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GALACTIC SUPERWINDS

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Abstract. We review the galactic 'superwind' phenomenon: global outflows powered by the collective effect of the supernova explosions and stellar winds associated with powerful, compact starbursts. We briefly summarize the theoretical and astrophysical underpinnings of the superwind concept, stressing how even simple idealized models can provide an informative interpretational guide to the observations.

We then discuss the growing body of multi-waveband observations of superwinds. X-ray emission from superwinds is probably produced by a combination of internal shocks in the high-speed superwind and by interactions between the superwind and inhomogeneous ambient gas ('clouds'). Most of the available data on superwinds comes from optical emission-line imaging and spectroscopy. Such optical line-emission is most likely produced as the wind shock-heats and accelerates ambient gas in the disk or halo of the starburst galaxy. These optical data provide morphological, kinematic, and physical evidence for the existence of superwinds, and even allow us to estimate some of the key superwind parameters. The interaction between the wind and cool atomic gas has been probed by both optical absorption-lines and radio observations of the H I 21cm line. Evidence for outflowing molecular gas in starbursts is also summarized. The nonthermal radio continuum halos associated with some starbursts probably represent relativistic magnetized plasma convected out of the starburst by the superwind.

We then summarize our attempts to take a census of superwinds in the local universe. We use this census to estimate the rates at which superwinds eject metals and energy at the present epoch. Finally, we briefly consider the implications of superwinds for diverse topics in extragalactic astronomy. Superwinds may play a crucial role in the chemothermal evolution of the intergalactic medium, in the chemical evolution of galaxies, in the evolution (destruction?) of dwarf galaxies, in the stimulation or suppression of galaxy formation at early times, in the quasar absorption-line phenomenon (through their effect on galactic gaseous halos), and in the production of part of the X-ray background at $E < 10$ keV.

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1. INTRODUCTION

'Superwinds' - galactic-scale mass outflows driven by the collective effect of supernovae and winds from massive stars - have a rich legacy in theoretical astrophysics. They figure prominently in models for the formation and evolution of galaxies (e.g., Dekel & Silk 1986; White & Frenk 1991; Mathews 1989; Berman & Suchkov 1991) and of the intergalactic medium (e.g., DeYoung 1978; Ostriker & Cowie 1981), for the dynamics and structure of the interstellar medium and Galactic Halo (e.g., MacLow & McCray 1988, hereafter MM; Heiles 1990; Dettmar 1993), for the origin of the cosmic X-ray background (e.g., Bookbinder et al. 1980), and for some types of QSO absorption-lines (e.g., York et al. 1986).

Despite their potential importance, superwinds have remained largely in the realm of theoretical *deus ex machina* until quite recently. This situation has changed dramatically in the last several years, and our primary goal in this paper is to review how X-ray, optical, IR, and radio observations of starburst galaxies have been used to discover superwinds and to quantify many of their basic physical properties. This review is designed to complement two other recent reviews by Dettmar (1993) and Begelman (this volume). While Dettmar's emphasis is on the 'disk-halo connection' in typical spiral galaxies, the emphasis in the present review is on starburst galaxies (e.g., galaxies in which the gas depletion time is much less than a Hubble time and in which the region of star-formation is largely concentrated to the central kpc or so of the galaxy). Likewise, we leave to Begelman the discussion of outflows driven by powerful AGNs. It is indeed possible that some of the outflows we will discuss in this review are driven by AGNs rather than by starbursts. As we have argued elsewhere (Heckman, Lehnert, & Armus 1993), this is not likely to be true in the majority of cases however.

In order to place the importance of these multi-waveband observations in context, we will begin our review in Section 2 with a brief summary of the basic theoretical and astrophysical underpinnings of the superwind concept. After extensively discussing the most relevant observations in Section 3, we will describe in Section 4 how our recent 'census' of superwinds can be used to estimate the rate at which they eject mass and energy in the local universe. We will then conclude the review in Section 5 with a summary of the potential implications superwinds have for many of the topics considered during this Summer School. We direct motivated readers to the paper by Heckman, Armus, & Miley (1990 - hereafter HAM) for a more detailed discussion of some of the material to follow.

2. THE BASIC PHYSICS AND ASTROPHYSICS OF SUPERWINDS

The theoretical astrophysics pertinent to superwinds has been extensively discussed in the literature. A comprehensive review of models of the closely related phenomenon of 'supershells' can be found in Tenario-Tagle & Bodenheimer (1988), while more specific theoretical aspects of the superwind phenomenon are treated by - for example - Chevalier & Clegg (1985 - hereafter CC), Tomisaka & Ikeuchi (1988), Norman & Ikeuchi (1989), Leitherer, Robert, & Drissent (1993 - hereafter LRD), and Balsara, Suchkov, & Heckman (1993).

Briefly, we expect a superwind to occur when the kinetic energy in the ejecta supplied by supernovae and winds from massive stars in a starburst is efficiently thermalized. This means that the collisions between stellar ejecta convert the kinetic energy of the ejecta into thermal energy via shocks, with little energy subsequently lost to radiation. This situation is expected to arise when the (suitably normalized) kinetic energy input rate is so high that most of the volume of the starburst's ISM is filled by hot, tenuous supernova-heated gas (e.g., McKee & Ostriker 1977; MM). The collective action of the supernovae and stellar winds then creates a 'bubble' of very hot (T up to 10^8 K) gas with a pressure that is much larger than that of its surroundings.

As the over-pressured bubble expands and sweeps up ambient gas, it will rapidly enter the 'snowplow' or radiative phase, which

occurs when the radiative cooling time of swept-up and shock-heated ambient material becomes shorter than the wind's expansion timescale. Should the bubble be expanding inside a disk-like ISM (as expected in a typical starburst), the bubble will expand most rapidly along the direction of the steepest pressure gradient (the disk's minor axis). It is likely that once the bubble has a diameter that is a few times the scale-height of the disk, it will evolve from the 'snowplow' phase into the 'blow-out' phase as the swept-up shell accelerates outward and fragments via Rayleigh-Taylor instabilities. The wind can then propagate out into the intergalactic medium at velocities of several thousand km s^{-1} (provided that radiative losses have been small - cf. CC).

2.1. Momentum & Energy Input in Starbursts

Superwinds will be driven by the kinetic energy and momentum supplied by the starburst. Supernovae (primarily types II and Ib), winds from massive stars, and radiation pressure will all contribute significantly in this regard.

In very useful recent paper, LRD have calculated the predicted return of mass, momentum, and kinetic energy from an ensemble of massive stars. These calculations have been made for a range of different metallicities and initial mass functions. The time-evolution of these injection rates has been followed for two extreme starburst 'histories': 1. an instantaneous burst with all stars formed at once, and 2. a constant star-formation rate lasting up to 5×10^7 yr. LRD show that stellar winds are most important at early times, for the most top-heavy IMF's, and for the highest metallicities. Their results are relatively insensitive to the IMF and metallicity for starbursts older than about 10^7 yr when supernovae start to dominate the injection rates. This is fortunate from the standpoint of comparisons of the models with the data, since most starbursts are believed to last 10^7 to 10^8 yr (e.g., Rieke et al. 1980; Bernlohr 1993a, b).

For concreteness and ease of comparison to the LRD models, we will assume a constant star-formation rate lasting for 5×10^7 yr, a normal Salpeter IMF extending up to 100 $M_\odot$, and solar metallicity. These seem reasonable approximations for the typical starbursts we will discuss later. Scaling of the corresponding LRD model for M 82 then leads to the following predicted relationships between the starburst bolometric luminosity and the various injection rates:

$$Kinetic\,energy:\ \dot{E} = 8 \times 10^{42} L_{bol,11}\ \mathrm{erg\ s^{-1}}, \quad (1)$$

$$Mass:\ \dot{M} = 3 L_{bol,11} M_\odot\ \mathrm{yr^{-1}}, \quad (2)$$

$$Momentum:\ \dot{p} = 5 \times 10^{34} L_{bol,11}\ \mathrm{dyne}, \quad (3)$$

where the bolometric luminosity is in units of $10^{11}\ L_\odot$.

Several comments are in order. First, for the IR-selected starbursts that will dominate most of the discussion in Sections 3 and 4 to follow, it is probably a reasonable approximation to equate the starburst bolometric luminosity to the total (1 to 1000μ) IR luminosity of the galaxy - as given (for example) by the two-dust-temperature fits to the IRAS data in Rice et al. (1988). Second, note that the momentum flux associated with the starburst's radiation pressure (L_{bol}/c) is about 25% as large as the momentum flux due to supernovae and stellar winds given in Equation 3. It is also worth noting that the mechanical energy output of the starburst is about 2% of the bolometric luminosity, and that the mass injection rate represents about 10% (25%) of the star-formation rate for a Salpeter IMF with a lower mass cut-off of 0.1 $M_\odot$ (1 $M_\odot$) respectively.

The above equations are meant to represent 'typical' starbursts with durations of at least 10^7 yr. Clearly, the relationships between such quantities as bolometric luminosity, Lyman continuum luminosity, and the input rates of mass, momentum, and energy could vary substantially with time for an instantaneous starburst. Since the kinetic energy input at times later than 10^7 yr in a starburst is dominated by supernovae, since a normal IMF rises towards low mass, and since the kinetic energy per supernova is roughly independent of progenitor mass (e.g., Woosley & Weaver 1986), the rate at which an instantaneous starburst injects kinetic energy will actually peak at about the time the least massive type II supernova progenitors explode. A minimum supernova progenitor mass of 8 $M_\odot$ corresponds to an implied maximum kinetic energy injection rate at a time of about 5×10^7 yr (cf. LRD). Thus, a starburst in which the duration of star-formation is much shorter than this time-scale (e.g., Bernlohr 1993a, b), will have a peak in the superwind's mechanical energy output at a time when no stars more massive than about 8 $M_\odot$ remain (i.e., at a main sequence turn-off at B4V).

Such a post-burst galaxy would have a significantly reduced bolometric (IR) luminosity. The instantaneous burst models of Charlot & Bruzual (1991) show that L_{bol} has dropped by a factor of about 40 at 5×10^7 yr with respect the peak value. Even more importantly, the very steep dependence of the Lyman continuum luminosity with stellar mass means that this post-burst would have a truly negligible ionizing luminosity: the models of Charlot & Bruzual (1991) and those of De-Gioia-Eastwood

(1985) together imply a drop in L_{LyC} by a factor of about 30,000 with respect to the peak value. Kornneef (1993) has dubbed such objects 'Postburst Infrared Galaxies' ('PIGs'), and has proposed that the superwind system NGC 4945 (HAM) represents the prototype. Other superwind galaxies like Arp 220, NGC 6240, and NGC 3079 in HAM which all have unusually small ratios of Brγ to bolometric luminosity (cf. Beck 1993) may be additional examples of PIGs. The dwarf galaxy NGC 1705 seems to be an example of a low-mass post-burst that is driving a global outflow (Meurer et al. 1992).

2.2. Simple Models of Superwind Hydrodynamics and Radiation

The simplest possible hydrodynamical model for a superwind would be spherically-symmetric and would ignore the effects of gravity, radiative cooling, and ambient gas (i.e., a 'free wind'). CC have discussed such a model in the context of M 82. They assume that there is a spherical region of radius r_* (the starburst) inside which mass and kinetic energy are injected at a constant rate per unit volume. The result is a region of hot gas which slowly expands through a sonic radius (located approximately at the radius of the starburst) and is then transformed into a supersonic outflow.

