.

Absorption-Line Probes of Gas and Dust in Galactic Superwinds

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ABSTRACT

We have obtained moderate resolution ($R =$ a few thousand) spectra of the $NaI\lambda\lambda5890,5896$ (NaD) absorption-line in a sample of 32 far-IR-bright starburst galaxies. In 18 cases, the NaD line in the nucleus is produced primarily by interstellar gas, while cool stars contribute significantly in the others. In 12 of the 18 "interstellar-dominated" cases the NaD line is blueshifted by over 100 km s^{-1} relative to the galaxy systemic velocity (the "outflow sources"), while no case shows a net *redshift* of more than 100 km s^{-1}. The absorption-line profiles in these outflow sources span the range from near the galaxy systemic velocity to a maximum blueshift of $\sim$ 400 to 600 km s^{-1}. The outflow sources are galaxies systematically viewed more nearly face-on than the others. We therefore argue that the absorbing material consists of ambient interstellar material that has been entrained and accelerated along the minor axis of the galaxy by a hot starburst-driven superwind. The NaD lines are optically-thick, but indirect arguments imply total Hydrogen column densities of $N_H \sim$ few $\times10^{21}$ cm^{-2}. This implies that the superwind is expelling matter at a rate comparable to the star-formation rate. This outflowing material is evidently very dusty: we find a strong correlation between the depth of the NaD profile and the line-of-sight reddening. Typical implied values are $E(B-V) = 0.3$ to 1 over regions several-to-ten kpc in size. We briefly consider some of the potential implications of these observations. The estimated terminal velocities of superwinds inferred from the present data and extant X-ray data are typically 400 to 800 km s^{-1}, are independent of the galaxy rotation speed, and are comparable to (substantially exceed) the escape velocities for L_* (dwarf) galaxies. The resulting selective loss of metals from shallower potential wells can establish the mass-metallicity relation in spheroids, produce the observed metallicity in the intra-cluster medium, and enrich a general IGM to of-order 10^{-1} solar metallicity. If the outflowing dust grains can survive their journey into the IGM, their effect on observations of cosmologically-distant objects would be significant.

Subject headings: galaxies: starburst – galaxies: nuclei – galaxies: active – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: halos – galaxies: intergalactic medium – galaxies: evolution – infrared: galaxies – ISM: dust, extinction

1. Introduction

By now, it is well-established that galactic-scale outflows of gas (sometimes called 'superwinds') are a ubiquitous phenomenon in the most actively star- forming galaxies in the local universe (Heckman, Lehnert, & Armus 1993; Dahlem 1997; Bland-Hawthorn 1995). They are powered by the energy deposited in the interstellar medium by massive stars via supernovae and stellar winds. Over the history of the universe, outflows like these may have polluted the intergalactic medium with metals (e.g. Giroux & Shull 1997) and dust (Alton, Davis, & Bianchi 1999; Aguirre 1999a,b), heated and polluted the intracluster medium (e.g. Gibson, Loewenstein, & Mushotzky 1997; Ponman, Cannon, & Navarro 1999), and may have established the mass-metallicity relation and radial metallicity gradients in galactic spheroids (e.g. Carollo & Danziger 1994). However, the astrophysical relevance of superwinds can not be reliably assessed without first understanding their physical, dynamical, and chemical properties. To date, most of the pertinent information has come from observations of the X-ray emission produced by the hot gas (e.g. Dahlem, Weaver, & Heckman 1998) or the optical line-emission produced by the warm gas (e.g. Lehnert & Heckman 1996a).

In the present paper, we take a complementary approach, and discuss an extensive body of new data that probes the outflowing gas via its interstellar absorption-lines. This technique has some important advantages. First, since the gas is seen in absorption against the background starlight, there is no possible ambiguity as to the sign (inwards or outwards) of any radial flow that is detected. Second, the strength of the absorption will be related to the column density of the gas. In contrast, the X-ray or optical surface-brightness of the emitting gas is proportional to the emission-measure. Thus, the absorption-lines more fully probe the whole range of gas densities in the outflow, rather than being strongly weighted in favor of the densest material (which may contain relatively little mass). Finally, provided that suitably- bright background sources can be found, interstellar absorption-lines can be used to study outflows in high-redshift galaxies where the associated X-ray or optical *emission* may be undetectably faint. This promise has already been realized in the case of the 'Lyman Dropout' galaxies, where the kinematic signature of outflows is clear in their rest-frame UV spectra (Franx et al 1997; Pettini et al 1998, 1999).

A few pioneering studies have already detected interstellar absorption-lines from superwinds in local starburst galaxies. Phillips (1993) discussed spatially-resolved optical spectroscopy of the NaI "D" doublet in NGC 1808, showing that an outflow of gas at velocities of up to 700 km s^{-1} could be traced over a region several kpc in size, coincident with a region of extra- planar dust plumes. Several recent papers (Lequeux et al. 1995; Heckman & Leitherer 1997; Sahu & Blades 1997; Kunth et al. 1998; Gonzalez-Delgado et al

1998a) have detected blueshifted interstellar absorption-lines in HST and HUT UV spectra of a handful of starburst galaxies, implying outflows of metal- bearing gas at velocities of 10^2 to 10^3 km s^{-1}.

Most of the strong resonance lines of cosmically-abundant ions are found in the UV (e.g. Morton 1991; Savage & Sembach 1996), and so must be studied with HST or $FUSE$ in local starbursts. In the present program, we have instead exploited the relatively greater sensitivity and availability of ground-based telescopes at visible wavelengths to study a large sample of starbursts/superwinds using the NaI doublet at $\lambda\lambda5890,5896$ Å. In a few cases, we have also observed the KI $\lambda\lambda7665,7699$ Å doublet, since it probes gas with nearly the same ionization state as NaI, but is more likely to be optically thin (the K abundance is down from Na by a factor of 15, while the two doublets have similar oscillator strengths). The ionization potentials of NaI and KI are only 5.1 eV and 4.3 eV respectively, so these species should primarily probe the HI and H_2 ISM phases. Observations in vacuum-UV will be required to study the hotter and more highly ionized gas in absorption.

2. The Data

2.1. Sample Selection

Table 1 lists the salient properties of the 32 objects in our sample. These objects have been drawn from the larger samples of infrared-selected galaxies studied by Armus, Heckman, & Miley (1989 - hereafter AHM) and by Lehnert & Heckman (1995 - hereafter LH95). The specific selection criteria used in these in two programs are described in detail in these references. Briefly, AHM selected on the basis of far-IR flux and very warm far-IR color-temperatures. LH95 selected on the basis of far-IR flux, moderately warm far-IR color-temperatures, and high galaxy inclination (disk galaxies seen within $\sim30°$ of edge-on). The AHM and LH95 samples overlap in galaxy properties, but the former preferentially selects more powerful and more distant objects.

AHM measured the equivalent widths of the NaD lines in their sample using low-resolution spectra. The galaxies from AHM were selected for the present program on the basis of the brightness of their nucleus at ~ 5900Å and the equivalent width of NaD. The galaxies from LH95 had no prior measures of the NaD line, and were selected based primarily on their proximity and availability at the time of the observations.

Of the 32 objects, only 3 are classified as *bona fide* AGN of the basis of their optical spectra: the type 2 Seyferts NGC7582 and Mrk273 and the highly peculiar AGN IRAS11119+3257. No published classification exists for IRAS10502-1843. The remaining

objects are optically classified as $HIInuclei$ or $LINER's$, and are presumed to be primarily powered by dusty starbursts (Lutz, Veilleux, & Genzel 1999). Even in the Seyfert galaxies NGC7582 and Mrk273, optical spectra show the presence of a young stellar population in the nucleus (Schmitt, Storchi- Bergmann, & Cid-Fernadez 1999; Gonalzez-Delgado, Heckman, & Leitherer 2000). Thus, with the possible exception of IRAS11119+3257 and IRAS10502-1843, the objects in our sample all contain powerful starbursts that can drive superwinds.

2.2. Observations

The observations were undertaken during the period from 1988 through 1994 using three different facilities: the 4-meter Blanco Telescope with the Cassegrain Spectrograph at $CTIO$, the 4-meter Mayall Telescope with the RC Spectrograph at $KPNO$, and the 2.5-meter Dupont Telescope with the Modular Spectrograph at the Las Campanas Observatory. Various spectrograph configurations were used at each observatory, the details of which are listed in Table 2. The spectral resolution used to study the NaD lines ranged from 55 to 170 km s^{-1}. While low by the standards of interstellar absorption-line studies, the resolution was good enough to cleanly resolve the NaD lines in most cases (deconvolved line widths of 100 to 600 km s^{-1} - see below).

