting gas and the warm optical line-emitting material of the bubble, suggesting that the X-rays are being emitted either as upstream, standoff bow shocks or by cooling at cloud/wind conductive interfaces. This good spatial correlation between the hot and warm gas phases appears to be common in galactic winds (Strickland et al. 2000, 2002; Veilleux et al. 2003, and references therein). The total energy involved in the outflow of NGC 3079 appears to be slightly smaller than that in M 82, although it is a lower limit since the total extent of the X-ray emitting material beyond the nuclear bubble of NGC 3079 is not well constrained (Cecil et al. 2002). Contrary to M 82, the hot wind fluid that drives the outflow in NGC 3079 has not yet been detected, and evidence for entrained molecular gas is sparse and controversial (e.g., Irwin & Sofue 1992; Baan & Irwin 1995; Israel et al. 1998; but see Koda et al. 2002).

3.3. Luminous and Ultraluminous Infrared Galaxies.

Given that the far-infrared energy output of a (dusty) galaxy is a direct measure of its star formation rate, it is not surprising *a posteriori* to find evidence for large-scale galactic winds in several luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs; e.g., Heckman et al. 1990; Veilleux et al. 1995). Systematic searches for winds have been carried out in recent years in these objects to look for the unambiguous wind signature of blueshifted absorbing material in front of the continuum source (Heckman et al. 2000; Rupke et al. 2002). The feature of choice to search for outflowing neutral material in galaxies of moderate redshifts ($z \lesssim 0.6$) is the Na ID interstellar absorption doublet at 5890, 5896 Å. The wind detection frequency derived from a set of 44 starburst-dominated LIRGs and ULIRGs is high, of order $\sim 70-80\%$ (Rupke et al. 2002, 2003 in prep.; also see Rupke's and Martin's contributions at this conference). The outflow velocities reach values in excess of 1700 km s^{-1} (even more extreme velocities are found in some AGN-dominated ULIRGs).

A simple model of a mass-conserving free wind (details of the model are given in Rupke et al. 2002) is used to infer mass outflow rates in the range $\dot{M}_{\rm tot}({\rm H})$ = few $-$ 120 for galaxies hosting a wind. These values of $\dot{M}_{\rm tot}$, normalized to the corresponding global star formation rates inferred from infrared luminosities, are in the range $\eta \equiv \dot{M}_{\rm tot}/{\rm SFR} = 0.01-1$. The parameter η, often called the "mass entrainment efficiency" or "reheating efficiency" shows no dependence on the mass of the host (parameterized by host galaxy kinematics and absolute R- and K'-band magnitudes), but there is a possible tendency for η to decrease with increasing infrared luminosities (i.e. star formation rates). The large molecular gas content in ULIRGs may impede the formation of large-scale winds and reduce η in these objects. A lower thermalization efficiency (i.e. higher radiative efficiency) in these dense gas-rich systems may also help explain the lower η (Rupke et al. 2003, in prep.; see Rupke's contribution at this conference).

3.4. Lyman Break Galaxies

Evidence for galactic winds has now been found in a number of z $\sim 3-5$ galaxies, including an important fraction of Lyman break galaxies (LBGs; e.g., Franx et al. 1997; Pettini et al. 2000, 2002; Frye, Broadhurst, & Benitez 2002; Dawson et al. 2002; Ajiki et al. 2002; Adelberger et al. 2003; Shapley et al. 2003). The best studied wind at high redshift is that of the gravitationally lensed LBG MS 1512-cB58 (Pettini et al. 2000, 2002). An outflow velocity of $\sim$ 255 km s^{-1} is derived in this object, based on the positions of the low-ionization absorption lines relative to the rest-frame optical emission lines (Lyα is to be avoided for this purpose since resonant scattering and selective dust absorption of the Lyα photons may severely distort the profile of this line; e.g., Tenorio-Tagle et al. 1999). The mass-conserving free wind model of Rupke et al. (2002) applied to MS 1512-cB58 (for consistency) results in a mass outflow rate of ~ 20 $M_\odot$ yr^{-1}, equivalent to about 50% the star formation rate of this galaxy based on the dust-corrected UV continuum level. Similar outflow velocities are derived in other LBGs (Pettini et al. 2001). The possibly strong impact of these LBG winds on the environment at high z is discussed in the next section (§4.2).