HAM have found that this model is a reasonable fit to the radial pressure profiles in a sample of well-studied starburst superwind systems (see Section 3.2 below). In such a model, the gas pressure inside the starburst (and hence inside the sonic radius of the wind) is just the static thermal pressure of the hot fluid that has been produced by thermalization (shock-heating) in high-speed collisions between material ejected in stellar winds and supernova explosions. As discussed by CC, this pressure is essentially determined by the size of the starburst and the rate at which mass and kinetic energy is injected. Since the sound-crossing time inside the starburst is much shorter than the outflow time (e.g., since the flow is subsonic inside the starburst itself), the pressure is roughly constant throughout this central region. Following CC, and using Equations 1 & 2 above to relate the injection rates to the starburst luminosity, we expect the central pressure to be given by:

$$P_0/k = 3.5 \times 10^6 L_{bol,11}[r_*/\mathrm{kpc}]^{-2}\ \mathrm{K\ cm^{-3}}. \quad (4)$$

Thus, the smaller the starburst radius (r_*), the higher the central pressure for a given starburst luminosity.

For radii much larger than the starburst radius, the pressure of the outflow is dominated by the wind's ram pressure. This will essentially be set by the rate at which the starburst injects momentum into the flow, and will drop like the inverse square of distance from the starburst. Following CC and using Equation 3 above we get:

$$P(r)/k = 3 \times 10^6 L_{bol,11}[r/\mathrm{kpc}]^{-2}\ \mathrm{K\ cm^{-3}}, \quad (5)$$

where r is the distance from the starburst, assuming $r >> r_*$.

The temperature inside the starburst is just set by the mean amount of kinetic energy per gram in the material injected by supernovae and stellar winds, and the models of LRD then imply that $T_0 = 1.2 \times 10^8$ K for the assumptions discussed in Section 2.1. As this hot fluid expands out though the sonic radius, it is adiabatically cooled (it is easy to show in the context of the CC models that adiabatic cooling dominates radiative cooling for the wind fluid). The CC models combined with the LRD models then imply that for $r >> r_*$:

$$T(r) = 6 \times 10^7 (r/r_*)^{-4/3}\ \mathrm{K}. \quad (6)$$

Finally, the terminal velocity of the outflow (velocity at $r >> r_*$) is just the square root of twice the kinetic energy per gram in the material injected by the supernovae and stellar winds (cf. CC). Equations 1 and 2 above imply that the terminal velocity will be about 2900 km s^{-1}.

The next level of complication is to retain spherical symmetry, but to put in a homogeneous ambient medium that the wind must push against. This is a well-understood problem first considered in the context of wind-blown bubbles inflated by individual stars (e.g., Castor, McCray, & Weaver 1975). Dyson (1989) has recently published an excellent review of the relevant physics.

Briefly, in this situation one has an 'onion-skin' structure of five concentric zones. From inside-out these are: 1. An innermost region inside which the mass and energy is injected (the starburst), 2. A region of supersonic outflow, 3. A region of hot gas (wind material that has passed through an internal shock that divides regions 2 and 3), 4. A thin, dense shell of ambient gas that has been swept-up, shocked, compressed, and then radiatively cooled as the 'piston' of hot gas in zone 3 expands into the

ambient medium, and 5. The undisturbed ambient gas. Such an expanding bubble may be either energy-conserving or momentum-conserving (depending on whether radiative losses in zone 3 are negligible or not).

For concreteness, let us adopt an energy-conserving structure inflating in a medium of constant density n_0 (cm^{-3}). Two of the most relevant properties of the gas in zone 3 (shocked wind material) are then given by (cf. MM):

$$T = 3 \times 10^7 n_0^{2/35} L_{bol,11}^{8/35} t_{15}^{-6/35} \text{ K}, \quad (7)$$

$$L_X = 2 \times 10^{40} n_0^{18/35} L_{bol,11}^{37/35} t_{15}^{13/35} \text{ erg s}^{-1}, \quad (8)$$

where t_{15} is the age of the bubble in units of 10^{15} s (about 32 Myr, and we have again used the relations from LRD in Equations 1 though 3 above to express T and L_X in terms of the starburst luminosity. We therefore expect zone thee to be a strong source of X-rays (though note that the X-ray luminosity is only about 10^{-4} of the starburst luminosity). It is also helpful to note that an ambient density of unity inside a sphere of radius r corresponds to a total gas mass of 10^8 $[r/\text{kpc}]^3$ $M_\odot$.

For the same model the chief parameters of zone 4 (the expanding shell of shocked ambient gas) are given as (cf. Castor, McCray, & Weaver 1975):

$$r_{shell} = 5 L_{bol,11}^{1/5} \, n_0^{-1/5} \, t_{15}^{3/5} \text{ kpc}, \quad (9)$$

$$v_{shell} = 100 L_{bol,11}^{1/5} \, n_0^{-1/5} \, t_{15}^{-2/5} \text{ km s}^{-1}. \quad (10)$$

Thus, the shell expands far more slowly than would a freely expanding wind. The typical shock-speeds implied by Equation 10 yield post-shock temperatures in zone 4 of order few times 10^5 K. This is near the peak of the cooling curve (e.g., Spitzer 1978), and cooling times in zone 4 should be much shorter than the bubble expansion time.

We would expect zone 4 to be a strong source of optical and UV line emission, with a predicted Hα luminosity (from shocks alone) of-order:

$$L_{H\alpha} = 10^{41} L_{bol,11}^{3/5} \, n_0^{2/5} \, t_{15}^{4/5} \text{ erg s}^{-1}. \quad (11)$$

Thus, the Hα luminosity of zone 4 is a few times larger than the X-ray luminosity of zone 3, and is a few times 10^{-4} of the starburst luminosity. Since the Hα line typically represents 1 to 2% of the total emission-line luminosity in a shock (e.g., Shull & McKee 1979), the total line luminosity due to shock-heating of zone 4 will be of-order 1 to 2% of the starburst bolometric luminosity. Since the total wind kinetic energy flux is about 2% of the starburst bolometric luminosity (see Equation 1 above), this may be regarded as an upper bound on the luminosity of gas that has been shock-heated by the wind.

For the more general case in which an energy-conserving bubble is inflated into an ambient medium in which the density declines with radius like $n \propto r^{\beta}$, the expression corresponding to Equation 10 above has $v \propto t^{-(\beta+2/\beta+5)}$ - cf. Dyson (1989). For values of $\beta < -2$ the shell therefore accelerates outward. Thus, it is expected that Rayleigh-Taylor instabilities will cause the shell to fragment, allowing the wind fluid in zones 2 and 3 to then freely escape from the ruptured bubble. Such a situation is referred to as 'blow-out' in the jargon of the trade.

As a more geometrically realistic model, we can consider a bubble being inflated in a plane-parallel stratified atmosphere (e.g., the gaseous disk of a starburst). The structure and evolution of the bubble is very similar to the spherical model above. However, in the disk case, the bubble will expand most rapidly along the direction of the steepest pressure gradient (e.g., normal to the plane of the disk). This process has been studied by numerous authors (e.g., Schiano 1985; MM; Tomisaka & Ikeuchi 1988; Balsara, Suchkov, & Heckman 1993; and see the review by Tenario-Tagle & Bodenheimer 1988). For an exponential density law in the vertical direction, the shell of shocked ambient gas will accelerate and fragment (e.g., blow-out will occur) when the bubble's radius reaches a few disk scale heights. Thereafter, the hot gas injected inside the starburst could vent directly out into the galactic halo (or beyond).

A schematic version of the evolution of this process is shown in Figure 1a, b. Figure 1a shows the radiative phase before 'blow-out'. The molecular disk fueling the starburst is labeled 'MD', and the associated supernovae and stellar winds are

indicated by stylized stars. The starburst has partially evacuated a central cavity (labeled 'C') that is filled with the hot (T ~ 10^8 K) thermalized supernova and stellar wind ejecta. This hot fluid passes through a sonic radius and then expands outward at several thousand km s^{-1} as a free wind (arrows labeled 'FW'). It passes though an internal wind shock (dashed line labeled 'WS') and is then reheated back to T ~ 10^8 K. This shocked-wind material ('SW') can be an important source of thermal X-ray emission. The pressure of the wind inflates a 'bubble' which is elongated along the vertical axis, the direction of the maximum pressure gradient in the gaseous halo ('GH'). The solid contours are isodensity contours of the gaseous halo, which has a vertical scale-height labeled 'SH'. The shock driven by the expanding hot bubble will sweep up the ambient gas, accelerating it to velocities of a few hundred km s^{-1} (with a velocity field indicated by the short arrows). The shocked gas then cools radiatively into a thin shell ('S'). This shock-heated shell will be an important source of optical line-emission.

Figure 1b shows the situation after the bubble expands more than a couple of vertical scale-heights it can 'blow-out' of the halo. The bulk of the interior of the region evacuated by the wind is now occupied by the freely expanding wind fluid, with a small shell of shocked-wind fluid at the leading edge of the outflow separated from the ambient halo gas by a contact discontinuity (dot-dashed line labeled 'CD'). Bow shocks in the wind ('BS') will form around density inhomogeneities in the galaxy halo ('SC' for 'shocked clouds'). These clouds will be accelerated outward (short arrows), and may radiate optical/UV emission-lines and soft X-rays depending on the speed of the shocks driven into them.

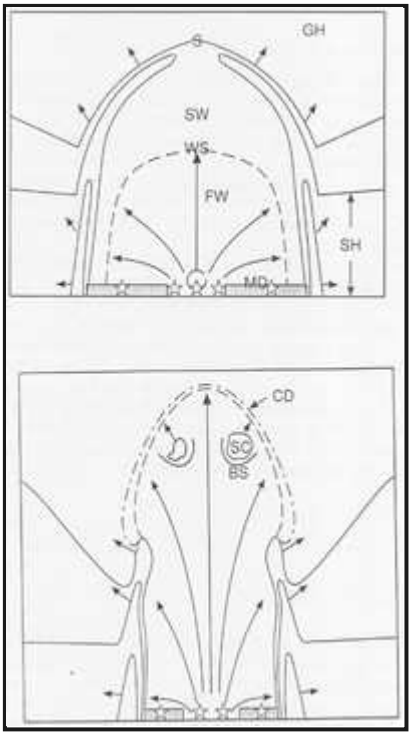

Figure 1. Schematic diagrams showing the essential features predicted for two evolutionary phases of a superwind expanding into the gaseous halo of a disk galaxy.

2.3. Conditions for Driving Superwinds

In this section, we will argue that there are two basic conditions to be met if a starburst is to drive a superwind. First, the energy injection rate inside the starburst must be high enough to create a cavity of hot gas whose radiative cooling time is much greater than its expansion time, and second, the wind must be sufficiently powerful to ultimately blow out of the ISM of the starburst (i.e., not remain trapped as a hot bubble inside the galaxy). We will show that these conditions are in fact met in typical starbursts (see HAM for details). Norman & Ikeuchi (1989) have reached the same conclusion using related arguments.