2.3. Data Reduction & Analysis

The spectra were all processed using the standard $LONGSLIT$ package in $IRAF$. All the data were bias-subtracted using the overscan region of the chip and then flat-fielded using observations of either a quartz-lamp- illuminated screen inside the dome or of a quartz lamp inside the spectrograph. The spectra were then rectified using observations of bright stars to determine and remove the distortion perpendicular to the dispersion direction and observations of a $HeNeAr$ arc lamp to determine the two- dimensional dispersion solution. The zero-points in the wavelength scale were verified by measuring the wavelengths of strong night-sky emission- lines. Corrections to the heliocentric reference-frame were computed for the spectra. The spectra were then sky-subtracted by interactively fitting a low-order polynomial along the spatial direction, column-by-column. For a few of the galaxies we obtained relatively low-dispersion spectra that will be used to measure the reddening (Balmer decrement and continuum color). These data were flux-calibrated using observations of spectrophotometric standard stars, and otherwise were reduced in the same way as the other data.

The spectra were analyzed using the interactive $SPLOT$ spectral fitting package in $IRAF$. In all cases, a one-dimensional 'nuclear' spectrum was extracted, covering a region with a size set by the slit width and summed over 3 to 5 pixels in the spatial direction (typically 2 by 3 arcsec). The corresponding linear size of the projected aperture is generally a few hundred to a few thousand parsecs in these galaxies (median diameter 700 pc). This is a reasonable match to the typical sizes of powerful starbursts like these (e.g. Meurer et al 1997; Lehnert & Heckman 1996b). Prior to further analysis, each 1-D spectrum was normalized to unit intensity by fitting it with, and then dividing it by, a low-order polynomial. These nuclear spectra are shown in Figure 1. Similar one-dimensional spectra for off- nuclear regions were extracted over the spatial region with adequate signal- to-noise in the continuum for each galaxy. The primary focus of the present paper is on the nuclear spectra, but we will describe the results obtained in the off-nuclear bins when these are particularly illuminating or interesting.

Given the relatively low resolution of our spectra, the likelihood that the observed NaD line profile contains many unresolved and/or blended kinematic sub-components, and the saturated nature of the NaD lines, we have chosen to parameterize the lines as simply as possible. Thus, for each extracted spectrum, we have fit the NaD doublet with a single pair of Gaussians, constrained to have the same line width and a wavelength separation appropriate to the redshifted doublet. In a few objects, the adjacent $HeI\lambda5876$ nebular emission-line was strong and broad enough to slightly contaminate the blue half of the $NaD\lambda5890$ profile. For these cases, we first fit and subtracted the HeI emission line. Only the parameters of the stronger member of KI doublet at 7665 Å were measured. The weaker member at 7699 Å was detected, with a strength consistent with the doublet being optically-thin (i.e. an equivalent width ratio of ∼2:1).

We have not attempted a rigorous determination of the measurement uncertainties associated with these data. The relatively high signal-to-noise in the nuclear spectra (typically better than 30:1 per pixel) means that the uncertainties in the measured quantities will be dominated in most cases by systematic effects due to the contamination of the NaD line by weaker stellar photospheric features (whose ubiquity likewise makes it difficult to determine the true continuum level to use in the line-fitting) and by the mismatch in profile shape between the actual data and the single Gaussian component used to fit each member of the doublet (see section 3.2 below). The most straightforward way to estimate the measurement uncertainties is to compare the measurements for the 11 galaxies in the sample for which we have more than one independent spectrum (taken at a different position angle). We have done so, and the results are reported in the Notes to Table 3.

3. Results

3.1. The Stellar *vs.* Interstellar Contribution

Before using the NaD line to diagnose conditions in the starburst galaxies, it is imperative to establish that the line is primarily interstellar in origin in these galaxies. The NaD line is strong in the spectra of cool stars, reaching a peak strength in the range from K3 through M0 (see Jacoby, Hunter, & Christian 1984). These stellar types can make a significant contribution to the optical spectrum of a starburst galaxy. First, the oldest underlying population in the galaxy bulge will have a dominant contribution from K -type giants (indeed the NaD line is one of the strongest stellar absorption-lines in optical spectra of early-type galaxies and bulges - e.g. Heckman 1980; Bica et al 1991). Second, for starbursts with ages greater than about 10 Myr, cool supergiants make a significant contribution to the optical and near-IR light (Bruzual & Charlot 1993; Leitherer et al 1999).

We have therefore tried to estimate empirically what fraction of the measured equivalent width of the NaD doublet is contributed by late-type stars in our sample galaxies. To do so, we have considered other absorption-lines that are conspicuous in the spectra of late-type stars and galactic nuclei, but which arise from highly-excited states and are therefore of purely stellar origin (i.e. they are not resonance lines like NaD). The best-studied example is the MgI b-band at 5174Å. The strength of this line is well-correlated with the strength of the NaD line in spectra of the nuclei of normal galaxies (Bica et al 1991; Heckman 1980) and in stars (Jacoby, Hunter, & Christian 1984). We have used the latter two data sets to determine a best-fit to the correlation: $W_{NaD} \sim 0.75\ W_{Mg-b}$. The measured strength of $Mg - b$ in our galaxies (from AHM, Veilleux et al 1995, or our own unpublished spectra) was then used to predict the equivalent width of the *stellar* contribution to the observed NaD line. We have also compared our data to spectra of K giant stars obtained during the same observing runs listed in Table 2. Rather than measuring the strengths of a few particular stellar features, we have used the entire ensemble of features in the range between about 5750 and 6450 Å to estimate by-eye the fractional stellar contribution to the NaD line. The agreement between these two methods is generally satisfactory (the predicted NaD stellar equivalent widths agree on-average to ~ 0.1 dex). Heckman & Lehnert (2000) have measured the fraction of the red continuum contributed by cool stars for the seven nuclei in the present sample having the highest quality detection of the *interstellar* component of the NaD line. They find that this fraction is 20 to 30%, consistent with the rough estimates reported here.

As listed in Table 3, the estimated stellar contribution to the observed NaD line in our sample galaxies ranges from negligible (<10%) to substantial (>70%), with hints of

a bimodal distribution. Thus, rather than attempting a very uncertain direct correction for the effects of the stellar contribution, we have taken the simpler approach of dividing our sample into two bins: the strong-stellar-contamination objects ('SSC') in which stars produce $\geq 40\%$ of the measured NaD equivalent-width, and the interstellar-dominated objects ('ISD') in which the stellar contribution is $\leq 30\%$. In the discussion to follow, we will see that the NaD lines in the two sub-samples have significantly different properties, which can be readily understood as reflecting the relative importance of the stellar and interstellar components.

3.2. Kinematics

The most robust indicator of an outflow is the presence of interstellar absorption-lines that are significantly blueshifted with respect the the systemic velocity of the galaxy (v_{sys}). Thus, we have first compiled the best available measures of v_{sys} for our galaxies The velocities of the *nuclear* emission-lines are potentially affected by radial gas flows and are not always reliable indicators of v_{sys} (Mirabel & Sanders 1988; Lehnert & Heckman 1996a). We have therefore determined v_{sys} from (in order of preference) spatially-resolved galactic rotation curves, global mm-wave CO line profiles, nuclear stellar velocities, global $HI\lambda 21$cm *emission-line* profiles, and optical nuclear emission- line velocities (only used for 4 objects). See Table 1 for details and the estimated uncertainties.

The results are shown in Figure 2. For the ISD subsample there is strong trend for the centroid of the NaD feature to be blueshifted with respect to v_{sys}. Specifically, 11 of the 18 ISD nuclei have NaD blueshifts Δv greater than 100 km s^{-1} (hereafter the 'outflow sources'). In addition, while the nuclear NaD absorption-line in NGC1808 lies close to v_{sys}, the galaxy exhibits strongly blueshifted absorption over a several-kpc-scale region along its minor axis (Phillips 1993). We therefore include it as a 12th member of the outflow sample. The net blueshifts in the ISD nuclei are in the range $\Delta v \sim 100$ to 300 km s^{-1}, (with the exception of IRAS11119+3257). [1] In contrast to these large blueshifts, no net *redshifts* greater than 100 km s^{-1} are observed in the ISD sample. Moreover, none of the 14 members of the SSC sample show a net NaD blueshift or redshift that is greater than

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[1] IRAS11119+3257 has perhaps the most peculiar optical spectrum of any ultra-luminous system. It shows very broad (1500 km s^{-1}) Balmer, [OIII]$\lambda\lambda$4959,5007, FeII, HeI, and [OI]λ6300 emission-lines. It appears to be a member of the "I Zw 1" class of quasars (e.g. Phillips 1976), or possibly related to Mrk 231. It is very compact (barely resolved) in optical images (Armus, Heckman, & Miley 1987). The NaD absorption profile is complex, with a strong narrow system that is blueshifted by 934 km s^{-1}, and a weaker system blueshifted by 1410 km s^{-1}. See Table 3 and Figure 1.