4. Implications

Starburst-driven winds may have a strong influence on structure formation at high redshifts, on the "porosity" of star-forming galaxies (i.e. the probability for ionizing photons to escape their host galaxies), hence the nature of the extra-galactic UV and infrared background, and on the chemical and thermal evolution of galaxies and their environment. Due to space limitations, this review only addresses the last issue.

4.1. Heating and Enrichment of the ISM and IGM

Hot Metal-Enriched Gas. Nuclear starbursts inject both mechanical energy and metals in the centers of galaxies. This hot, chemically-enriched material, the driving engine of galactic winds, is eventually deposited on the outskirts of the host galaxies, and contributes to the heating and metal enrichment of galaxy halos and the IGM. Surprisingly little evidence exists for the presence of this enriched wind fluid. This is due to the fact that the wind fluid is tenuous and hot and therefore very hard to detect in the X-rays. The current best evidence for the existence of the wind fluid is found in M 82 (Griffiths et al. 2000; Stevens et al. 2003), NGC 1569 (Martin, Kobulnicky, & Heckman 2002), and possibly the Milky Way (e.g., Koyama et al. 1989; Yamauchi et al. 1990). The ratio of alpha elements to iron appears to be slightly super-solar in the winds of both NGC 1569 and M 82, as expected if the stellar ejecta from SNe II are providing some, but not all of the wind fluid.

Selective Loss of Metals. The outflow velocities in LIRGs and ULIRGs do not appear to be correlated with the rotation velocity (or equivalently, the escape velocity) of the host galaxy, implying selective loss of metal-enriched gas from shallower potentials (Heckman et al. 2000; Rupke et al. 2002). If confirmed over a broader range of galaxy masses (e.g., Martin 1999; but see the contribution by Martin at this conference for a word of warning), this result may help explain the mass-metallicity relation and radial metallicity gradients in elliptical galaxies and galaxy bulges and disks (e.g., Bender, Burstein, & Faber 1993; Franx & Illingworth 1990; Carollo & Danziger 1994; Zaritsky et al. 1994; Trager et al. 1998). The ejected gas may also contribute to the heating and chemical enrichment of the ICM in galaxy clusters (e.g., Dupke & Arnaud 2001; Finoguenov et al. 2002, and references therein).

Dust Outflows. Galactic winds also act as conveyor belts for the dust in the hosts. The evidence for a large-scale dusty outflow in our own Galaxy has already been mentioned in §3.1 (Bland-Hawthorn & Cohen 2003). Far-infrared maps of external galaxies with known galactic winds show extended dust emission along the galaxy minor axis, suggestive of dust entrainment in the outflow (e.g., Hughes, Gear, & Robson 1994; Alton et al. 1998, 1999; Radovich, Kahanpää, & Lemke 2001). Direct evidence is also found at optical wavelengths in the form of elevated dust filaments in a few galaxies (e.g., NGC 1808, Phillips 1993; NGC 3079, Cecil et al. 2001). A strong correlation between color excesses, $E(B-V)$, and the equivalent widths of the blueshifted low-ionization lines in star-forming galaxies at low (e.g., Armus, Heckman, & Miley 1989; Veilleux et al. 1995; Heckman et al. 2000; Rupke et al. 2003) and moderate-to-high redshifts (e.g., Rupke et al. 2003; Shapley et al. 2003) provides additional support for the prevalence of dust outflows. Assuming a Galactic dust-to-gas ratio, Heckman et al. (2000) estimate that the dust outflow rate is about 1% of the total mass outflow rate in LIRGs. Dust ejected from galaxies may help feed the reservoir of intergalactic dust (e.g., Coma cluster; Stickel et al. 1998).

4.2. Zone of Influence of Winds

The impact of galactic winds on the host galaxies and the environment depends sensitively on the size of the "zone of influence" of these winds, i.e. the region affected either directly (e.g., heating, metals) or indirectly (e.g., ionizing radiation) by these winds. This section summarizes the methods used to estimate this quantity.