In order to drive a superwind, the kinetic energy supplied by supernovae and stellar winds must be efficiently converted into the bulk kinetic energy of the outflow - that is, very little of the energy should be lost in the form of radiation from the hot gas at the base of the outflow. This condition will be met if the energy injection rate is high enough to create a hot, tenuous gas phase that dominates the ISM of the starburst (i.e., has a volume-filling factor near unity). In this case, supernova and stellar wind ejecta will expand into a low-density medium and the radiative cooling time of the ejecta will exceed the wind outflow time. This

criterion can be expressed in terms of the well-known McKee - Ostriker (1977) 'porosity' parameter. The volume filling factor of the hot, tenuous phase is given by:

$$ff_{HOT} = 1 - \exp[-Q_{SNR}], \quad (12)$$

where

$$Q_{SNR} = 3E_{51}^{1.28}\ S_{-8}\ n_{0,100}^{-0.14}\ P_7^{-1.3}. \quad (13)$$

In Equation 13, E_{51} is the kinetic energy per supernova in units of 10^{51} ergs, S_{-8} is the supernova rate in units of 10^{-8} SNe per year per pc^3, $n_{0,100}$ is the mean gas density in starburst in units of 100 cm^{-3}, and P_7 is the pressure in the starburst in units of 10^7 K cm^{-3}. For typical parameters appropriate to starbursts, HAM concluded that Q_{SNR} will be of-order ten, so that ff_{HOT} is near unity.

An alternative way of evaluating whether radiative losses from the hot gas are important enough to stall the superwind is to use the expression derived by MM for the ratio of the radiative cooling time to the bubble expansion time for a supernova-driven bubble expanding in an disk with an exponential vertical density law with scale-height H and mid-plane density

$$t_{cool}/t_{exp} = 80 n_{0,100}^{-1.1}\ L_{bol,11}^{0.61}\ H_{100pc}^{-1.7}, \quad (14)$$

where we have used Equations 1 - 3 from the LRD models to write Equation 14 in terms of the starburst luminosity. Again, HAM showed that $t_{cool} >> t_{exp}$ for typical starburst parameters.

Finally, for the same 'bubble in an exponential disk' model, MM conclude that blow-out will occur if the dimensionless wind power $\Lambda > 100$. Using our Equations 1 - 3 to express this power in terms of the starburst bolometric luminosity, and following MM, we find:

$$\Lambda = 24000 L_{bol,11}\ H_{100pc}^{-2}\ P_7^{-3/2}\ n_{0,100}^{1/2}. \quad (15)$$

Typical parameters appropriate to starbursts then imply that blow-out is likely (see HAM for details).

2.4. The Effect of Clouds

So far, we have considered the theory of superwinds only in the context of a wind blowing into a homogeneous (single-phase) medium. In reality, the gaseous halos of star-forming galaxies are clearly multi-phase 'cloudy' systems (cf. Dettmar 1993; Bloemen 1991; and the review of QSO absorption-line systems by Steidel and Lanzetta in this volume). Such clouds could have a profound impact on the thermal and dynamical evolution of a superwind, and on the strength and character of the radiation they produce.

Let us then imagine a case in which clouds occupy only a small fraction of the volume swept by the superwind, but contribute a significant fraction of the gas mass within that volume. The evolution of the wind-blown cavity will still be qualitatively similar to the scenarios discussed above. The wind will propagate though and shock-heat the tenuous intercloud medium, inflating an expanding cavity. The clouds engulfed by the wind will suddenly find themselves highly over-pressured (and hence shock-heated) as they are subjected to the thermal pressure of the hot intercloud medium and/or the ram pressure of the wind itself (cf. Fig 1). The clouds will then presumably be destroyed by either hydrodynamical processes (cf. Hartquist & Dyson 1988; Stone & Norman 1992), by evaporation due to conductive heating (e.g., Cowie & McKee 1977), or by a combination of these processes in the 'mixing layers' at the cloud-intercloud interface (e.g., Begelman & Fabian 1990; Slavin, Shull, & Begelman 1993).

This 'mass-loading' by clouds of the intercloud medium will have several important consequences. First, the clouds will provide a source of cool, dense material which (when mixed with the intercloud medium) could significantly decrease the cooling time inside the wind-blown cavity. This could turn an energy-conserving outflow into a momentum-conserving one, and could even rob the bubble's interior of so much thermal energy that the bubble collapses before blow-out occurs (cf. Hartquist & Dyson 1988; White & Long 1991; McKee, Van Buren, & Lazareff 1984; Berman & Suchkov 1991). Second, the increased radiative

cooling inside the superwind cavity should make the superwind's emission more readily detectable.

Since this review is primarily about the observational manifestations of superwinds, we will address this second point in a bit more detail. It is likely that engulfed clouds may in fact be the dominant sources of the soft X-rays and optical emission-lines observed from superwinds (see Sections 3.1 and 3.2 below). For example, Begelman & Fabian (1990) and Slavin, Shull, & Begelman (1993) have proposed that hydrodynamical processes at the interface between a cloud and the intercloud medium through which it moves will lead to the development of a 'mixing layer': a region containing gas from both media whose temperature will be roughly equal to the logarithmic average of the temperatures of the two media. These mixing layers and the clouds they irradiate can be a copious source of optical, EUV, and soft X-ray emission.

Clouds heated by shocks driven into them by the superwind will also be sources of radiation. Balancing momentum across the shock implies that the speed of the shock driven into the cloud will be related to the superwind velocity by the inverse of the square root of the cloud-wind density contrast. Using Equation 2 above for the mass outflow rate in the wind, and adopting a wind speed of 2900 km s^{-1} for consistency (Section 2.2 above), implies:

$$v_{shock} = 166 L_{bol,11}^{1/2}\ r_{kpc}^{-1}\ n_{cloud}^{-1/2}\ \mathrm{km\ s^{-1}}, \quad (16)$$

for a cloud with a particle density n_{cloud} (cm^{-3}) located a distance r (in kpc) from the starburst.

Such a shock will heat the cloud to a temperature

$$\begin{aligned} T_{cloud} &= 1.4 \times 10^5 (v_{cloud}/100\ \mathrm{km\ s^{-1}})^2\ \mathrm{K} \\ &= 3.9 \times 10^5 L_{bol,11}\ r_{kpc}^{-2}\ n_{cloud}^{-1}\ \mathrm{K}, \end{aligned} \quad (17)$$

and we therefore see that such shocked clouds would produce soft X-rays, ionizing radiation, and optical emission-lines (cf. Shull & McKee 1979; Binette, Dopita, & Tuohy 1985).

The wind will also accelerate these clouds outward. Following CC, we can estimate the terminal velocity reached by a cloud with a column density typical of interstellar clouds in the Milky Way (N_{21} in units of 10^{21} cm^{-2}) accelerated outward from an initial location r_{kpc} (well outside the sonic radius of the wind):

$$v_{cloud} = 400 L_{bol,11}^{1/2}\ r_{kpc}^{-1/2}\ N_{21}^{-1/2}\ \mathrm{km\ s^{-1}}. \quad (18)$$

Here we have used Equations 1 and 2 above to relate the mass and energy flux in the wind to the starburst luminosity. We therefore expect the shocked clouds responsible for optical emission-lines to have typical outflow speeds of a few hundred km s^{-1}.

3. OBSERVATIONAL DIAGNOSTICS OF SUPERWINDS

3.1. X-Ray Observations of Superwinds

The overall X-ray properties of starburst galaxies have been recently reviewed by Petre (1993), so we will focus on the interplay between the X-ray data and the superwind phenomenon. X-ray observations of superwinds are crucial to our understanding of the phenomenon, because (potentially at least) they offer the most direct probe of the hot, tenuous superwind fluid itself (rather than simply probing the interaction of the wind with ambient gas, as is most likely the case for the optical line emission).

The characteristic temperature corresponding to the complete thermalization of the kinetic energy from an ensemble of supernovae and winds from massive stars is about kT = 10 keV (e.g., 10^{51} ergs per 10 $M_\odot$) - see Section 2 above. Thus we expect hard X-ray emission from a galaxy driving a superwind to come from the hot and tenuous supernova/wind-heated gas inside the starburst (i.e., inside the sonic radius of the wind). Since the corresponding terminal velocity of the outflowing superwind fluid is several thousand km s^{-1}, hard X-rays will also arise from internal shocks in the superwind (cf. Tomisaka & Ikeuchi 1988; Balsara, Suchkov, & Heckman 1993). In the idealized expanding bubble discussed in Section 2 above, these X-rays will be coming from zone 3.

Soft X-rays will be produced by dense ambient material that is shock-heated and/or evaporated by the superwind (cf. Watson, Stanger, & Griffiths 1984; White & Long 1991). In the idealized 'expanding bubble' model discussed in Section 2, this would correspond to the thin shell of shocked ambient gas at the interface with the undisturbed ambient gas (zone 4). In a more realistic situation, the soft X-rays will arise as the wind collides with, shock-heats, and evaporates density inhomogeneities ('clouds') in the galaxy halo. H I observations of starbursts show that such cool, dense material indeed exists in the environs of starbursts (see Section 3.4 below). Note that the typical outflow velocity of dense, wind-accelerated ambient material is observed in the optical to be several hundred km s^{-1} (see Section 3.2 below), corresponding to post-shock temperatures of $kT \sim 200$ eV.

This theoretical/phenomenological picture is in reasonable agreement with the limited amount of X-ray data presently available for starburst galaxies. The X-ray luminosity of starburst galaxies correlates rather well with both the IR luminosity (e.g., Griffiths & Padovani 1990; David, Jones, & Forman 1992; Green, Anderson, & Ward 1992) and the Lyman continuum luminosity (Ward 1988) of the starburst. Moreover, the observed average ratio of X-ray and bolometric starburst luminosities agrees roughly with the predictions of simple theoretical models for starburst-driven superwinds (HAM - and see the discussion in Section 2 above). X-ray spectra of starbursts imply characteristic temperatures of kT = 6 to 9 keV for the global X-ray emission (e.g., Kim, Fabbiano, & Trinchieri 1992; Ohashi et al. 1990; Petre 1993), again in agreement with simple models (see Section 2 above).

Spatially-resolved X-ray images of well-studied starburst galaxies whose large-scale stellar disks are viewed nearly edge-on (M 82, NGC 253, NGC 2146, and NGC 3628) show striking X-ray 'halos' or 'plumes' that can extend out to a radius of 10 kpc or more along the galaxy minor axis. These have been interpreted as direct evidence for galactic superwinds (e.g., Watson, Stanger, & Griffiths 1984; Fabbiano 1988; Fabbiano, Heckman, & Keel 1990; Heckman & Fabbiano 1993; Armus, Heckman, & Weaver 1993). The transgalactic-scale X-ray nebulae associated with such 'ultraluminous' IR galaxies as Arp 220, NGC 3690, and Mrk 266 are likely to be more energetic versions of this phenomenon (Eales & Arnaud 1988; Armus, Heckman, & Weaver 1993).

In general, the estimated thermal energy content and mass of the X-ray gas are consistent with the time-integrated kinetic energy and mass output of the starburst (cf. HAM and references therein). However, these estimates are based on several simplifying assumptions. The most important of these are that all the observed X-rays arise from hot gas at a uniform - and high - temperature equal to that deduced on the basis of the integrated X-ray spectrum, and that this gas has a volume filling factor of unity. As we now discuss, the actual situation is likely to be considerably more complex.