70 km s^{-1}. This is consistent with expectations that the velocity of the nuclear stellar NaD component will be very close to v_{sys}.

The NaD linewidths in the ISD and SSC subsamples are also significantly different (Figure 3). The lines are relatively narrow in the SSC subsample ($W \sim 100$ to 300 km s^{-1}, with a median of 180 km s^{-1}), and much broader in the ISD nuclei ($W \sim 150$ to 600 km s^{-1}, with a median of 425 km s^{-1}). The lines are especially broad (typically 400 to 600 km s^{-1}) in the outflow sources. As shown in Figure 4, the net blueshift in these sources is typically about half the line width ($\Delta v \sim 1/2\ W$). The peculiar AGN IRAS11119+3257, with $W << \Delta v$, is the notable exception. Thus, in a typical outflow, the redmost absorption occurs close to v_{sys}. This is strongly suggestive of a flow in which matter is injected at roughly zero velocity and then accelerates outward. The approximate implied terminal velocity of the flow is then $v_{term} \sim \Delta v + 0.5W$, which ranges from 220 to 1450 km s^{-1} in our sample (Table 4). This picture is quite different from the standard one of a simple expanding 'superbubble' in which the absorption is due to a thin layer of cooled post-shock gas, and for which $W << \Delta v$ would be expected (e.g. Weaver et al. 1977).

It is instructive to compare the observed velocities in the absorbing material to the velocities expected from purely gravitational forces in the starburst galaxy. This is shown in Figure 5, where we plot W *vs.* the galaxy rotation speed (v_{rot} - see Table 1 for details). This figure has several interesting implications. First, neither the sample as-a-whole nor any of the above subsamples show any correlation between the velocity dispersion in the absorbing material and the galaxy rotation speed. This suggests that gravity does not play a dominant role in determining the dynamics of the absorbing gas.

Figure 5 also shows that the NaD lines are surprisingly narrow in the SSC sources compared with expectations for either stars or gas in the bulge of the starburst 'host' galaxy. The lines are exceptionally narrow if they are stellar in origin, since in this case the observed line broadening (W_{obs}) will be produced by both the intrinsic stellar line broadening (W_*) and that produced by galactic dynamics (W_{gal}): $W_{gal} = \sqrt{W_{obs}^2 - W_*^2}$. The observed equivalent widths of the $Na\lambda5890$ line are in the range 2.45±0.4 Å in the SSC nuclei. If the absorption were purely stellar, the *minimum* required values for W_* would be 125±20 km s^{-1} (corresponding to completely black stellar lines). The typical implied values for W_{gal} in the SSC sample would then be 60 to 200 km s^{-1}, with a median value of 130 km s^{-1}.

To emphasize how narrow the lines are in the SSC sample, we show in Figure 5 the empirical relation (Whittle 1992; Franx 1993) between the galaxy rotation speed and the bulge velocity dispersion as a function of Hubble type for a sample of normal disk galaxies. The values for W_{obs} in the SSC objects are on-average ~ 0.2 dex below this relation for

normal galaxies of the same rotation speed and Hubble type (typically Sa to Sc), while the implied values for W_{gal} would be even more discrepant (see above). Put another way, based on the Hubble types and the galaxy absolute magnitudes ($M_B \sim$ -19 to -21) for the SSC subsample, the Faber- Jackson relation for normal galactic bulges would predict typical values of $W_{gal} \sim 200$ to 300 km s^{-1} (e.g. Nelson & Whittle 1996), while the observed widths are typically only 140 to 200 km s^{-1}, even without a correction for the line broadening due to W_*.

The nebular *emission* lines are also narrow in the SSC nuclei, as has been shown to be more generally true for starbursts by Weedman (1983). In this case, Lehnert & Heckman (1996b) showed that the narrowness of the nuclear emission-lines could be understood because the ionized gas was rotationally supported and did not fairly sample the galaxy rotation curve (it lies within the region of the galaxy with solid-body rotation). If this explanation applies to the NaD lines in the SSC nuclei, it implies that a significant fraction of the stellar contribution comes from a dynamically-cold (disk/starburst) component rather than from the bulge.

Finally, Figure 5 shows that the NaD linewidths are relatively large in the outflow sources ($W \sim 1$ to 3 v_{rot}). As we have argued above, the kinematic properties of the NaD profiles suggest that gas is 'loaded' into the outflow at $v \sim v_{sys}$ and is then accelerated up to some terminal velocity that corresponds to the most-blueshifted part of the NaD line profile. We plot v_{term} *vs.* v_{rot} in Figure 6, from which it is clear that v_{term} is significantly larger than v_{rot}, but is uncorrelated with it. This suggests that the outflows *may* be able to selectively escape the shallower galactic potential wells, as we will discuss in section 4.2 below.

Neither the SSC nor the ISD subsamples show a significant correlation between the widths of the NaD absorption-line and the $H\alpha$ emission-line. In particular, the outflow sources with very broad (400 to 600 km s^{-1}) NaD absorption-lines have $H\alpha$ emission-line widths ranging from 145 km s^{-1} (NGC7552) to 1500 km s^{-1} (IRAS11119+3257). This presumably means that the dynamics of the more tenuous outflowing absorbing gas is largely decoupled from that of the dense (high emission-measure) gas that provides most of the nuclear line-emission.

As described above, we have fit the profile of the NaD doublet with a single pair of Gaussians constrained to have the same widths and a fixed separation. Inspection of Figure 1 clearly shows that the observed profiles of many of the ISD sample are more complex than this. The ISD profiles generally have a larger kurtosis than a Gaussian (i.e. narrower core and broader wings) and are sometimes asymmetric with a weak blueward wing on the $\lambda5890$ profile (e.g. NGC 1808, IRAS 10565+2448, IRAS 11119+3257, NGC 6240), and/or

definite substructure (e.g. NGC 1614, NGC 3256, IRAS 11119+3257). Observations at higher spectral resolution should prove instructive.

3.3.   The Roles of Luminosity and Geometry

Of the 32 galaxies in our sample, 14 show relatively weak *interstellar NaD* absorption-lines (the SSC sample, in which the *stellar* contribution to the line is strong), 6 have predominantly interstellar NaD lines lying close to the systemic velocity of the galaxy, and 12 have interstellar lines that are blueshifted by more than 100 km s^{-1} relative to v_{sys}. These 12 outflow sources differ systematically from the other objects in two striking respects: they are more luminous starbursts and they are preferentially located in galaxies seen relatively face-on.

Specifically, 64% (9/14) of the galaxies with $L_{IR} > 10^{11}$ L$_\odot$ show outflows, compared to only 28% (5/18) of the less luminous galaxies. The mean values for $logL_{IR}$ are 11.44±0.18 and 10.86±0.13 for the outflow and other sources respectively, a difference that is significant at the 2.6 σ level. The relationship to galaxy inclination is stronger: 69% (11/16) of the galaxies with a ratio of semi-major to semi-minor axes $a/b \le 2.0$ show outflows, while this is true for only 6% (1/16) of the flatter (more highly inclined) galaxies. The mean values for $log(a/b)$ are 0.20±0.03 and 0.42±0.03 for the outflow and other sources respectively, a difference that is significant at the 4.6 σ level.

It is likely that the primary correlation is between an observed outflow and low galaxy inclination (small a/b). The weaker apparent correlation with L_{IR} is probably induced by the loose anti-correlation in our sample between L_{IR} and a/b. This anti- correlation reflects our selection of galaxies from both the LH95 'edge-on' galaxy sample (large a/b and moderate L_{IR}) and the AHM 'FIR-warm' sample (broad range in a/b and large L_{IR}).

Taken at face value, the correlation with galaxy inclination implies that there is a high probability (∼70%) that an observer located within ∼60° of the rotation axis of a starburst galaxy will see outflowing gas in absorption. This geometrical constraint is consistent with the observed loosely-collimated outflows seen in emission along the minor axes of edge-on starburst galaxies (e.g. Dahlem, Weaver, & Heckman 1998).

3.4.   Column Densities and Optical Depths

The NaD line is clearly optically-thick in these galaxies. The ratio of the equivalent widths of the $\lambda5890$ and $\lambda5896$ members of the doublet (R) can be used to estimate the

optical depth (e.g. Spitzer 1968). The distribution of R is markedly different in the SSC and ISD subsamples. In the former, there is a very narrow observed range ($R \sim 1.1$ to 1.3). This is consistent with a strong stellar contribution to the NaD line, since $R \sim 1.0$ to 1.3 (indicative of large optical depths) is characteristic of cool stars. The range is much broader for the ISD sample, from $R = 1.1$ to 1.7. This range corresponds to central optical depths in the $\lambda5896$ line of $\tau \sim 20$ to 0.5.

