Part 3. Ejection and Outflow

Stellar Winds

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Multiwavelength Observations of Galactic Winds: Near and Far

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Abstract. This paper provides a critical discussion of the observational evidence for winds in our own Galaxy, in nearby star-forming and active galaxies, and in the high-redshift universe. The implications of galactic winds on the formation and evolution of galaxies and the intergalactic medium are briefly discussed. A number of observational challenges are mentioned to inspire future research directions.

1. Introduction

Active galactic nuclei (AGN) and nuclear starbursts may severely disrupt the gas phase of galaxies through deposition of a large amount of mechanical energy in the centers of galaxies. As a result, a large-scale galactic wind that encompasses much of the central regions of these galaxies may be created (e.g., Chevalier & Clegg 1985; Schiano 1985). Depending upon the extent of the gaseous halo and its density and upon the wind's mechanical luminosity and duration, the wind may ultimately blow out through the halo and into the intergalactic medium. The effects of these winds may be far-reaching. Bregman (1978) has suggested that the Hubble sequence can be understood in terms of a galaxy's greater ability to sustain winds with increasing bulge-to-disk ratio. Galactic winds may affect the thermal and chemical evolution of galaxies and the intergalactic medium by depositing large quantities of hot, metal-enriched material on the outskirts of galaxies and beyond. This widespread circulation of matter and energy between the disks and halos of galaxies may be responsible for the mass-metallicity relation between galaxies.

This paper reviews the observed properties (§2) and impact (§3) of starburst- and AGN-driven winds in both the local and distant universe; the discussion on starburst-driven winds is largely borrowed from Veilleux (2003), while new elements on AGN outflows are also included. The last section (§4) discusses future avenues of research. The theory and numerical modelling of galactic winds are not discussed here due to space limitations (see, e.g., Veilleux et al. 2002; Strickland 2002; Heckman 2002; Veilleux 2003). Collimated jet outflows and

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unresolved nuclear winds in AGNs are also beyond the scope of this paper; recent reviews of these topics include Zensus (1997), Veilleux et al. (2002), and Crenshaw, Kraemer, & George (2003).

2. Observed Properties of Galactic Winds

AGN- and starburst-driven winds are common among local galaxies. 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, often show signs of large-scale winds. This general rule-of-thumb also appears to apply to ultra/luminous infrared galaxies (see §2.3) and distant Lyman break galaxies (see §2.4). "Quiescent" galaxies with lower star formation rates per unit area often show thick ionized disks, but no galactic-scale outflow (e.g., Miller & Veilleux 2003a, 2003b). This rule-of-thumb is conservative since a number of known starburst-driven wind galaxies, including our own Galaxy (§2.1) 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). The production of detectable winds depends not only on the characteristics of the energy source (AGN vs starburst, power, 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 active and 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, and mass outflow rates ranging from $<$ 1 M$_\odot$ yr^{-1} to $>$ 100 M$_\odot$ yr^{-1}. In AGNs, the mass outflow rates on kpc scale are larger than the mass accretion rates needed to power the central nucleus. In starbursts, the mass outflow rates scale roughly with the star formation rates (see §2.3 below).

In the remainder of this section, we repeat the discussion of Veilleux (2003) on 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.

2.1. 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 $\sim$ 350 pc ($\sim 1°$) 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 $\sim$ 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 $b = +80°$ (e.g., Sofue 2000), can naturally be explained as an open-ended bipolar wind,

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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 $\sim$ 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.

2.2. 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 $\sim$ 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 the *Chandra* X–ray Observatory (*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 ($\sim$ 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 ($\sim$ 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. indexo:NGC 3079 An outstanding example of a 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 $\sim$ 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).

2.3. 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 starburst-dominated 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.). The outflow velocities reach values in excess of 1700 km s^{-1} (even more extreme velocities are found in some AGN-dominated ULIRGs; e.g., Mrk 231; Rupke et al. 2002).

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 $\dot{M}_{\rm tot}({\rm H}) = {\rm few} - 120$ 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.).

2.4. 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

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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 ~ 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 $\sim 20\ M_\odot$ 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 (§3.2).

3. Impact of Galactic Winds on the Environment

Due to space limitations, it is not possible to discuss in detail the profound influence of galactic winds on galaxy formation and evolution and on the properties of the intergalactic medium. This section reviews a few key results on the heating and enrichment of the ISM and IGM, and describes new optical constraints on the size of the zone of influence of galactic winds.