The X-ray emission from the halo of M 82 is significantly softer than that from the central starburst (Petre 1993), as is also the case in NGC 3628 (Fabbiano, Heckman, & Keel 1990; Heckman & Fabbiano 1993) and NGC 3690 (Armus, Heckman, & Weaver 1993). Within the context of the superwind model, this could imply that the wind has broken free of the galaxy and has suffered severe adiabatic cooling on its way out (cf. CC and Equation 6 above). However, this is unlikely to be the case, since the X-ray nebulae are far too bright to simply be an adiabatically-cooled free-wind (e.g., Mathews & Doane 1993). Our new ROSAT images of several starbursts with superwinds also show a considerable amount of fine-scale structure: X-ray-bright 'lumps' and 'filaments' with sizes of a few hundred pc to a few kpc (Heckman & Fabbiano 1993; Armus, Heckman, & Weaver 1993). We believe it is most likely that the soft (kT Petre (1993) emphasizes that BBXRT data on starbursts show clear evidence for multiple X-ray spectral components, and Armus, Heckman, & Weaver (1993) have reached similar conclusions based on ROSAT PSPC data. X-ray images of the two nearest starburst galaxies (M 82 and NGC 253) also show that the X-ray emission is produced by both the spatially-extended component discussed above and a collection of discrete sources in or near the starburst (Watson, Stanger, & Griffiths 1984; Fabbiano & Trinchieri 1984). Thus, it may well be that much of the hard X-ray emission from starbursts is produced by the ensemble of X-ray binary systems in the starburst (e.g., Griffiths & Padovani 1990). Inverse Compton scattering of IR photons off the relativistic electrons responsible for the radio continuum emission may also contribute substantially to the hard X-ray emission (e.g., Schaaf et al. 1989; but Seaquist & Odegard 1991 and Tsuru 1992 argue otherwise). A composite thermal plus nonthermal origin for the hard X-rays could explain the relative weakness of the 6.7 keV Fe K line in M 82 and NGC 253 compared to expectations for optically thin thermal emission from gas with solar Fe abundances and kT = 5 to 10 keV (Tsuru 1992; Ohashi et al. 1990; Petre 1993).

One of the most interesting X-ray observations of a likely superwind is the Ginga data on the center of our own Milky Way (Yamauchi et al. 1990). Emission-line images using the 6.7 keV Fe K line imply a region of gas with a temperature of about 10^8 K, dimensions of about 270 × 150 pc, gas pressures of $P/k = 8 \times 10^6$ K cm^{-3}, and total thermal energy content of $6 times 10^{53}$ ergs. Since the sound speed in this gas (~ 1500 km s^{-1}) greatly exceeds the escape velocity from the Galactic Center, the gas should flow out as a high speed wind (unless it is confined by some other mechanism). If this outflow is a steady-state phenomenon, collisional heating with a supernova rate of about 0.6 per century within this volume is required to balance adiabatic cooling.

To summarize, while the current situation regarding X-ray emission from superwinds is unclear, we can expect dramatic progress over the next few years as the avalanche of new ROSAT, BBXRT, and ASTRO-D data on starbursts is analyzed and

digested. Certainly the data already in hand are very tantalizing.

3.2. Optical Line Emission from Superwinds

Most of the existing data on superwinds concern the optical line emission associated with such outflows. Such data provide a whole array of diagnostics of the dynamical and physical state of the outflow.

In the simple schematic pictures described in Section 2 above, the optical line emission would not arise from the very hot and tenuous superwind fluid itself (the cooling times are excessively long, and most of the relatively feeble radiation that is produced there is in the form of hard X-rays). Instead, we would expect the optical line emission to come from relatively dense ambient material into which the wind's ram pressure drives slow (< few hundred km s^{-1}) radiative shocks (e.g., McKee & Hollenbach 1980 and see Section 2.2 above). In the wind-blown bubble 'onion-skin' model, this material would be the thin, dense shell of compressed and shock-heated ambient gas at the leading edge of the bubble. In a more realistic situation in which blow-out has occurred, and/or in which the wind is propagating through a inhomogeneous, multi-phase medium, the optical line emission will come from clouds (e.g., fragments of the ruptured shell, pre-existing density inhomogeneities in the halo, or material carried out of the galactic disk by the superwind).

We therefore expect that the optical data will provide a detailed - but indirect - view of the superwind phenomenon. The largest compilations of such data are found in the recent spectroscopic and narrow-band imaging surveys by HAM, Armus, Heckman, & Miley (1989, 1990 - hereafter AHM89, AHM9O), Lehnert (1992 - hereafter L92), and Lehnert & Heckman (1993 - hereafter LH).

3.2.1. *Structure and Luminosity*

Galaxies selected to be both luminous and warm in the far-IR have optical emission-line nebulae whose size and luminosity correlate reasonably well with the far-IR luminosity, and hence with the estimated formation rate of massive stars (AHM9O; L92; LH). The Hα luminosities of the extra-nuclear portion of the nebulae (e.g., well outside the starburst region) are just consistent with the predictions of the superwind model (see Equation 11 and the associated discussion in Section 2 and in HAM).

We (L92, LH) have recently completed an Hα imaging survey of a sample of edge-on disk galaxies selected on the basis of far-IR flux and color, and find many examples which show emission-line filaments, loops, or bubbles extending out one to ten kpc along the optical minor axis of the galaxy (four examples are shown in Figure 2). In general, we find a pronounced excess of optical line emission along the optical minor axis compared to what would be expected for ordinary emission-line gas confined to the galactic disk. At the highest levels of IR luminosity (L > few × 10^{11} $L_{\odot}$), the Hα nebulae approach transgalactic dimensions (30-100 kpc), with the large-scale morphology often dominated by filaments, loops, or bubbles (e.g., Heckman, Armus, & Miley 1987; AHM90). Some examples of such nebulae are shown in Figure 3.

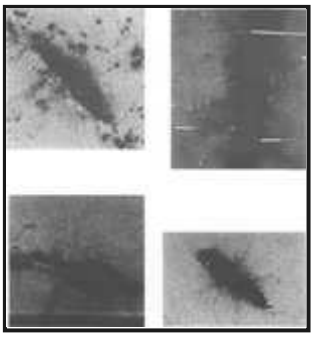

Figure 2. Hα+[NII] images of IR-bright, edge-on disk galaxies exhibiting large-scale optical emission-line filaments extending several kpc out of the galaxy disk and into the halo. (a) NGC 660; (b) NGC 3079; (c) NGC 3628; and (d) NGC 4666 - see AHM90; Fabbiano, Heckman, & Keel 1990; L92; LH).

Figure 3. Hα+[NII] images of two galaxies with IR luminosities greater than 10^{45} erg s^{-1}: (a) Arp 220 (from Heckman, Armus, & Miley 1987) and (b) Mrk 266 (from AHM90). These represent the superwind phenomenon at the high-luminosity end, where the emission-line nebulae are tens of kpc in size

HAM, L92, and LH have measured radial electron density profiles in the emission-line nebulae associated with about 20 IR-selected starburst galaxies. Densities range from 10^3 to $< 10^2$ cm^{-3}. The observed Hα luminosities and the measured densities allow us to estimate the mass and the volume-filling factor of optical emission-line gas. The derived masses range from 10^5 $M_\odot$ to 10^7 $M_\odot$, and the volume-filling factors are typically 10^{-3} to 10^{-4}. Thus, the emission-line gas represents a modest amount of relatively dense material distributed in the form of clumps, sheets, or filaments that occupy only a very small fraction of the volume of the halo of the starburst galaxy.

In the few starburst galaxies for which both Hα and X-ray images are available, there is a clear correspondence between the two images (e.g., Watson, Stanger, & Griffiths 1984; Armus, Heckman, & Weaver 1993). In some cases, the optical line emission is preferentially located along the outer boundary of the X-ray nebula (Fabbiano, Heckman, & Keel 1990; Heckman & Fabbiano 1993; McCarthy, Heckman, & van Breugel 1987 - and see Figure 4). This suggests that the optical line emission arises at the interface between the hot superwind and the ambient interstellar gas in the halo of the starburst galaxy (in good agreement with both the theoretical picture sketched above and the kinematics of the optical emission-line gas in several well-studied cases, as summarized below). New ROSAT images should allow us to conduct many more such comparisons, in order to better test this idea.

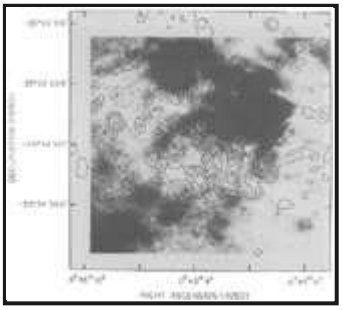

Figure 4. Overlaid Hα+[N II] image (greyscale) and Einstein HRI X-ray image (contour plot) of the central few kpc of the prototypical IR starburst galaxy NGC 253. The starburst nucleus is located in the upper right corner. Note how the filamentary optical line emission to the SE of the nucleus seems to enclose the X-ray plume (cf. McCarthy, Heckman, & van Breugel 1987 ; Fabbiano & Trinchieri 1984; LH; L92).

3.2.2. *Kinematics and Dynamics*

The kinematics of the optical emission-line gas associated with IR-luminous galaxies also suggest that outflows are common. Optical spectra of the nuclei of IR-luminous galaxies show that they often have blue-asymmetric emission-line profiles (e.g., AHM89; LH; Phillips 1992). Mirabel & Sanders (1988) find that the optical emission-line velocities in the nuclei of high-luminosity IR galaxies are blueshifted with respect to the galaxy systemic velocity by an average of about 100 km s^{-1}. Both the blue-asymmetric profiles and blueshifts suggest an outflow of ionized gas whose redshifted back side is obscured by dust.

For the edge-on starburst galaxies investigated by L92 and LH, in many cases the line widths actually increase with increasing radius along the minor axis. The emission-lines are also systematically broader along the minor than along the major axis (with typical FWHM's of 150 to 350 km s^{-1} vs. × 100 to 200 km s^{-1} respectively). The line widths along the minor axis correlate strongly with the starburst IR luminosity, but not with the galaxy rotation speed, thus favoring a starburst-driven outflow over simple orbital motions in the galaxy gravitational potential (see Figure 5). This interpretation is further supported by the strong trend found by L92 and LH for the largest measured velocity shears along the minor axis to occur in the galaxies viewed more nearly face-on (as expected for a starburst-driven radial outflow along the minor axis) and in the galaxies with the highest IR luminosities (see Figure 6).