At first sight, it might appear odd that the NaD line is optically-thick, yet is not black at line center. This can be seen for the ISD sample in Figure 7, where we have plotted R vs. the normalized residual intensity at the center of the $\lambda5890$ feature: $I_{5890} = F_{5890}/F_{cont}$ (with the respective fluxes measured at line center and in the adjacent continuum). There is a broad range in I_{5890} from 0.14 (nearly black) to 0.7. More tellingly, there is no correlation between R and I_{5890} . This implies that the absorbing gas does not fully cover the background continuum light, and that I_{5890} is determined more by this covering factor (C_f) than by the optical depth. A covering factor less than unity is natural in these galaxies. First, the continuum light may arise in part from stars in the galaxy that are located in front of most of the absorbing gas (i.e. this is not the idealized case of a purely foreground absorbing screen: the gas and stars are likely to be mixed). Secondly, the gas is likely to be quite clumpy and inhomogeneous (e.g. Calzetti 1997; Gordon, Calzetti, & Witt 1997).

In the limit of large optical depth, $C_f = (1 - I_{5890})$, but for low or moderate optical depth $C_f > (1 - I_{5890})$. For the typical optical depths in this sample, we can approximate C_f by (1 - I_{5890}). This can be demonstrated quantitatively for those members of the ISD sample in which the NaD lines are well-resolved, narrow enough so that the two doublet members are cleanly separated from one-another ($W < 300$ km s^{-1}), and that have high signal-to-noise spectra. These constraints leave us with only three objects: NGC1808, NGC2146, and M82. Following Hamann et al. (1997) and Barlow & Sargent (1997), we have:

$$C_f = (I_{5896}^2 - 2I_{5896} + 1)/(I_{5890} - 2I_{5896} + 1) \tag{1}$$

where I_{5896} is the normalized intensity at the center of the $\lambda5896$ line. The measured values of C_f are 0.83, 0.84 and 0.84 for NGC1808, NGC2146, and M82 respectively, while the corresponding values for $(1 - I_{5890})$ are 0.83, 0.82, and 0.82.

In this circumstance - in which optically-thick gas only partially covers the continuum source - the measured equivalent width of the NaD doublet (EQ) will be insensitive to the NaI column density, and will instead be primarily determined by the product of C_f and the line-of-sight velocity dispersion in the gas. We plot the separate dependences of EQ on

I_{5890} and W in Figures 8 and 9 respectively for the ISD sample. It is clear from these two figures that EQ is determined largely by the covering factor (Figure 8), since there is no correlation between W and EQ (Figure 9).

Given that the NaD doublet is moderately optically-thick in these galaxies, it is not straightforward to estimate a NaI column density (N_{NaI}). We have taken three approaches, and emphasize that these are designed to give us only a rough (order-of-magnitude) estimate. Our techniques can potentially underestimate N_{NaI}, because they are insensitive to any NaI sub-component that is highly optically-thick, yet kinematically quiescent.

The first is the classical doublet ratio method (e.g. Spitzer 1968), which relates R directly to the optical depth at line center, and thereby allows the column density to be deduced from the equivalent width. In the spirit of this analysis, we will not attempt to measure columns for all the individual cases, but will instead estimate a characteristic value based on the typical observed parameters. The median value observed in the ISD sample is $R \sim 1.2$, implying that the corresponding median optical depth at the center of the $NaD\lambda5896$ line is $\tau_{5896} \sim 4$ (see Table 2.1 in Spitzer 1968). The median observed value $EQ \sim 6$ Å for the doublet, equation 2-41 and Table 2.1 in Spitzer (1968), and the oscillator strength from Morton (1991), together imply $N_{NaI} \sim 10^{14}$ cm^{-2}. Note that this assumes $C_f = 1$, and should be increased by C_f^{-1}, or a typical factor of ~ 1.6.

A variant of the doublet-ratio technique can be applied to the three cases discussed above in which the two members of the NaD doublet are cleanly separated and well-resolved (NGC1808, NGC2146, and M82). Again, following Hamann et al (1997) we have:

$$\tau_{5896} = ln[C_f/(I_{5896} + C_f - 1)] \tag{2}$$

The resulting values for τ_{5896} are 2.3, 2.1, and 1.9 for NGC1808, NGC2146, and M82 respectively. These are smaller than the values implied by R by a factor of ~ 2 in these cases. The implied values for N_{NaI} are 1.0×10^{14}, 6×10^{13}, and 6×10^{13} cm^{-2} after correction by C_f^{-1}.

We have also measured the equivalent width of the $KI\lambda7665$ line in three of the nuclei (NGC1614, NGC1808, and NGC3256). Since KI and NaI have very similar ionization potentials, and since K and Na show similar grain depletion patterns (Savage & Sembach 1996), the expected ratio of the NaI and KI column densities should be 15 for gas with a solar Na/K ratio. The measured values for the NaD doublet ratio imply optical depths at the center of the $NaD\lambda5890$ line of 8, 16, and 1.6 for NGC1614, NGC1808, and NGC3256 respectively. The implied optical depths for the $KI\lambda7665$ line would then be 0.5, 1.1, and 0.1 respectively. Using the oscillator strength tabulated by Morton (1991), the measured

equivalent widths of the line imply that $N_{KI} = 3 \times 10^{12}$, 4×10^{12}, and 1.3×10^{12} cm^{-2} respectively. Assuming $N_{NaI} = 15\ N_{KI}$, the corresponding NaI columns are 4.5×10^{13}, 6×10^{13}, and 2×10^{13} cm^{-2}. These values are about a factor of two or three smaller than would have been deduced for these three cases using the NaD doublet ratio alone. The value for NGC1808 is in good agreement with that derived from Equation 2. Under the circumstances, we regard the agreement between the three methods as satisfactory, and conclude that the typical value in the ISD sample is $logN_{NaI} = 13.5$ to 14. A final indirect indication that these NaI column densities are roughly correct comes from the detections of the "Diffuse Interstellar Bands" in the seven highest-quality spectra of the ISD sample (Heckman & Lehnert 2000). The observed strengths of these features agree with the strengths seen in Galactic sight-lines with $logN_{NaI} \sim 13.5$ to 14.

What is the *total* gas column density associated with the outflow? To calculate this directly from the (already uncertain) NaI column requires knowing the metallicity of the gas, the fractional depletion of Na onto grains (typically a factor of ~ 10 in diffuse clouds in the Milky Way) and the potentially substantial ionization correction to account for ionized Na. Assuming solar Na abundances and a factor of ten correction for depletion onto grains (e.g Savage & Sembach 1996), $N_{NaI} = 10^{14}$ cm^{-2} implies a typical value for N_H of 5×10^{20} (N_{Na}/N_{NaI}) cm^{-2}. We can also take an empirical approach suggested by the correlation between N_{NaI} and the total gas column towards stars in our own Galaxy. Using the data in Herbig (1993), values for N_{NaI} in the range we estimate ($logN_{NaI} \sim 13.5$ to 14) correspond to sight-lines with $N_H \sim 1.5$ to 4×10^{21} cm^{-2}. Interestingly, this is just the range of values for N_H deduced from the amount of reddening along the line-of-sight to these nuclei based on either the Balmer decrement or the colors of the optical continuum, assuming a normal Galactic extinction-curve and dust-to gas ratio (section 3.5, and see also AHM; Veilleux et al 1995).

These estimates suggest that the ionization correction factor is significant but not huge (i.e. $N_{Na}/N_{NaI} \sim 3$ to 10). Since its ionization potential is only 5.1 eV, the presence of relatively significant amounts of NaI implies that it is associated with gas having a significant dust optical depth in the near-UV: for a Galactic extinction curve and dust-to-gas ratio, a Hydrogen column density of $N_H = 8 \times 10^{20}$ cm^{-2} is required to produce $\tau_{dust} = 1$ at 5.1 eV ($\lambda \sim 2420$ Å).

It is instructive to compare the total column densities we infer for the outflows of a few $\times 10^{21}$ cm^{-2} to the column densities in the other components of the ISM in these galaxies. Column densities to the nucleus for the hot X-ray-emitting gas are estimated to be of-order 10^{21} cm^{-2} in superwinds (e.g. Suchkov et al 1994; Heckman et al 1999; Strickland 1998). In the nuclei themselves, the dominant ISM component is molecular, and the inferred columns

range from $\sim 10^{23}$ to 10^{25} cm^{-2} (e.g. Sanders & Mirabel 1996).