3.1. Heating and Enrichment of the ISM and IGM

Hot Metal-Enriched Gas in Starburst-Driven Winds. Nuclear starbursts inject both mechanical energy and metals in the centers of galaxies. This hot, chemically-enriched material 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 in Starburst-Driven Winds. The outflow velocities in starburst-dominated 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 Martin 2003 and Rupke et al. 2003, in prep.), 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

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clusters (e.g., Dupke & Arnaud 2001; Finoguenov et al. 2002, and references therein).

Heating by AGN-Driven Outflows. The large "cavities" in the X-ray surface brightness of several cooling flow clusters with radio-loud cD galaxies (e.g., Böhringer et al. 1993; Fabian et al. 2000; McNamara et al. 2000, 2001; David et al. 2001; Heinz et al. 2002) point to the direct influence of AGN-driven outflows on the ICM. The hot/relativistic buoyant gas injected into the ICM by the AGN reduces and perhaps even quenches the mass accretion rates associated with the cooling flows, possibly through thermal conduction or "effervescent" heating (e.g., Quilis, Bower, & Balogh 2001; Churazov et al. 2002; Ruszkowski & Begelman 2003; see Kim & Narayan 2003, however).

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 §2.1 (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; note, however, that tidal and ram-pressure stripping may be more efficient than winds at carrying dust into the ICM; see contribution by Stickel at this conference).

3.2. 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. But the true extent of galactic winds is often 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 (see, e.g., Rupke et al. 2002 for an application of this method). Another method is to rely 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

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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). Both of these methods make the important assumption 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).

The large uncertainties on these indirect estimates of the zone of influence of galactic winds emphasize the need for more direct measurements; these are discussed next.

Deep Multiwavelength Maps of Local Galaxies. 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). Technological advancements have also allowed to detect galactic winds on very large scales at radio wavelengths (e.g., Irwin & Saikia 2003). A discussion of these results is beyond the scope of this short review.

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. The data acquisition methods used to reach very faint flux limits are discussed in Veilleux (2003) and references therein, and are not repeated here. The Taurus Tunable Filter (TTF; Bland-Hawthorn & Jones 1998; Bland-Hawthorn & Kedziora-Chudczer 2003) has been used 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 flux levels.

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 §2.2). 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, 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

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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). In the cases of AGN-driven winds, the hard radiation from the central source sometimes produces highly ionized winds and/or large-scale ionization cones (e.g., NGC 1068, NGC 1365 and NGC 4388; Veilleux et al. 2003).

Lyman Break Galaxies. 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.

4. Future Avenues of Research

Although great strides have been made over the last decade in understanding the physics and impact of galactic winds in the local and distant universe, much work remains to be done to be able to quantify the overall role of these winds on the formation and evolution of galaxy-sized structures. Absorption-line studies of bright background galaxies (e.g., high-z quasars, LBGs) have proven to be a very powerful tool to constrain the zone of influence of galactic winds at large redshifts. The next generation of instruments on *HST* will provide the capabilities to extend the sample to a larger set of wind galaxies. *CXO* and *XMM*-Newton will continue their harvest of high-quality data on the hot medium in galactic winds, and within five years a new generation of radio telescopes (e.g.. *EVLA, SKA, CARMA, ALMA*) will probe the hot relativistic component of galactic winds better than ever before and provide the sensitivity to better quantify the role of the molecular gas in the dynamics of local winds. This component may be particularly important in determining the overall thermalization efficiency of galactic winds, or the percentage of the mechanical energy from the starburst or AGN that goes into heating the gas and driving the outflow; this quantity is currently very poorly constrained. The advent of tunable filters on 8-meter class telescopes [e.g., OSIRIS on the GranTeCan (Cepa et al. 2000) and the Maryland-Magellan Tunable Filter on the Baade 6.5-m telescope] should improve the sensitivity of optical wind surveys at least tenfold. Measurements with this second generation of tunable filters will provide direct quantitative constraints on the gaseous cross-section of active and star-forming galaxies, and the importance of mass exchange between galaxies and their environment. These powerful instruments will be ideally suited to search for galaxies with starburst-driven winds, exploiting the contrast in the excitation properties of the wind component and the star-forming disk (Veilleux & Rupke 2002).

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