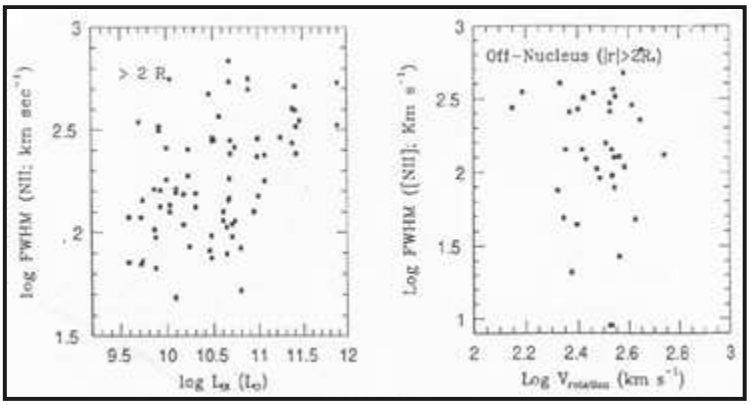

Figure 5. Summary of the kinematics of the emission-line gas located outside the central starburst and along the optical minor axis for the IR-selected edge-on disk galaxies investigated by L92 and LH. The x-axis in both plots is the FWHM of the [N II]6584 line. This line width correlates strongly with the IR luminosity of the galaxy (left plot), but not with the rotation speed of the galaxy (right plot), implying that the gas dynamics is influenced much more strongly by the starburst-driven wind than by gravity.

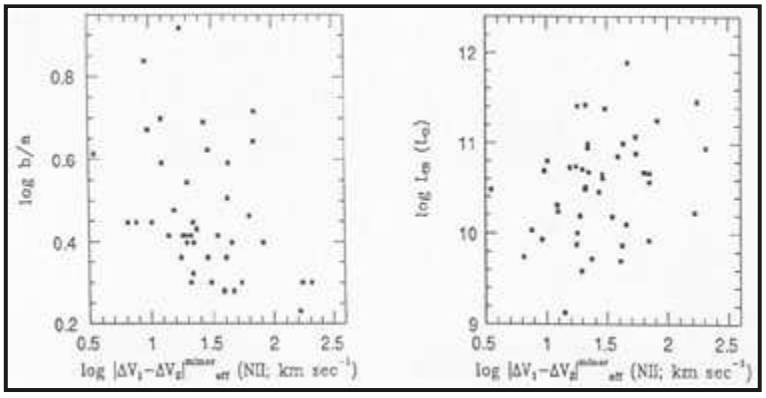

Figure 6. Summary of the kinematics of the emission-line gas located along the optical minor axis for the IR-selected edge-on disk galaxies investigated by L92 and LH. These two plots show that the velocity shear along the minor axis is largest in the galaxies that are viewed more nearly face-on (left plot) and in the galaxies with the largest IR luminosities (right plot).

The detailed kinematic properties of the gas located along the minor axes of such nearby and well-studied edge-on starbursts as

M 82 (e.g., Bland & Tully 1988; HAM), NGC 253 (Ulrich 1978; HAM), NGC 3079 (HAM; Filippenko & Sargent 1992), and NGC 4945 (HAM) provide more direct evidence for outflows. All four galaxies have bubble-like or filamentary emission-line nebulae that protrude out about a kpc along the optical minor axis. The kinematics of these structures (broad, double-peaked emission-line profiles in the center of the bubble, narrowing to single-peaked profiles along the bubble periphery) imply that they are either expanding bubbles or the walls of cone-like or cylindrical outflows, with inferred outflow/expansion speeds ranging from about 200 km s^{-1} to nearly 1000 km s^{-1} (see Figure 7). The sizes and expansion speeds of these structures are in good agreement with the quantitative predictions of the simple wind-blown-bubble model discussed in Section 2 (see equations 9 and 10 above, and HAM). Additional examples of similar outflow structures are found in the composite Seyfert/starburst galaxies NGC 1365 (Phillips et al. 1983a), NGC 5506 (Wilson, Baldwin, & Ulvestad 1985), NGC 7582 (Morris et al. 1985), and Mrk 509 (Phillips et al. 1983b).

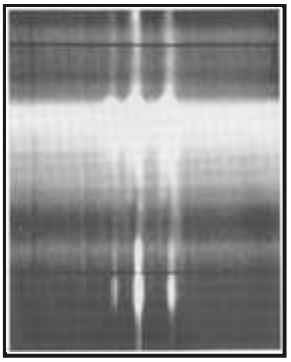

Figure 7. Long-slit spectrum of (from left to right) the [N II] Å 6548, H α, [N II] Å 6584 emission-lines in the central few kpc of NGC 253. The slit was oriented in a position angle of 135 degrees, along the minor axis of this edge-on galaxy. Note that each of the three lines has a double-peaked profile shape throughout a region about 600 pc in extent to the SE of the nucleus. This line-splitting has a magnitude of about 300 to 400 km s^{-1}, and suggests either an expanding bubble or outflow along the surface of a hollow cone-like structure (cf. HAM). This region of expanding gas also corresponds to the bright X-ray plume seen in Fig. 4 (cf. Fabbiano & Trinchieri 1984 ; McCarthy, Heckman, & van Breugel 1987).

Qualitatively similar, but even larger and more energetic examples of such expanding structures, are found in several 'ultraluminous' IR galaxies (HAM). These are the 'double-bubble' emission-line nebula in Arp 220, the central 'hour-glass' structure in NGC 6240, and the extraordinary nebula associated with IRAS 00182-7112 in which line-widths are nearly 1000 km s^{-1} over a region 30 kpc in extent. Colina, Lipari, & Macchetto (1991) have also published kinematic evidence for a superwind in the ultraluminous galaxy IRAS 19254-7245.

On the 'micro-starburst' level, Meurer et al. (1992) have found a kpc-scale bubble of ionized gas expanding at about 50 km s^{-1} in the core of the post-starburst dwarf galaxy NGC 1705. They show that this expansion was probably powered by the kinetic energy supplied by a burst of star-formation that occurred some 10 Myr ago. Roy et al (1991) have found a kinematically similar 200 pc-scale expanding bubble of ionized gas in the starbursting dwarf irregular galaxy NGC 2366, while de Vaucouleurs, de Vaucouleurs, & Pence (1974) found evidence for large-scale outflow in the similar system NGC 1569. JHU graduate student A. Marlowe with T. Heckman, R. Wyse, and R. Schommer have now found an additional half-dozen similar examples in their echelle and Fabry-Perot Hα survey of UV-bright dwarf galaxies (Marlowe et al. 1993). Because the potential wells of dwarfs are so shallow, there is a broad theoretical consensus that starburst-driven mass loss plays a crucial role in the evolution of such systems (e.g., Silk, Wyse, & Shields 1987). We will discuss related H I observations of several dwarf galaxies in Section 3.4 below.

As a closing comment on the kinematics of the optical emission-line gas, we note that the outflow velocities as deduced from all the evidence summarized above are quite modest (typically < several hundred km s^{-1}). These velocities are much lower than the predicted outflow speed for the hot, tenuous superwind fluid (a few thousand km s^{-1} - see Section 2), but are quite consistent

with our expectations for ambient gas that is being shocked and accelerated outward by the wind (see the discussion in Sections 2.2 and 2.4 above). This may be seen by considering Equations 10, 16, and 18 above, or by noting that strong optical line emission will only be produced by material into which radiative shocks are being driven (e.g., shocks in which the radiative cooling time behind the shock is short compared to the shock dynamical timescale). As reviewed by McKee & Hollenbach (1980), radiative shocks in the ISM generally have shock speeds less than a few hundred km s^{-1}. Since we expect the velocity to which a shocked cloud is accelerated by the superwind to be similar to the speed of the shock driven into it, the observed outflow velocities therefore represent additional indirect evidence for the schematic picture we have developed above.

3.2.3. *Emission-Line Ratios and the Ionization Source*

The relative emission-line intensities in the nebulae associated with superwinds provide indirect evidence for a high-speed outflow. Key emission-line ratios like [S II]ΛΛ6716,6731 / Hα, [N II]Λ6584 / Hα, and [O I]Λ6300 / Hα have values that are more similar to those seen in gas that has been shock-heated (e.g., old supernova remnants and Herbig-Haro objects - cf. Hartigan, Raymond, & Hartmann 1987; Fesen, Blair, & Kirshner 1985) than to what is observed in H II regions in spiral and irregular galaxies (e.g., McCall, Rybski, & Shields 1985). We (L92; LH) find that all these ratios tend to increase with increasing radius along the minor axis in edge-on starburst galaxies (see also AHM89 and HAM) and are also systematically larger along the minor axis than along the major axis.

The simplest picture is that the heating and ionization of the gas in the central starburst and in the large-scale disk of the galaxy is dominated by photoionization by hot stars. In contrast, shocking of ambient gas by the superwind probably makes a significant contribution to heating the gas located out in the galaxy halo and seen most clearly along the minor axis. The transfer of energy from the hot superwind gas to imbedded cool, dense material via the 'mixing layer' phenomenon (Begelman & Fabian 1990; Slavin, Shull, & Begelman 1993) may also contribute to the heating and ionization of the optical emission-line gas. It is also possible that the halo gas is photoionized by an extremely dilute radiation field 'leaking' out of the starburst (e.g., Sokolowski & Bland-Hawthorn 1993; see also Dettmar 1993 and references therein).

Perhaps the strongest indirect evidence for mechanical heating of the gas by the superwind is the strong correlation found by HAM, L92, and LH between the dynamical state of the gas (as measured by the emission-line widths) and the thermal/ionization state of the gas (as probed by the strengths of the [O I], [S II], and [N II] lines relative to Hα). This strongly suggests that the same mechanism is responsible for both heating and accelerating the gas. The most decisive way of testing whether the gas is collisionally ionized or photoionized would be to determine whether the electron temperature in the O III zone is higher than can be explained by photoionization (e.g., T > 20,000 K - cf. Osterbrock 1989). HAM attempted such measurements using the ratio of the [O III]Λ4363 and Λ5007 lines, but the results were inconclusive (in some cases shock-heating was favored and in other cases photoionization).

3.2.4. *Densities and Pressures as Diagnostics*

One of the most useful diagnostics of superwinds is to use the ratio of the [S II]Λ6716 and Λ6731 lines to determine the radial run of density within the superwind nebulae. In many cases, the average temperature of the nebula can also be deduced from the ratio of the [N II]Λ5755 and Λ6584 lines, so that the radial run of pressure can be determined. According to superwind models, the central pressure in the starburst is set by the starburst radius and the rate at which momentum is injected by supernovae and stellar winds (cf. CC; HAM; see Equation 4 above). HAM have used the measured central pressures and the predicted momentum injection rates to estimate starburst radii for 12 IR-selected galaxies. These radii agree surprisingly well (typically within 0.1 dex) with radii measured directly from radio, IR, and optical imaging of the starbursts (see also L92; LH).

The superwind model also predicts that once the wind 'blows out' of the galactic disk and is in free expansion, the pressure within the wind is dominated by ram pressure. The ram pressure will drop like the inverse square of the radius and will be proportional to the rate at which the starburst injects momentum into the wind (see Equation 5 above). HAM have used the measured pressure profiles in 12 IR-selected galaxies to estimate the momentum flux of the wind, and find excellent agreement between these estimates and the predicted rate of momentum input from the starburst. This analysis has been extended to an additional set of galaxies by L92 and LH, and the good agreement between theory and observation verified over a range of nearly three orders-of-magnitude in starburst luminosity.

It is worth emphasizing that an ultraluminous starburst/superwind can produce pressures over galactic-scale volumes that are three to four orders-of-magnitude higher than the general pressure in the ISM in the Milky Way: e.g., P/k > few × 10^6 K cm^{-3} (see HAM, L92, and LH for details). The radius of the over-pressured region (as measured out to some fixed isobar) should scale as the square-root of the star-formation rate, and this dependence has been confirmed by HAM, L92, and LH. HAM and LRD have further shown that the $P\,\Delta V$ work represented by the measured pressure profiles in the halos of starbursts with superwinds is in satisfactory agreement with the time-integrated kinetic energy input predicted from the starburst (cf. Equation 1 above).