The $HI\lambda 21$cm line is observed in absorption against the bright nonthermal radio sources in starburst nuclei (e.g. Koribalski 1996; Heckman et al 1983; Mirabel & Sanders 1988). The implied column densities are typically a few $\times$ 10^{21} to $10^{22}(T_{spin}/100K)$ cm^{-2}. The absorption is centered close to v_{sys} and spans a velocity range similar to that of the molecular gas. This strongly suggests that this gas is a trace atomic component in the starbursting molecular disk or ring. The kinematics of the gas responsible for the $\lambda 21$cm absorption are therefore quite distinct from the gas that produces the blueshifted NaD absorption. This has several plausible explanations. First, the outflowing HI is probably too hot ($T > 10^3$ K) to produce strong absorption at $\lambda 21$cm. Second, the background radio continuum source against which the gas that produces the λ 21cm absorption is observed will almost certainly be invisible in the optical: it lies behind a total column density (overwhelmingly H_2) of $\sim 10^{23}$ to 10^{25} cm^{-2}, corresponding to $A_V = 60$ to 6000! Clearly, such material will not contribute to the observed NaD absorption-lines.

3.5.   Dust Associated with the Absorbing Gas

We have argued in section 3.4 that the NaD lines are are optically thick, and that EQ is set primarily by the covering fraction for the absorbing gas (C_f) rather than by the line width (W - see Figures 8 and 9). This inference helps explain the otherwise puzzling correlations found by AHM and Veilleux et al (1995) between EQ and the reddening inferred from either the Balmer decrement or the color of the optical continuum in the nuclear spectra of large samples of starbursts. For $\tau_{NaD} >> 1$ and $C_f = 1$, EQ would be set by W, and so no correlation with the reddening would be expected. If instead EQ is principally determined by the fraction of the starburst that is covered by gas containing NaI (and dust grains), then this correlation is more reasonable.

Veilleux et al (1995) have also shown (via the Balmer decrement) that the region of significant reddening extends far beyond the nucleus in many far-IR-bright galaxies. Thus, to gain further insight into the relationship between the NaD absorption and dust-reddening, we have mapped out the spatial variation in the depth of the NaD line (I_{5890}) and the reddening in the six galaxies in our ISD sub-sample for which we have the relevant data on the reddening (M82, NGC3256, NGC6240, Mrk273, IRAS03514+1546, and IRAS10565+2448). The size of the region mapped was set by the detectability of the NaD line, and ranges from 3 to 9 kpc (except for M 82, where the mapped region is only 500 pc in diameter). In each case, we have corrected the Hα and Hβ emission-line fluxes for the effects of stellar absorption-lines (using measures of the equivalent widths of the high-order

stellar Balmer absorption-lines in NGC 3256 and NGC 6240 and an assumed value of 2 Å for the other galaxies). We have also corrected the data for foreground reddening using the measured Galactic HI column density and assuming a standard extinction curve.

Figure 10 shows that not only do the extra-nuclear data points for these six galaxies define a good correlation between the amount of reddening and the depth of the NaD line along a given line-of-sight through the starburst and its outflow, they define the *same* correlation as that defined by the ensemble of all the ISD nuclei in our sample. The nuclear and off-nuclear points are pretty well-mixed in Figure 10, although there is some tendency for the nuclear lines-of-sight to have the larger values of reddening and deeper NaD absorption-lines. The correlation of I_{5890} is better with the color of the stellar continuum than with the Balmer decrement. This is reasonable because the NaD line is observed in absorption against the background stellar continuum (rather than against the emission-line gas) and because the Balmer decrement is likely to be significantly affected by dust directly associated with the emission-line gas itself (in addition to the dust in the foreground material responsible for the NaD absorption).

The observed Balmer decrements imply extinctions of $A_V \sim 1$ to 5 for a standard Galactic extinction curve. Similar values are implied by the continuum colors: a typical starburst is predicted (in the absence of reddening) to have a color of $log[C_{65}/C_{48}] \sim$ -0.3 (Leitherer & Heckman 1995), while the observed colors in Figure 10 range from $log[C_{65}/C_{48}] \sim$ -0.2 to +0.3 (corresponding to $A_V = 0.7$ to 4.2). Note also that in both Figure 10a and 10b, the extrapolation of the correlation to $I_{5890} = 1.0$ (no absorption, $C_f = 0$) has an x-intercept at the intrinsic values expected for an unreddened starburst ($log[C_{65}/C_{48}] \sim$ -0.3 and $log[H\alpha/H\beta] = 0.46$).

In summary, the data imply that over regions with sizes of several or many kpc, the outflows contain inhomogeneous *highly dusty* material. For a standard Galactic extinction law and dust-to-gas ratio, the typical implied HI columns are a few $\times\ 10^{21}$ cm^{-2}. These HI column densities agree well with the estimates in section 3.4 above based upon the NaI column density.

3.6. Sizes, Masses, and Energies

We have measured the size of the region over which significantly blueshifted NaD absorption is detected ($\Delta v > 100$ km s^{-1}) for the 12 outflow sources. The sizes are listed in Table 4, and range from 1 to 10 kpc in diameter. They must be regarded as lower limits (since the background starlight usually becomes too faint to detect the absorption at larger

radii). Tracing the full extent of the absorbing material farther out into the galactic halos will probably require observing suitably bright background QSO's (see Norman et al 1996).

These lower limits to the size of absorbing region can be used to estimate the (minimum) mass and kinetic energy in the outflow. That is, for a region with a surface area A, a column density N_H, and an outflow velocity Δv:

$$M > 5 \times 10^8 (A/10kpc^2)(N_H/3 \times 10^{21} cm^{-2}) M_\odot \tag{3}$$

$$E > 2 \times 10^{56} (A/10kpc^2)(N_H/3 \times 10^{21} cm^{-2})(\Delta v/200km/s) erg \tag{4}$$

We have scaled these relations using values for A, N_H, and Δv that are typical, and have assumed an equal contribution to M and E from the front (observed) and back sides of the outflow.

If we adopt a simple model of a constant-velocity, mass-conserving superwind flowing into a solid angle Ω_w, extending to arbitrarily large radii from some minimum radius (r_* - taken to be the radius of the starburst within which the flow originates), we obtain:

$$\dot{M} \sim 60 (r_*/kpc)(N_H/3 \times 10^{21} cm^{-2})(\Delta v/200km/s)(\Omega_w/4\pi) M_\odot/yr \tag{5}$$

$$\dot{E} \sim 8 \times 10^{41} (r_*/kpc)(N_H/3 \times 10^{21} cm^{-2})(\Delta v/200km/s)^3 (\Omega_w/4\pi) erg/s \tag{6}$$

The statistics of the ISD subsample in the present paper imply that outflows are commonly observed in absorption in IR-selected starbursts (12/18 cases). On the other hand, many of the outflow galaxies in the present sample were selected from AHM on the basis of the strength of their NaD line (objects above the $\sim$ 70th percentile in EQ). If the presence of observable blueshifted absorption is determined by viewing angle (see section 3.3), this suggests that $\Omega_w/4\pi$ lies in the range ~ 0.2 to 0.6 (consistent with the weakly-collimated bipolar outflows seen in well-studied superwinds).

To put the above estimates into context, we can consider the rate at which mass and energy are returned by massive stars. The median bolometric luminosity of the 12 outflow galaxies in our sample is $L_{bol} \sim 2 \times 10^{11}$ L$_\odot$. The implied median rates of mass and kinetic energy returned from supernovae and stellar winds are roughly $\dot{M_{ret}} = 5$ M$_\odot$ per year and $\dot{E_{ret}} = 10^{43}$ erg s^{-1} respectively (e.g. Leitherer & Heckman 1995). Since $(\dot{M}/\dot{M_{ret}}) \sim$ 3 to 10, the absorption-line gas in the outflow must be primarily ambient gas that has

been loaded into the flow. This inference agrees with similar conclusions about the hot X-ray-emitting gas in superwinds (section 4.2 below, and see e.g. Strickland 1998; Suchkov et al 1996; Heckman et al 1999). Since $(\dot{E}/\dot{E}_{ret}) < 10\%$, the absorbing gas does not carry the bulk of the energy supplied by the starburst. Most of this energy probably resides in the form of the thermal and kinetic energy of the much hotter ($T > 10^{5.5}$ K) X-ray-emitting gas.

A bolometric luminosity of 2×10^{11} L$_\odot$ corresponds to a star-formation rate of about 12 M$_\odot$ per year (for a Salpeter IMF extending from 1 to 100 M$_\odot$). Thus, the outflow rates estimated from the NaD lines are comparable to the star-formation rate: *the feedback from massive stars drives the ejection of as much gas as is being converted into stars.* Similar inferences for starbursts have been made using the X-ray and optical emission-line data (e.g. Suchkov et al 1996; Heckman et al 1999; Della Ceca et al 1996,1999; Martin 1999).