Indirect Measurements based on Estimates of the Escape Velocity. The true extent of galactic winds is difficult to determine in practice due to the steeply declining density profile of both the wind material and the host ISM. The zone of influence of galactic winds is therefore often estimated using indirect means which rely on a number of assumptions. A popular method is to use the measured velocity of the outflow and compare it with the local escape velocity derived from some model for the gravitational potential of the host galaxy. If the measured outflow velocity exceeds the predicted escape velocity *and* if the halo drag is negligible, then the outflowing material is presumed to escape the host galaxy and be deposited in the IGM on scales $\gtrsim 50-100$ kpc. This method was used for instance by Rupke et al. (2002) to estimate the average escape fraction $\langle f_{\rm esc}\rangle \equiv \sum \dot{M}^i_{\rm esc}/\sum \dot{M}^i_{\rm tot}$ and "ejection efficiency" $\langle\delta\rangle \equiv \sum \dot{M}^i_{\rm esc}/\sum {\rm SFR^i}$ for 12 ULIRGs, which were found to be $\sim 0.4-0.5$ and ~ 0.1, respectively. These calculations assumed that the host galaxy could be modeled as a singular isothermal sphere truncated at some radius $r_{\rm max}$. Neither the escape fraction nor the ejection efficiency were found to be sensitive to the exact value of $r_{\rm max}$. Other strong cases for escaping material include the "Hα cap" of M 82 and the ~ 1500 km s^{-1} line-emitting material in the superbubble of NGC 3079; both objects were discussed in §3.2.

Note that the outflow velocities measured by Rupke et al. (2002) refer to the neutral component of the outflow, not the hot enriched wind fluid. Unfortunately, direct measurements of the wind velocity are not yet technically possible so one generally relies on the expected terminal velocity of an adiabatic wind at the measured X-ray temperature T_X [$v_X \sim (5KT_X/\mu)^{0.5}$, where μ is the mean mass per particle] to provide a lower limit to the velocity of the wind fluid (this is a lower limit because it only takes into account the thermal energy of this gas and neglects any bulk motion; e.g., Chevalier & Clegg 1985; Martin 1999; Heckman et al. 2000).

Arguably the single most important assumption made to determine the fate of the outflowing gas is that halo drag is negligible. Silich & Tenorio-Tagle (2001) have argued that halo drag may severely limit the extent of the wind and the escape fraction. Drag by a dense halo or a complex of tidal debris may be particularly important in ULIRGs if they are created by galaxy interactions (e.g., Veilleux, Kim, & Sanders 2002b).

Deep X-ray and Optical Maps of Local Starbursts. The fundamental limitation in directly measuring the zone of influence of winds is the sensitivity of the instruments. Fortunately, *CXO* and *XMM*-Newton now provide powerful tools to better constrain the extent of the hot medium (e.g., M 82, Stevens et al. 2003; NGC 3079, Cecil et al. 2002; NGC 6240, Komossa et al. 2003; Veilleux et al. 2003; NGC 1511, Dahlem et 2003). The reader should refer to the contribution of M. Ehle at this conference for a summary of recent X-ray results (see also Strickland et al. 2003 and references therein).

The present discussion focusses on optical constraints derived from the detection of warm ionized gas on the outskirts of wind hosts. Progress in this area of research has been possible thanks to advances in the fabrication of low-order Fabry-Perot etalons which are used as tunable filters to provide monochromatic images over a large fraction of the field of view of the imager. The central wavelength (3500 Å – 1.0 μm) is tuned to the emission-line feature of interest and the bandwidth (10 – 100 Å) is chosen to minimize the sky background. Continuum and emission-line images are produced nearly simultaneously thanks to a "charge shuffling/frequency switching" mode, where the charges are moved up and down within the detector at the same time as switching between two discrete frequencies with the tunable filter, therefore averaging out temporal variations associated with atmospheric lines and transparency, seeing, instrument and detector instabilities. The narrow-band images are obtained in a straddle mode, where the off-band image is made up of a pair of images that "straddle" the on-band image in wavelength (e.g., λ_1 = 6500 Å and λ_2 = 6625 Å for rest-frame Hα); this greatly improves the accuracy of the continuum removal since it corrects for slopes in the continuum and underlying absorption features.