The high measured pressures and the systematic dependence of the radial pressure profile upon the starburst luminosity clearly establish that starbursts are able to regulate the gas pressure over very large volumes (at least one hundred times the volume of the starburst itself). But must this regulation be due to a wind? Might it not be possible for the measured pressure profiles to reflect the static thermal pressure in a hot volume-filling phase that is gravitationally bound to the starburst galaxy?

In fact, it is rather easy to rule out the above idea for those starbursts in HAM that have X-ray data available. Since the X-ray luminosity depends on density squared, and since the density (at fixed pressure) is inversely proportional to the temperature, it follows that the hotter the volume-filling phase (at fixed pressure), the lower its X-ray luminosity. Specifically, we calculate that a volume-filling hot phase in pressure-balance with the optical emission-line clouds would have an X-ray luminosity that exceeds the measured X-ray luminosity unless it has a temperature in excess of 4×10^7 K. The sound-speed in gas at $T > 4 \times 10^7$ K is $c_S > 1000$ km s^{-1}, which is in turn much greater than the escape velocity from the starburst potential well. Thus, any such gas could not be bound to the starburst and will flow out as a wind (QED!).

The shapes of the measured pressure profiles can also be used to argue against an AGN as the source of the wind. If, as would be the case with an AGN, the region of mass/energy injection is small compared to the seeing-disk (which has a typical radius of 100 pc for the starbursts in HAM and LH), then the radial pressure profile should follow an inverse square law all the way in to the center. Such a r^{-2} radial density/pressure profile is directly measured in the classical AGN (type 1 Seyfert nucleus) NGC 4151 by Mediavilla et al. (1992) over a range in radii between about 70 and 400 pc (e.g., into the approximate radius of the seeing disk). Pronik (1989) has used the observed correlations between critical density and line width for many different forbidden lines in the nucleus to conclude that the density in NGC 4151 continues to follow a r^{-2} law all the way in to sub-pc scales. In contrast, the observed radial pressure profiles in most IR-bright galaxies show flat central zones (within the starburst, where mass and energy are injected) and then steepen to approximately r^{-2} at large radii (in reasonable agreement with theoretical models - cf. CC; HAM; LH). This behavior can be clearly seen in Figure 8 for the two galaxies in HAM for which the measured radial pressure profiles are of the highest quality (M 82 and NGC 3256). The shapes of the radial pressure profiles are remarkably similar in the two galaxies, and the larger radial scale associated with the 8-times-more-luminous starburst in NGC 3256 is exactly as predicted by the superwind model. Note that both profiles are relatively flat in the central region (within the starburst radius denoted r_* in the plot), and then steepen to an r^{-2} dependence at large radii.

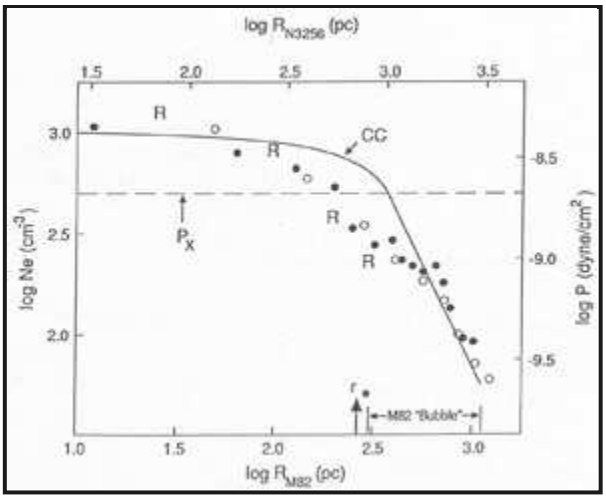

Figure 8. A log-log plot of the electron density (left axis) and gas pressure (right axis) vs. radius for two well-studied starburst galaxies (M 82 - solid dots; NGC 3256 - hollow dots). Note that the radial scale for NGC 3256 (upper axis) has been shifted by 0.45 dex (factor 2.8) with respect to that for M 82 (lower axis). The radial pressure profile predicted for both galaxies by the simple spherically-symmetric wind model of CC is indicated by the solid curve. We have also indicated estimates of the pressures in the X-ray and radio plasma in M 82. See HAM for further details.

3.2.5. *The Role of Scattering*

Finally, in closing our discussion of optical line emission, it must be emphasized that imaging polarimetry of the famous M 82 nebula shows that Hα emission from a portion of the starburst nucleus is being scattered into our line-of-sight by dust grains in the halo of M 82, and that this scattered light makes a significant contribution to the observed Hα emission in the halo (Scarrott, Eaton, & Axon 1991 and references therein). On the other hand, the systematic spatial variations in the optical emission-line ratios measured in the inner portion of the minor-axis nebula (that is, the gas located within about 30 degrees of the minor axis and within about a kpc from the nucleus) show that the majority of the Hα emission from this region must be intrinsic to the filament system rather than scattered light (e.g., McCarthy, Heckman, & van Breugel 1987; Bland & Tully 1988; HAM). Indeed, the polarization of the Hα within this region is typically only 4 to 10%, compared to values of 10 to 30% at greater angles off the minor axis (Scarrott, Eaton, & Axon 1991). It is also this inner region with lower polarization in which the clear kinematic signature of an outflow is seen (HAM; Bland & Tully 1988). We suggest that scattered light contributes no more than about 30% of the Hα flux in this inner region. A spectropolarimetric, multi-emission-line mapping of the M 82 nebula with a spectral resolution of an Ångstrom or better would clearly be a magnificent Ph.D. thesis project!

3.3. The Relativistic Plasma Associated with Superwinds

Several starburst galaxies have been discovered to have large-scale nonthermal radio halos. These presumably arise as relativistic magnetized plasma is convected by the superwind out of the central starburst, where it was created by supernovae (e.g., Lerche & Schlickeiser 1980).

The galaxy M 82, studied most recently by Seaquist & Odegard (1991), has a synchrotron-emitting halo extending out to a radius of at least 8 kpc. The spectrum of the radio emission steepens markedly with increasing radius, which Seaquist & Odegard attribute to the more rapid cooling of the most energetic electrons by inverse Compton scattering of the starburst IR photons. They then derive an outflow speed for the relativistic plasma of about 2000 km s^{-1} (consistent with the expected outflow speed of the tenuous superwind fluid - cf. CC and the discussion in Section 2 above). They also use the radio data to argue that inverse Compton radiation contributes a negligible fraction of the X-ray emission from M 82 (see Section 3.1 above), and they estimate that relativistic particles comprise only a few percent of the energy content of the wind. They note that this ratio is similar to that observed in supernova remnants, as expected in the superwind model. Reuter et al. (1992) have obtained higher resolution maps of the M 82 halo, and find a considerable amount of structure (radially-oriented filaments and gaps). They interpret this as clear evidence that magnetized plasma is being convected out of the M 82 starburst, creating a bipolar (poloidal) magnetic field geometry.

Hummel & Dettmar (1990) have studied the nonthermal radio halo of the edge-on actively-star-forming galaxy NGC 4631, and have argued that the radial spectral index gradient they measure for the radio emission is consistent with models in which relativistic plasma is convected out of the galaxy by a wind, and is then cooled by synchrotron, inverse Compton, and/or adiabatic-expansion losses. As in M 82, the magnetic field geometry in the halo of NGC 4631 is inferred to be poloidal (field lines directed radially outward). Hummel & Dettmar suggest this is due to the operation of a strong galactic wind in this galaxy (though a dynamo model for the field can not be ruled out).

Most recently, Carilli et al. (1992) have discovered a radio halo around the edge-on starburst galaxy NGC 253 which extends out to at least 9 kpc. As in the case of M 82 and NGC 4631, the radio spectrum steepens with increasing distance from the disk/starburst, and Carilli et al. interpret this as evidence for an outflow from the galactic disk into the halo. The magnetic field geometry in this case appears more nearly toroidal (field lines parallel to the galactic disk), except along a bright radio spur that attaches to the inner disk of the galaxy. Dettmar (1993) has also discussed the radio halo of the IR-bright edge-on disk galaxy NGC 5775 (Hummel 1991), and emphasized the close connection between the radio halo and the system of faint Hα filaments extending many kpc out of the galactic disk.

There are also less complete data indicating the presence of thick radio disks and/or radio halos in the edge-on starburst systems NGC 1808 (Dahlem et al. 1990), NGC 3628 (Reuter et al. 1991), and NGC 4945 (Harnett et al. 1989). The smaller (few-kpc-scale) radio sources extending out along the minor axes of some edge-on radio-bright disk galaxies (e.g., Duric et al. 1983; Hummel, van Gorkom, & Kotanyl 1983) may also be related phenomena.

3.4. The Cool Gas Associated with Superwinds

Studies of the interaction of superwinds with cool atomic and molecular gas are potentially very important, since such gas is expected to comprise the major fraction of the mass of the ISM inside starburst galaxies or in their surrounding halos. One of the most important insights provided by such studies is that starburst galaxies are often immersed in large (transgalactic-scale) HI envelopes or halos, presumably of tidal origin (e.g., Yun & Ho 1993; Hibbard et al. 1993; Fisher & Tully 1977; Haynes et al. 1979; Stanford 1990; Stanford & Wood 1989; Gottesman & Mahon 1990). This is of crucial significance, because the interaction between the wind and this comparatively dense halo gas probably accounts for the relative brightness of superwinds in the optical and X-ray domain. Were such gas not present - i.e., if superwinds instead flowed into a very low density intergalactic medium - they would quickly adiabatically cool, their density would rapidly drop, and they would then become

undetectably faint sources of either X-rays or optical line emission (cf. Mathews & Doane 1993). Thus, it is likely that the interaction of the superwind with the H I envelope/halo is fundamental in determining what we observe at optical and X-ray wavelengths.

Studies of the cool gas in the environs of starbursts have also provided direct evidence for outflows. Indeed, possibly the single most convincing piece of evidence to date for an outflow from a starburst galaxy is the recent analysis of the kinematics of the Na I D doublet seen in the well-known starburst galaxy NGC 1808 (Phillips 1992). He has studied the kinematics of the system of radial dust-filaments that extend several kpc out along the minor axis of this galaxy. The Na D doublet is seen in absorption on the near side of the outflow, and has a strongly blueshifted component (by up to 400 km s^{-1} with respect to the systemic velocity). Since the kinematics are being probed with absorption-lines in this case, there is no possible ambiguity in the sign of the observed (outward) radial motions. Assuming a standard gas-to-dust ratio in the outbound dust filaments, the implied mass of the ejected material is about 6×10^7 $M_\odot$. The kinetic energy of this material is then about 10^{56} ergs, or about 20% of the time-integrated kinetic energy of the starburst in NGC 1808 over a period of 10^7 yr (the dynamical lifetime of the dust filament system). This is in good agreement with the prediction that the kinetic energy in the shell of an energy-conserving wind-blown bubble should be about 20% of the total time-integrated amount of injected kinetic energy (cf. Dyson 1989).