4. Discussion & Implications

4.1. The Origin & Dynamics of the Absorbing Material

As discussed above, the red-most part of absorption-line profile in the outflow objects is close to v_{sys}, suggesting that absorbing material is injected from quiescent material at or near v_{sys}, and is then accelerated up to some terminal velocity as it flows outward. This is physically plausible, as the hot (X-ray emitting) outflowing gas interacts hydrodynamically with colder denser material that is located either inside the starburst, or in the inner portions of the galactic halo (see for example Hartquist, Dyson, & Williams 1997; Suchkov et al 1994; Strickland 1998).

Let us assume that a cloud of gas with a column density N, originally located a distance r_0 from the starburst, is accelerated by a constant- velocity superwind that carries an outward momentum flux $\dot{p}$ into a solid angle Ω_w. Ignoring the effects of gravity for the moment, the clump's terminal velocity will be (Strel'nitskii & Sunyaev 1973):

$$v_{term} = 420(\dot{p}/7 \times 10^{34} dynes)^{1/2}(\Omega_w/1.6\pi)^{-1/2}(r_0/kpc)^{-1/2}(N/3 \times 10^{21} cm^{-2})^{-1/2} km/s \quad (7)$$

In this expression, we have used the momentum flux supplied by stellar winds and supernovae (Leitherer & Heckman 1995) in a starburst having a bolometric luminosity equal to the median value for the outflow sample (2×10^{11} L$_\odot$) and have adopted the estimates in section 3 above for N and Ω_w. Starbursts with this luminosity have typical estimated

radii of roughly 1 kpc (see for example Heckman, Armus, & Miley 1990; Meurer et al 1997). From these elementary considerations, we conclude that the observed terminal velocities (typically 400 to 600 km s^{-1}) are easily accommodated.

Equation 7 also predicts that the outflow speeds will be larger in more luminous starbursts. This trend is mitigated to some degree by the fact that more powerful starbursts tend to be larger. Lehnert & Heckman (1996b) and Meurer et al (1997) argue that starbursts have a maximum characteristic surface-brightness, which then implies $\dot{p} \propto L_{bol} \propto r^2$. Together with Equation 7, this implies that such 'maximum starbursts' will have $v_{term} \propto L_{bol}^{1/4}$ (although the clouds can not be accelerated to velocities larger than that of the flow that accelerates them!). Our sample shows no convincing evidence of a trend for larger v_{term} in the more luminous systems, but this sample covers a rather small range in starburst luminosity. It will be instructive to extend this study to dwarf starbursts with $L_{bol} < 10^9 \; L_{\odot}$.

Assume now that the cloud immersed in the outflow is subjected to a gravitational force imposed by an isothermal galaxy potential whose depth corresponds to a circular rotation speed v_{rot}. In order that the outwardly-directed force due to the superwind exceed the inwardly-directed force of gravity, the value for the cloud column density must satisfy the condition:

$$N < 7 \times 10^{21} (\dot{p}/7 \times 10^{34})(\Omega_w/1.6\pi)^{-1}(r/kpc)^{-1}(v_{rot}/200km/s)^{-2} cm^{-2} \qquad (8)$$

Thus, the typical column densities estimated for the outflows ($\sim$ few $\times \; 10^{21}$ cm^{-2}) lie near the upper bound for material that will flow out (rather than falling in). This may not be a coincidence: given a range of cloud column densities, the blueshifted absorption-line will be dominated by the largest-column-density clouds that can be expelled. Alternatively, the observed column densities may simply arise because $N_H \sim 2\times \; 10^{21}$ cm^{-2} corresponds to a dust optical depth of unity in the continuum at the wavelength of the NaD doublet (for a standard Galactic dust- gas ratio). That is, continuum-emitting regions in these nuclei lying behind sight-lines with much higher columns are invisible in optical light and sources behind sight-lines with much lower columns contain little NaI. It would be interesting to test Equation 8 by measuring values of N for outflows in 'low-intensity' starbursts (small $\dot{p}/r$) and starbursts occurring in dwarf galaxies (small v_{rot}).

4.2. Insights from Numerical Simulations

The above elementary considerations give some simple physical insights into the origin and dynamics of the absorbing material. More detailed insight comes from hydrodynamical simulations of starburst-driven superwinds (e.g. Tomisaka & Bregman 1993, Suchkov et al 1994, Strickland 1998, Tenorio-Tagle & Munoz-Tunon 1998). In these simulations the coolest densest gas that has been hydrodynamically disturbed by the starburst is associated with the swept-up shell of ISM that propagates laterally in the plane of the galaxy, and fragments of the cap of the original superbubble shell now being carried vertically out of the disk by faster, more tenuous, wind material.

Shear between the hot shocked starburst ejecta and the cool dense shell in the disk of the galaxy leads to entrainment and stripping of cool dense gas into the wind flowing out of the disk (through Kelvin-Helmholtz instabilities, and presumably additional interchange processes such as thermal conduction and turbulent mixing layers that can not be included in current simulations). Dense gas already in the wind interior, for example the superbubble shell fragments, is accelerated outward via the ram pressure of the wind.

This process can be seen in Figure 11, in which the outward trajectories of four typical entrained clouds are traced over an interval of 1.5 Myr from a 2-D hydrodynamic simulation of M82's galactic wind (Strickland 1998). This is based on the thick-disk ISM distribution of Tomisaka & Bregman (1993). In this model a mass of 10^8 M$_\odot$ is turned into stars in an instantaneous burst (Salpeter IMF over the mass range 1 to 100 M$_\odot$). At a time 7 Myr after the burst, the resulting wind has properties that are a reasonable match to M82. By this time, supernovae and stellar winds have returned 1.3×10^7 M$_\odot$ and 6×10^{56} ergs to the ISM.

Within $|z| \leq 1.5$ kpc of the disk there is $M = 1.9 \times 10^8 M_\odot$ of gas cooler than $T = 3 \times 10^5$ K. The majority of this gas is at the minimum temperature allowed in these simulations of $T \sim 6 \times 10^4$ K. This material occupies a projected area of ~ 2 kpc^2, so the average hydrogen column density of this gas is $N_H \sim 9 \times 10^{21}$ cm^{-2}. This cool gas has a broad range of velocities, from $v \sim 10 - 10^3$ km s^{-1}, with a mode of ~ 60 km s^{-1} (which is associated with the slow expansion of the outer shock in the plane of the galaxy). The associated kinetic energy is 1.3×10^{55} ergs.

At higher distances above the disk there is much less cool gas. For gas above $|z| = 1.5$ kpc the mass of cool gas, associated primarily with the fragments of superbubble shell cap, is $M = 1.5 \times 10^7 M_\odot$. For a projected area of ~ 8.5 kpc^2, the average column density is $N_H \sim 1.6 \times 10^{20}$ cm^{-2}. This cool gas high above the plane typically has higher velocities than the gas within the plane of the galaxy, the distribution of mass with velocity being

approximately flat between velocities of $v = 10^2 - 10^3$ km s^{-1}. The kinetic energy associated with this gas is 1.7×10^{55} ergs.

Thus, the total mass of cool gas in the wind is 2×10^8 M$_\odot$. This is twice as large as the mass of stars formed in the burst, and is 16 times larger than the mass directly returned by massive stars. In contrast, the total kinetic energy in the cool gas (3×10^{55}) is only 5% of the kinetic energy returned by massive stars. The lion's share of this energy is the form of thermal and kinetic energy of the hot ($T > 10^{5.5}$ K) gas in the wind.

It is worth noting several of the limitations of these simulations with respect to their treatment of the cool dense ISM: none of these simulations can explicitly include the cool dense clouds of material within the ISM and starburst region that are known to exist, and are thought to play a key role in "mass-loading" the outflow (e.g. Hartquist, Dyson, & Williams 1997). As a result, the cool dense gas in these simulations is confined to larger radii near the outer shock and to the shell fragments (e.g. there is no way of explicitly treating the entrainment of clouds from within the starburst region itself). [2] These simulations also have a minimum allowed gas temperature of $T \sim 6 \times 10^4$ K, due to the method of simulating ISM turbulent pressure support by an enhanced thermal pressure. Hence all the gas that would in reality have lower temperature is forced to have this minimum temperature, which in turn affects the density of this gas, and prevents us from knowing the exact distribution of this mass between the gas phases cooler than this minimum temperature. Similarly the processes of entrainment and acceleration of cool gas into the wind are both uncertain and occur at (or below) the scale of the physical resolution of these simulations.

Nevertheless, the results of these simulations are encouragingly similar to the observed parameters in our sample of starburst outflows: the cool gas is predicted to have column densities of several $\times 10^{20}$ to $\sim 10^{22}$ cm^{-2}, a mass that is comparable to that of the stars formed in the burst, outflow velocities in the range $v \sim 10^2 - 10^3$ km s^{-1}, and a kinetic energy that is of-order 10^{-1} of the total kinetic energy returned to the ISM by the starburst. Since the cool gas was originally cold dense material entrained and accelerated by the hot outflow, the presence of substantial amounts of dust (section 3.5) is perhaps not too surprising.