These techniques have been used with the Taurus Tunable Filter (TTF; Bland-Hawthorn & Jones 1998; Bland-Hawthorn & Kedziora-Chudczer 2003) on the AAT and WHT to produce emission-line images of several "quiescent" disk galaxies (Miller & Veilleux 2003a) and a few starburst galaxies (Veilleux et al. 2003) down to unprecedented emission-line fluxes. Gaseous complexes or filaments larger than $\sim$ 20 kpc have been discovered or confirmed in a number of wind hosts (e.g., NGC 1482 and NGC 6240; the presence of warm ionized gas at $\sim$ 12 kpc from the center of M 82 was discussed in §3.2). Multi-line imaging and long-slit spectroscopy of the gas found on large scale reveal line ratios which are generally not H II region-like. Shocks often contribute significantly to the ionization of the outflowing gas on the outskirts of starburst galaxies. As expected from shock models (e.g., Dopita & Sutherland 1995), the importance of shocks over photoionization by OB stars appears to scale with the velocity of the outflowing gas (e.g., NGC 1482, NGC 6240, or ESO484-G036 versus NGC 1705; NGC 3079 is an extreme example of a shock-excited wind nebula; Veilleux et al. 1994), although other factors like the starburst age, star formation rate, and the dynamical state of the outflowing structure (e.g., pre- or post-blowout) must also be important in determining the excitation properties of the gas at these large radii (e.g., Shopbell & Bland-Hawthorn 1998 and Veilleux & Rupke 2002).

Influence of the Wind on Companion Galaxies. Companion galaxies located within the zone of influence of the wind will be affected by the wind ram pressure. Irwin et al. (1987) noticed that the dwarf S0 galaxy NGC 3073 exhibits an elongated H I tail that is remarkably aligned with the nucleus of NGC 3079. Irwin et al. have argued that ram pressure due to the outflowing gas of NGC 3079 is responsible for this tail. If that is the case, the wind of NGC 3079 must extent to at least $\sim$ 50 kpc. This is the only system known so far where this phenomenon is suspected to take place.

Absorption-Line Studies. Absorption-line spectroscopy of bright background galaxies (e.g., high-z quasars, Lyman break galaxies) can provide direct constraints on the zone of influence of galactic winds. Norman et al. (1996) have used this method to estimate the extent of the wind in NGC 520. A strong and possibly complex Mg II, Mg I, and Fe II absorption-line system was found near the systemic velocity of NGC 520 at a distance from the galactic nucleus of 24 h^{-1} kpc. A weaker system at a distance of 52 h^{-1} kpc is also possibly present. Unfortunately, NGC 520 is undergoing a tidal interaction so the absorption may arise from tidally disrupted gas rather than material in the purported wind. Norman et al. also looked for absorption-line systems associated with the wind of NGC 253, but the proximity of this system to our own Galaxy and to the line of sight to the Magellanic Stream makes the identification of the absorption-line systems ambiguous. No other local wind galaxy has been studied using this technique.

Large absorption-line data sets collected on high-z galaxies provide new constraints on the zone of influence of winds in the early universe. Adelberger et al. (2003) have recently presented tantalizing evidence for a deficit of neutral hydrogen clouds within a comoving radius of $\sim 0.5\ h^{-1}$ Mpc from $z \sim 3$ LBGs. The uncertainties are large and the results are significant at less than the $\sim 2\sigma$ level. Adelberger et al. (2003) argue that this deficit, if real, is unlikely to be due solely to the ionizing radiation from LBGs (e.g., Steidel et al. 2001; Giallongo et al. 2002). They favor a scenario in which the winds in LBGs directly influence the surrounding IGM. They also argue that the excess of absorption-line systems with large CIV column densities near LBGs is evidence for chemical enrichment of the IGM by the LBG winds.

5. Summary

Tremendous progress has been made over the past five years in understanding the physics and impact of starburst-driven winds in the local and distant universe. We now know that starburst-driven winds are common in galaxies with high star formation rates per unit area, both locally (nearby starbursts, luminous and ultraluminous infrared galaxies) and at high redshifts (e.g., Lyman break galaxies). There is *direct* evidence that starburst-driven winds have had a strong influence on the chemical evolution of the host ISM and possibly also that of the IGM: (1) Enriched wind fluid has been detected in a few nearby galaxies. (2) Approximately half of the outflowing material in powerful starburst galaxies (ULIRGs) have velocities in excess of the escape velocities. (3) Deep emission-line maps of local wind galaxies indicate that the zone of influence of the wind often extends beyond $\sim$ 10 kpc. (4) Recent results on Lyman break galaxies suggest tentatively that the zone of influence of LBG winds may extent out to $\sim$ 500 h^{-1} kpc. Nevertheless, much work remains to be done in this area of research; the next five years promise to be equally exciting as the last five!

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