There are also several pieces of evidence for outflowing molecular gas in starbursts. High-resolution 115GHz CO observations of M 82 by Nakai et al. (1987) suggest that molecular gas is flowing out of the central starburst, and Irwin & Sofue (1992) have reached similar conclusions for the CO in the center of NGC 3079. Turner (1985) has found a molecular outflow traced by the OH emission lines extending out from the nucleus to about 1.5 kpc along the minor axis of NGC 253, and van der Werf et al. (1994) have found plumes of near-IR-emitting molecular hydrogen at the base of this apparent outflow. In the most detailed near-IR study to-date of the famous IR-luminous galaxy NGC 6240, van der Werf et al. (1993) have uncovered convincing kinematic and morphological evidence that the relatively warm molecular gas (as probed with the near-IR vibration-rotation lines of H_2) in this system is being ejected from the starburst at velocities of several hundred to 1000 km s^{-1} (in agreement with the kinematics of the ionized gas discussed by HAM).

Radio observations of H I in several starburst galaxies also reveal the impact a superwind can have on the cool ISM. Yun, Ho, & Lo (1992) have suggested that the wind from the starburst in M 82 has carved a channel through the inner part of that galaxy's H I envelope. Koribalski et al. (1992) have found clear kinematic evidence for H I flowing out along the minor axis of the starburst galaxy NGC 1808 at a velocity of at least 150 km s^{-1}. This is the same outflow studied optically at much higher spatial resolution via the Na I D line by Phillips (1992 - see above).

Recent VLA H I maps of several star-forming dwarf galaxies have revealed the presence of kpc-scale H I shells expanding at about 10 km s^{-1} (e.g., Puche et al. 1992; Westpfahl & Puche 1992). These authors argue that such expanding, hollow structures are the result of the collective effect of multiple stellar winds and supernovae. Moreover, since the sizes and expansion speeds of the bubbles are comparable to the total sizes and internal velocity dispersions in the smallest dwarf galaxies, these structures probably play a major role in the evolution of the ISM and of star-formation in such galaxies (e.g., Westpfahl & Puche 1992).

Perhaps the most spectacular phenomenon ascribed to a superwind is the ram pressure stripping of the H I out of the outer parts of the galaxy NGC 3073 by its starbursting, superwind-driving neighbor NGC 3079 (Irwin et al. 1987). The ram pressure that Irwin et al. estimate as being required to strip the H I from NGC 3073 implies a superwind momentum flux that agrees well with that estimated for NGC 3079 by HAM via three independent techniques (from the kinematics of the expanding bubble, from the radial pressure profile, and from the starburst luminosity using Equation 3 above).

4. A LOCAL CENSUS OF SUPERWINDS: THEIR GLOBAL SIGNIFICANCE

HAM presented preliminary estimates of the rates at which starbursts inject mass, metals, and energy into superwinds at the present epoch. These estimates were based on the following assumptions (see HAM for details): First, all galaxies in the local universe with large IR luminosities ($L_{IR} > 10^{44}$ erg s^{-1}), large IR excesses ($L_{IR} / L_{OPT} > 2$), and/or warm far-IR colors (flux density at 60 μm greater than 50% of the flux density at 100 μm) drive superwinds. Second, The superwind outflow rates are proportional to the far-IR luminosity, with the constants of proportionality determined from well-studied examples like M 82 and NGC 253.

The recent survey of optical line emission associated with a well-defined sample of nearly 50 IR-selected edge-on starbursting disk galaxies by L92 and LH have put these two assumptions on a much firmer observational foundation. They find that such indicators of a superwind as excess optical line-emission along the minor axis, broad emission-line widths and velocity shears along the minor axis, and 'shock-type' optical emission-line ratios (e.g., strong [O I] and [S II] emission relative to Hα) along the minor axis all correlate with such quantities as the IR luminosity, the IR/optical luminosity ratio, and the IR color-temperature. They conclude that superwinds are probably ubiquitous in galaxies meeting the IR criteria listed in the preceding paragraph.

Integrating over the local far-IR luminosity function for galaxies meeting the above criteria (Bothun, Lonsdale, & Rice 1989) then yields the superwind injection rates per unit volume in the local universe. The resulting injection rates per unit volume can be normalized by multiplying them by the age of the universe, and then dividing the result by the local space density of galaxies. This calculation then implies that superwinds have carried out approximately $5 \times 10^8\ M_\odot$ in metals and 10^{59} ergs in kinetic plus thermal energy per average (Schechter L^*) galaxy over the history of the universe. For reference, note that these two quantities are approximately equal to the mass of metals contained inside an average galaxy and the gravitational binding energy of an average galaxy respectively.

These values pertain to the conservative assumption that the superwind rate has not evolved with look-back time. Since the star-formation rate was presumably higher in the early universe, the true time-integrated values are likely to be about an order-of-magnitude higher (cf. Ostriker & Cowie 1981; HAM). On the other hand, it is unclear what fraction of the energy and mass injected into a superwind by a starburst ultimately escapes the galaxy and is delivered to the intergalactic medium (e.g., less energetic or more strongly confined superwinds may conceivably cool and turn into galactic fountains (cf. Norman & Ikeuchi 1989). In any case, it seems quite likely that superwinds do play an important role in enriching and heating the intergalactic medium (as we will discuss more fully below).

5. IMPLICATIONS OF SUPERWINDS

5.1. Heating & Enriching the IGM

The ejection of highly metal-enriched material by superwinds offers a very natural explanation for the long-standing puzzle that the intra-cluster medium in clusters of galaxies contains at least as much mass in the form of metals as do the galaxies in the cluster (e.g., Sarazin 1986). This idea has been explored by many authors, including Larson & Dinerstein (1975), DeYoung (1978), and (more recently) White (1991) and David, Forman, & Jones (1991).

Superwinds can heat the JCM as well as enrich it. The combination of gravitational and superwind heating of the ICM could readily account for the result that the temperature of the ICM seems to exceed the 'temperature' of the galaxies as they move within the cluster potential. That is, the parameter β defined as $\mu\ m_{\rm H}\sigma^2_{\rm gal} / kT_{\rm ICM}$ may be systematically less than unity in clusters (cf. David, Forman, & Jones 1991; White 1991). A good quantitative match of White's model to the data on superwinds and the ICM was found by HAM.

The idea that the ICM has been enriched and heated by superwinds makes several specific and testable predictions (cf. David, Forman, & Jones 1991; White 1991; and Donahue's contribution to this volume):

- β should be correlated with the cluster's velocity dispersion (since the relative effect of superwind heating will be greatest in the clusters with low velocity dispersions).
- The O/Fe ratio in the ICM should be significantly above the solar value (since this is true for type II supernova ejecta).
- The O abundance in the ICM should be inversely correlated with β and with the ratio of ICM gas mass to galaxy mass.
- β should be positively correlated with the ratio of ICM gas mass to galaxy mass.
- The ratio of ICM gas mass to galaxy mass should be larger in clusters with deeper potential wells (since more of the ICM can be retained in the face of superwind heating in clusters with large escape velocities).

While direct evidence for a hot, all-pervasive intergalactic medium remains scant, there are compelling theoretical reasons to believe it exists (cf. the recent review by Shapiro 1989). In order that a cosmologically significant IGM not violate Gunn-Peterson limits, it must be ionized at quite early epochs (e.g., already by the time at which the first known quasars appear). The mechanical energy input from superwinds driven by protogalaxies may be capable of heating and collisionally ionizing the IGM in the early 'pre-quasar' era of the universe (cf. Miralda-Escude & Ostriker 1991).

5.2. Galaxy Formation & Evolution

The most remarkable and profound constraints on our ideas of how galaxies actually form are the relatively tight relationships between such disparate quantities as velocity dispersion, mass and luminosity, length-scale, surface brightness, and chemical abundances (e.g., Djorgovski & Davis 1987; Dressler et al. 1987; Franx & Illingworth 1990). Recent attempts to understand the processes that regulated the conversion of gas into stars and the subsequent chemical enrichment in proto-galaxies have led to the concept of 'self-regulated galaxy formation' or 'feedback' (e.g., Silk 1987; White & Frenk 1991): the effect of the kinetic energy supplied by massive stars and supernovae on the gas in a (proto)galaxy may lead naturally to the creation of the specific properties of galaxies we see today.

For example, Dekel & Silk (1985), Vader (1986), and Silk, Wyse, & Shields (1987) have argued that the striking differences

between many of the global properties of dwarf and massive galaxies may reflect the existence of a critical escape velocity (potential well depth) below which galaxies suffer catastrophic superwind-driven loss of their ISM following the initial burst of star-formation that accompanies their formation. This process leads naturally to the low surface brightnesses and very low metal abundances of dwarf galaxies (see also DeYoung & Gallagher 1990). The catastrophic destruction of dwarfs by starburst-driven winds might be related to the apparently rapid disappearance of the 'faint, blue galaxies' (starbursting low mass systems) during the last few Gyr of the history of the Universe (cf. Broadhurst, Ellis, & Glazebrook 1992; Cowie et al. 1992).

Wyse & Silk (1985) have examined the consequences of supernova heating for the chemical enrichment of disk galaxies. Similarly, Larson & Dinerstein (1975), Vader (1986), Franx & Illingworth (1990), Lynden-Bell (1992) and others have proposed that superwinds are the mechanism that underlies the correlation between the metal abundance of the stellar population and the local escape velocity in elliptical galaxies (i.e., both the mass vs. metallicity relation between galaxies and the metallicity vs. radius relation within galaxies). That is, the deeper the local gravitational potential, the more difficult to drive a wind and hence the greater the ability of that locale to retain metal-rich processed material.

Mathews (1989) has explored the consequences of superwinds in normal ellipticals. He argues that the observed mass-to-light ratio of the stellar population is set by superwind-driven mass loss. Superwinds might also play an important role in the evolution of the star-bursting product of the merger of two major disk galaxies into a giant elliptical (see Hernquist's contribution to this volume): superwinds could shock-heat the cool ISM up to X-ray temperatures or even eject much of the ISM from the galaxy (e.g., Mathews & Baker 1971).

It has even been suggested that the superwinds ('explosions') associated with the formation of galaxies may have played some role in the formation of structure in the universe (Ostriker & Cowie 1981). They propose that superwinds swept up the IGM into large shells of dense radiatively-cooled material that then fragmented into Jeans-unstable lumps that became new galaxies. If the process of amplification via 'stimulated galaxy formation' is efficient enough, then superwinds may have helped induce structure in the early universe.

5.3. QSO Absorption Lines

The nature of the intervening clouds responsible for producing the absorption-lines in the spectra of QSO's remains unclear (cf. the collection of reviews in the volume compiled by Blades, Turnshek, & Norman 1988 - see also the reviews by Steidel, Lanzetta, Bechtold, Weymann, and Bajtlik in this volume). The sharp metal lines and Lyman-limit systems are believed to arise in the gaseous halos of intervening galaxies, and the implied cross-sectional area of absorbing material per galaxy significantly exceeds the traditional 'optical' dimensions of galaxies (even if every galaxy in the universe has such an extended gaseous halo).