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[2] The entrainment of material into the hotter, more tenuous phases, from the hydrodynamical destruction of such clouds can and has been simulated, but these "mass-loaded" simulations (Suchkov et al 1996, Strickland 1998) do not consistently treat the properties of the clouds themselves.

4.3.   The Fate of the Outflow & the Chemical Evolution of Galaxies

As Figure 6 shows, the inferred terminal velocity in the outflows is typically 400 to 600 km s^{-1}, or about two to three times larger than the rotation speed of the starburst's host galaxy. Are these velocities sufficient to expel the gas from the galaxy altogether, or will the gas return to the galactic disk as a fountain flow?

For an isothermal gravitational potential that extends to a maximum radius r_{max}, and has a virial velocity v_{rot}, the escape velocity at a radius r is given by:

$$v_{esc} = [2v_{rot}(1 + ln(r_{max}/r))]^{1/2} \tag{9}$$

Thus, $v_{esc} = 3.0\ v_{rot}$ for $(r_{max}/r) = 33$ (e.g. $r = 3$ kpc and $r_{max} = 100$ kpc). As shown in Figure 6, the estimated terminal velocities in the outflows are typically $v_{term} \sim 2\ v_{rot}$, but v_{term} is uncorrelated with v_{rot}.

Similar results have been obtained for the hot X-ray-emitting gas in starburst galaxies. This gas has temperatures of a few to ten million K in dwarf galaxies (e.g. Della Ceca et al 1996; Strickland, Ponman, & Stevens 1997), L_* disk galaxies (e.g. Dahlem, Weaver, & Heckman 1998; Read, Ponman, & Strickland 1997), and extremely powerful starbursts in galactic mergers (e.g. Heckman et al 1999; Moran, Lehnert, & Helfand 1999; Read & Ponman 1998). Martin (1999) has used these X-ray data to estimate that the gas will escape from galaxies with $v_{rot} < 130$ km s^{-1}.

We can place these disparate data on common ground by comparing the kinetic (NaD) and thermal (X-ray) energy per particle to the energy needed for escape. For convenience, we do so by defining an energetically- equivalent velocity for the X-ray gas. The terminal velocity in an adiabatic superwind fed by gas at a temperature T_X will be $v_X \sim (5kT_X/\mu)^{1/2}$, where μ is the mean mass per particle (Chevalier & Clegg 1985). [3]

These results are shown in Figure 12, which includes the data from Fig. 6 plus 14 far-IR-bright galaxies for which analyses of broad-band (~ 0.1 to 10 keV) X-ray data have been published. These are: M82, NGC253, NGC3628, NGC3079, NGC4631 (Dahlem, Weaver, & Heckman 1998), NGC1569 (Della Ceca et al. 1996), NGC1808 (Awaki et al. 1996), NGC2146 (Della Ceca et al. 1999), NGC3256 (Moran, Helfand, & Lehnert 1999),

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[3] This is a conservative approach as it ignores any kinetic energy the X-ray-emitting gas may already have. Currently the velocity and kinetic energy of the X-ray-emitting material in superwinds can not be measured directly, but numerical simulations suggest that the kinetic energy of the hot gas is typically 2 to 3 times its thermal energy (Strickland 1998).

NGC3310 (Zezas, Georgantopoulos, & Ward 1998), NGC4038/4039 (Sansom et al. 1996), NGC4449 (Della Ceca, Griffiths, & Heckman 1997), NGC6240 (Iwasawa & Comastri 1998), and Arp299 (Heckman et al 1999). In the cases where two-temperature plasma models were fit to the X-ray data, we have plotted both the corresponding outflow velocities. The agreement between the two data sets is satisfactory. There are three members of the NaD outflow sample with X-ray data in Figure 12, and the agreement between the NaD terminal velocity and the X- ray temperatures is reasonably good: $v_{term} = 700$ km s^{-1} $vs.$ $v_X = 520$ and 780 km s^{-1} for NGC1808, $v_{term} = 580$ km s^{-1} $vs.$ $v_X = 490$ and 800 km s^{-1} for NGC3256, and $v_{term} = 580$ km s^{-1} $vs.$ $v_X = 700$ and 940 km s^{-1} for NGC6240. This suggests that the fastest-moving NaD absorbers are roughly co-moving with the hot superwind fluid.

Figure 12 strongly suggests that shallower galaxy potential wells will be less able to retain the newly-synthesized metals that are returned to the ISM in the aftermath of a starburst. As has been suggested many times (e.g. Wyse & Silk 1985; Lynden-Bell 1992; Kauffmann & Charlot 1998) the selective loss of metal-enriched gas from shallower potential wells could explain both the mass-metallicity relation and radial metallicity gradients in elliptical galaxies and galaxy bulges (Bender, Burstein,& Faber 1993; Franx & Illingworth 1990; Carollo & Danziger 1994; Jablonka, Martin, & Arimoto 1996; Pahre, de Carvallo, & Djorgovski 1998; Trager et al 1998).

A simple prediction of this idea would be that the relationship between metallicity and escape velocity should saturate (flatten) for the deepest potential wells - i.e. locations where the local escape velocity exceeds the velocity of the outflowing metal-enriched gas. Lynden-Bell (1992) has parameterized this in a simple physically-motivated fashion by positing that the fraction of metals produced by massive stars that are retained by the galaxy ($f_{retained}$) is proportional to the depth of the galaxy's potential well (Φ) for low-mass galaxies, but asymtotes to $f_{retained} = 1$ for the most massive galaxies. We chose to cast his formulation as follows:

$$f_{retained} = v_{esc}^2/(v_{esc}^2 + v_{term}^2) \tag{10}$$

Here v_{term} is some characteristic velocity associated with the mixture of supernova (and stellar wind) debris and entrained gas that is ejected from the starburst. It is assumed to be a constant. For low-mass galaxies with $v_{esc} << v_{term}$, $f_{retained} \propto v_{esc}^2 \propto \Phi$, or $f_{retained} \propto L_{gal}^{1/2}$ via the Faber-Jackson relation. Lynden-Bell shows that this simple formula can reproduce the observed mass-metallicity relation for elliptical galaxies over a range of $\sim 10^6$ in galaxy mass, and finds that the characteristic mass at which $f_{retained} = 1/2$ (e.g. a galaxy in which $v_{esc} = v_{term}$) corresponds to an elliptical with $M_B \sim$ -18 (adjusted to our assumed value of

$H_0 = 70$). Such a galaxy would have a line-of-sight velocity dispersion $\sigma \sim 140$ km s^{-1}, corresponding to $v_{rot} = \sqrt{2}\sigma \sim 200$ km s^{-1} (Binney & Tremaine 1987). Using equation 9 above, this would correspond to $v_{esc} \sim 600$ km s^{-1}. This in turn is a reassuringly good match to the characteristic superwind outflow speeds implied by Figure 12 (~ 400 to 800 km s^{-1}).

Thus, starburst-driven outflows might imprint a relationship between metallicity and mass in ellipticals (and bulges) over most of observed ranges for these two parameters. While the loss of metal-enriched gas has the most severe impact on dwarf elliptical galaxies, it may nevertheless have general significance in galaxy chemical evolution.

4.4.   The Metal-Enrichment of the Intergalactic Medium

The data discussed in this paper directly establish the flow of *metals* out of highly-actively-star-forming galaxies in the local universe, and the process is observed at high-redshift as well (Franx et al 1997; Pettini et al 1998, 1999). Such data allow us to estimate the column densities, outflow rates, and outflow speeds of this material as a function of the rate of star-formation. Meanwhile, over the past few years, the rate of high-mass star-formation over the history of the universe has been measured for the first time (e.g. Madau et al 1996; Steidel et al 1999; Barger et al 1999). This emboldens us to attempt to estimate the amount of metals that have flowed out of galaxies, thereby polluting the inter-galactic medium, over the course of cosmic time.

The discussion in section 3.4 above implies that gas is flowing out of starbursts at a rate that is proportional to the rate of star-formation: $\dot{M} = \alpha\dot{M}_*$ where α is one-to-a-few (see also Martin 1999). The present-day mass in stars will be smaller than the total mass turned into stars, since mass has been subsequently returned from these stars: $M_{*,0} = \beta M_*$ where $\beta \sim 0.7$ is reasonable for an old present-day system like an elliptical or bulge. The discussion in section 4.3 implies that the outflowing gas will be mostly retained by galaxies with the deepest potential wells, but mostly lost by the less massive systems. Integrating equation 10 above over a Schechter luminosity function implies that $\dot{M}_{lost} = \gamma\dot{M}$ with $\gamma \sim 0.5$ (depending on the value of v_{term} and the 'mapping' of M_B to v_{esc} in spheroids).