While it is by no means obvious that superwinds are consistent with the myriad properties observed for the various classes of QSO absorption-line systems, at the very least, they offer a novel way to transport metals out into a galactic halo (or even out into the general IGM), and could perhaps help us understand some of the most salient properties of the absorption-line systems:

- This transport process could significantly increase the effective absorbing cross-sectional area available per galaxy.
- An evolution in the starburst rate (and hence superwind rate) with cosmic time could help explain the observed evolution with redshift of the sharp metal line and Lyman-limit systems.
- Superwinds might be responsible for some of the complex observed velocity structure of the metal-line systems: the absorption-line profiles typically consist of several narrow subcomponents spanning a velocity range of several tens to several hundred km s^{-1}. In extreme cases, velocity spreads of up to 2000 km s^{-1} are observed. Such substructures and velocities are a natural consequence of a line-of-sight that traverses a superwind.
- If such broad, multi-component absorption-lines originate in an organized outflow (rather than being due to turbulent motions of clouds in a galactic halo), it would explain why the halos are not destroyed in a fraction of a halo-crossing time by cloud-cloud collisions.
- The apparent lack of gaseous halos associated with low-mass galaxies noted in this volume by Steidel might be due to the preferential destruction/ejection of these loosely-bound halos by superwinds.

One obvious test of these ideas is to obtain far-UV spectra of QSO's viewed through the halos of known starburst/superwind galaxies, and then to compare these spectra to spectra of typical high-redshift QSO sharp metal-line systems. Some of us have recently embarked on an HST program to do that for a sample of QSOs seen behind the halos of the nearby starburst galaxies NGC 253, NGC 520, and NGC 3079.

5.4. The X-Ray background

Another enduring mystery concerns the origin of the cosmic X-ray background (CXRB). Bookbinder et al. (1980) first suggested that X-ray emission from the hot thermal plasma in superwinds might make an important contribution to the CXRB. More recently, Weedman (1987) and Griffiths & Padovani (1990) have shown that the X-ray luminosity function of local

starburst galaxies could provide a significant fraction of the CXRB if they evolve by only a modest amount with cosmic epoch.

It is worth emphasizing however that even if superwinds do make a non-negligible contribution to the CXRB, this will occur only at relatively low energies. More specifically, superwinds are not expected to radiate significantly above about 10 keV (see Section 2 above), while most of the overall energy in the CXRB is in the range 10-40 keV. If the superwinds contributing to the CXRB are located at a significant mean redshift this will only exacerbate this spectral deficiency at high energies.

5.5. The Disk-Halo Connection

One of the principal themes in the study of the interstellar medium (ISM) is the relationship between massive stars and the thermal and dynamical state of the ISM. Recently, there has been an explosive growth in the number of papers on this topic, spurred in part by the discovery of expanding HI 'supershells' (Heiles 1990) and of a warm, ionized medium which has a relatively large scale-height and contains a substantial fraction of the Milky Way's total gas mass (Reynolds 1991). As reviewed by Dettmar (1993), there also mounting evidence of a 'disk-halo connection' in external galaxies by which star-formation in the disk ISM can propel mass and thermal/kinetic energy up into the galactic halo.

Starbursts offer wonderful laboratories for studying these processes, with the advantage that conditions are so extreme in these systems that the number of relevant physical processes may be fewer than in a normal disk-halo system. Even if it does not prove to be easier to understand the disk-halo connection in starbursts, the spectacular superwind phenomena we have described above demonstrate that is clearly easier to observe the disk-halo connection there!

The ultimate goal of course will be to develop a comprehensive theory of the feedback effect of the formation of massive stars that explains a whole continuum of disk-halo systems from normal star-forming disks with their galactic fountains or chimneys to powerful starbursts with global superwinds. Some important steps in this direction have already been taken (cf. Norman & Ikeuchi 1989).

5.6. The Starburst-AGN Connection & Ultraluminous Galaxies

One of the most fascinating issues in extragalactic astronomy concerns the relationship between AGNs and starbursts (cf. Heckman 1991 ; Blandford 1992 ; Filippenko 1993). Roberto Terlevich and his colleagues have argued that ultra-compact starbursts occurring in conditions of very high gas density can reproduce all the phenomena associated with classical radio-quiet AGNs (e.g., Terlevich 1992). Our contention here is more limited in scope, but similar in spirit: superwinds driven by starbursts can significantly blur the phenomenological distinction between starbursts and AGNs.

First, superwinds are estimated to have terminal velocities of several thousand km s^{-1} , and so (at least in principle) can accelerate gas up to velocities well in excess of normal galaxian orbital velocities. Thus, the mere presence of broad emission-lines does not necessarily imply that a galaxy harbors an AGN.

Second, ambient material that has been shock-heated by the superwind will produce LINER-type line ratios (which again are often taken as firm evidence for the presence of an AGN). This classification problem is exacerbated by the much heavier obscuration suffered by the optical line emission produced within the central starburst compared to the emission originating in the superwind (thereby making it harder to clearly recognize the signature of the OB-star-photoionized gas in the integrated optical spectra of distant and powerful starbursts).

Third, superwinds are potential sources of X-rays (at least up to 10 keV or so). Now X-rays comprise an energetically trivial fraction of the bolometric luminosity (typically few times 10^{-4}) in IR-selected starburst galaxies (e.g., Griffiths & Padovani 1990; Green, Anderson, & Ward 1992). Since the fractional contribution of the X-ray luminosity is several orders-of-magnitude larger than this in type 1 Seyfert nuclei and QSOs (e.g., Sanders et al. 1989), there is no difficulty in using X-ray data to differentiate between these AGN classes and starbursts (cf. Rieke 1988). On the other hand, there is a considerable amount of overlap in the distribution of L_X / L_{bol}) between starbursts and type 2 Seyfert galaxies (e.g., Green, Anderson, & Ward 1992). Indeed, Wilson et al. (1992) have suggested that much of the hard X-ray emission from the type 2 Seyfert NGC 1068 is associated with the circumnuclear starburst rather than with the AGN itself.

Finally, superwinds are also capable of producing large-scale radio sources that extend at least 10 kpc out into the halo of the starburst galaxy. Such radio sources are very weak (the total core-plus-halo radio luminosity of M 82 is only about 10^{-5} of the bolometric luminosity of the starburst), and show only a weakly bipolar morphology. Thus, we suggest that spatially-extended (>kpc-scale) radio emission should be taken as unambiguous evidence for the presence of an AGN only if the radio source provides a much larger fraction than this of the bolometric luminosity and/or exhibits a highly-collimated, jet-type morphology.

Taking these points together, and noting that the observational manifestations of superwinds become more spectacular with

increasing starburst luminosity, we suggest that the evidence that most 'ultraluminous' IRAS galaxies are powered by buried quasars (e.g., Sanders et al. 1988) is not entirely persuasive, Indeed - based especially on the near-IR colors and the IR spectral energy distributions of the ultraluminous galaxies (see Sanders et al 1988 figures 14 & 15) - we suggest that only three of the ten ultraluminous galaxies (namely IRAS 05189-2524, IRAS 08572+3915, and Mrk 231) clearly have ultraluminous AGNs in their cores (see also Majewski et al. 1993).

6. SUMMARY

We have reviewed the theoretical basis for, the observational evidence pertaining to, and the astrophysical implications of starburst-driven galactic superwinds: global outflows driven by the collective effect of the mechanical energy supplied by supernovae and stellar winds in a nuclear or circumnuclear starburst.

Models of the superwind phenomenon imply that a starburst can create a highly over-pressured bubble of hot gas which will expand preferentially along the direction of the maximum pressure gradient in the ambient ISM of the starburst galaxy (i.e., probably along the galaxy minor axis). For typical starburst conditions, it is expected that this expanding bubble will quickly 'blow-out' into the galactic halo or beyond to form a high-speed (several thousand km s^{-1}) wind.

Hard X-rays (kT = 5 - 10 keV) will be produced by the hot fluid inside the wind's sonic radius and by internal shocks at larger radii. Much softer X-rays can arise as the wind shock-heats and/or evaporates dense ambient gas in the galactic halo. The available X-ray imaging and spectroscopic data on starburst galaxies are broadly consistent with this simple picture, though the weakness of the 6.7 keV Fe K line is a puzzle.

Optical line emission will also be produced as dense halo gas is shock-heated and/or evaporated by the wind. Optical data on starbursts spanning nearly three orders-of-magnitude in luminosity provide highly suggestive evidence for the ubiquity of superwinds. There is a marked excess of emission-line gas along the minor axes of starburst galaxies viewed edge-on. The gas along the minor axis is much more disturbed kinematically than that along the major axis, the line widths along the minor axis correlate better with the starburst luminosity than with the galaxy rotation speed, and the largest velocity shears along the minor axis are observed in the galaxies that are more face-on and have larger IR luminosities (all suggesting a starburst-driven outflow rather than simple orbital motions). In the best-studied (most-nearby) starbursts, the kinematics suggest an outflow along the walls of a cone-like structure at velocities of a few hundred km s^{-1}. The emission-line ratios produced by this gas are consistent with shock-heating, and the large measured pressures agree well with the predicted ram pressure of a superwind. In one case, the outflowing gas has been detected in optical absorption-lines (providing unambiguous evidence for an outflow).

Radio continuum data on a few starburst galaxies imply that relativistic particles and magnetic fields are probably being convected out in the wind at velocities of a few thousand km s^{-1}. Molecular-line observations of superwinds have been reported, and the HI morphology of a companion to the well-known starburst/superwind galaxy NGC 3079 is strongly suggestive of the ablation of the ISM in this galaxy by the ram pressure of the NGC 3079 superwind. HI observations of starburst galaxies show that many such systems are surrounded by large 'envelopes' of H I, presumably of tidal origin. The interaction between the superwind and such relatively dense and cool material probably plays a fundamental role in producing the observed optical line emission and X-rays.

The results from our on-going survey of JR-selected edge-on disk galaxies imply that superwinds are probably ubiquitous in galaxies with warm far-IR colors and total IR luminosities greater than about 10^{44} erg s^{-1}. The local IR luminosity function of galaxies then allows us to estimate the local injection rate of metals and energy via superwinds. Integrated over a Hubble time (with no cosmic evolution) and normalized to the present space density of all galaxies, we find that superwinds may have ejected a mass of metals comparable to the mass of metals contained inside galaxies and supplied an average of about 10^{59} ergs per galaxy to intergalactic medium. These figures could easily be an order-of-magnitude larger allowing for evolution of the superwind rate with cosmic time.

Superwinds may play a key role in heating and chemically enriching the intra-cluster and intergalactic media (especially during the epoch of galaxy formation). The 'feedback' between star-formation and the gaseous component of proto-galaxies (via the superwind phenomenon) may have helped imprint the basic and specific properties of galaxies we see today. Superwinds may also have stimulated or suppressed galaxy formation in the environs of newly-formed galaxies. Superwinds may be implicated in the QSO absorption-line phenomenon, as they offer a natural way to create a cosmically evolving population of large, metal-enriched, kinematically-complex gaseous halos. Superwinds also represent an ideal laboratory to study the 'disk-halo connection' under relatively extreme conditions. Superwinds probably contribute non-negligibly to the X-ray background at E < 10 keV. Finally, the superwind phenomenon blurs the empirical distinction between AGNs and starbursts: a starburst with a strong superwind can exhibit broad emission-lines, LINER emission-line ratios, (weak) X-ray emission, and even (weak) large-scale, (weakly) bipolar nonthermal radio emission (all of which are commonly taken to indicate the presence of an AGN).

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