We then assume that over cosmic time, we can attribute the construction of spheroidal systems (elliptical and bulges) to starbursts (see Kormendy & Sanders 1992; Elmegreen 1999; Renzini 1999; Lilly et al. 1999). If we further assume that *all* star-formation in spheroids over the history of the universe ejected gas at the relative rate seen in local starbursts, then the ratio of the mass of lost-gas to present-day stars in spheroids would

be $\sim \alpha\gamma/\beta$ (of-order unity). Fukugita, Hogan, & Peebles (1998 - hereafter FHP) estimate that the stars in spheroidal systems today comprise $\Omega_{*,sph} = 2.6 \times 10^{-3}$ (for $H_0 = 70$). Since the implied value for the gas expelled from forming spheroids is comparable to this, this gas is therefore a significant repository of baryons, but only of-order 10^{-1} of the total estimated baryonic content of the universe (FHP). In rich clusters, nearly the entire stellar mass resides in spheroidal systems, while the cluster potential well is deep enough to have retained all the mass expelled by superwinds (e.g. Renzini 1997). The *observed* average ratio of the mass of the intra-cluster medium to the stellar mass is ~ 6 (FHP), so gas ejected by superwinds during spheroid formation would comprise a significant, but minority share of this.

Equation 10 also implies that - integrated over the spheroid luminosity function - roughly half of the metals produced by the stars will have been lost from the galaxies and reside in the intergalactic medium or intracluster medium. Once mixed with the metal-poor "primordial" baryons, the net metallicity would be $\sim 1/6$th solar in both the intracluster medium and the general inter-galactic medium (assuming the FHP global value $\Omega_{*,sph}/\Omega_{IGM} \sim 6$, and assuming a mass-weighted mean metallicity equal to solar for stars in spheroids). The estimated metallicity agrees reasonably well with the measured value of 0.3 solar in rich clusters (e.g. Renzini 1997). A measure of the metal content of the present-day general IGM may be possible with the next generation of UV and X-ray space spectrographs (e.g. Cen & Ostriker 1999).

These are not new arguments by any means (e.g. Gibson, Loewenstein, & Mushotzky 1997; Renzini 1997). What *is* new is that we are now in a position to *observationally verify* that intense starbursts of the kind that plausibly built galactic spheroids do indeed drive mass and metals out at a rate and velocity perhaps high enough to account for the observed inter-galactic metals. The presence of such substantial amounts of inter-galactic metals does not violate constraints imposed by the "Madau diagram" (star-formation rate *vs.* redshift), once reasonable corrections for the effects of dust-extinction are made, nor does it violate the limits set by the far-IR/sub-mm cosmic background (see for example Calzetti & Heckman 1999; Renzini 1997).

4.5. The Outflow of Dust

The strong correlation between reddening and the strength of the NaD line in starbursts (AHM; Veilleux et al 1995; Figure 10) implies that there is an intimate relationship between the dust and gas, especially given the close way in which the two track one another spatially throughout the outflow (section 3.5, Figure 10, and see Phillips

1993 for the spectacular case of NGC 1808). Moreover, we have argued above that significant dust column densities in the absorbing matter are needed to shield the NaI from photoionization by the starburst's intense UV radiation field.

We therfore conclude that *dust is being expelled from starbursts at a significant rate.* More quantitatively, for normal Galactic dust, the observed reddening implies a dust surface mass density in the outflow region of $\sim10^{-4}$ gm cm^{-2}, an outflowing dust mass of $\sim 10^6$ to 10^7 M$_\odot$ (see equation 3), and a dust outflow rate of 0.1 to 1 M$_\odot$ yr^{-1} (see equation 5).

Additional evidence for dusty galactic outflows comes from a variety of observations. Spectroscopy with HST and HUT has established that - just as in the case of the NaD lines - the strong UV interstellar absorption-lines are frequently blueshifted by several hundred km s^{-1} in local starbursts (Lequeux et al 1995; Heckman & Leitherer 1997; Kunth et al 1998; Gonzalez-Delgado et al 1998a). Moreover, as discussed by Heckman et al (1998), there is a strong correlation between the equivalent widths of these UV absorption-lines and the reddening in the UV that is analogous to the correlation between reddening in the optical and the NaD equivalents widths. The IUE spectra discussed by Heckman et al (1998) do not resolve the UV absorption-lines, and so can not verify that the correlation is primarily driven by the covering fraction of the absorbing dusty material (as in the case of the NaD line). As the archive of HST UV spectra of starbursts grows, it will be possible to test this.

Images of several edge-on starburst and star-forming galaxies show far-IR and/or sub-mm emission extending one or two kpc along the galaxy minor axis (Alton, Davies, & Bianchi 1999; Alton et al 1998). Multi-color optical images show that kpc-scale extraplanar dust filaments are common in star-forming edge-on galaxies (Howk & Savage 1997, 1999; Sofue, Wakamatsu, & Malin 1994; Phillips 1993; Ichikawa et al 1994). Imaging polarimetry reveals light scattered by extraplanar dust in starburst galaxies (Scarrott, Eaton, & Axon 1991; Scarrott et al. 1993; Scarrott, Draper, & Stockdale 1996; Alton et al 1994; Draper et al 1995). Zaritsky (1994) finds evidence for very extended dust in the halos of spiral galaxies based on the possible detection of reddening in background field galaxies.

As discussed by Howk & Savage (1997) and Aguirre (1999b), there are a variety of mechanisms by which an episode of intense star-formation could lead to the outflow of dust grains. Radiation pressure can "photo-levitate" the grains (Ferrara et al 1991; Ferrara 1998; Davies et al 1997), the Parker instability could help loft material out of the starburst disk (e.g. Kamaya et al 1996), or cold, dusty gas in and around the starburst could be entrained and accelerated outward by the hot outflowing X-ray gas in the superwind (Suchkov et al 1994, and see section 4.2 above).

The superwind mechanism is of the most direct relevance to the present paper, so we briefly evaluate its plausibility. First, we can show that the outward force of the wind on even the largest grains will exceed the inward force of gravity on the grain. For an isothermal galactic potential this force-ratio at a distance r from the starburst is given by:

$$F_w/F_g = 3\dot{M}v_{term}/4\Omega_w r v_{rot}^2 a\rho \qquad (11)$$

where a and ρ are the radius and density of the grain (we take $\rho = 2$ gm cm^{-3} as representative). For the estimated properties of typical outflow sources in our sample ($\dot{M} \sim$ 25 M$_\odot$ per year, $v_{term} \sim 600$ km s^{-1}, and $\Omega_w/4\pi \sim 0.4$), F_w/F_g will be greater than unity for grains smaller than 7 μm $(r/10$ kpc$)^{-1}$.

Next, we follow Aguirre (1999b) and estimate the ratio of the sputtering and outflow times for graphite grains immersed in a hot galactic wind (τ_{sp}/τ_{out}). For the typical parameters we deduce for the outflows in our sample (see above), this ratio is $\tau_{sp}/\tau_{out} = 4$ $(a/0.1\mu m)(r/10$ kpc$)$. Thus, *large* grains could in fact survive the journey to the galactic halo and beyond. The survivability of grains may actually be higher than the above simple estimate if the grains are imbedded inside cold gas clouds propelled by the hot outflow (so that the grains are not directly exposed to the hot gas).

If starburst and star-forming galaxies are indeed capable of ejecting substantial quantities of dust, this could have a profound impact on observational cosmology (e.g. Heisler & Ostriker 1988; Davies et al 1997; Ferrara 1998; Ferrara et al 1999; Aguirre 1999a,b). However, to date, the direct evidence for the existence of intergalactic dust is very sparse. Thermal far-IR emission has been detected from the ICM of the Coma cluster (Stickel et al 1998), and a possible deficit of background QSO's seen through foreground galaxy clusters has been reported (Romani & Maoz 1992; but see Maoz 1995).

Aguirre (1999a,b) has recently calculated that a dusty inter-galactic medium with $\Omega_{dust} = $ few $\times 10^{-5}$ would have a visual extinction (~ 0.5 magnitudes out to z = 0.7) that would be sufficient to reconcile the Type Ia supernova Hubble diagram (Reiss et al 1998; Perlmutter et al 1999) with a standard $\Omega_M = 1$, $\Omega_\Lambda = 0$ cosmology. Data on the optical colors of high-redshift supernovae show no evidence for *reddening*, but Aguirre argues that intergalactic dust will have a much greyer extinction curve than standard Galactic dust. This is plausible because small grains will be more easily destroyed by sputtering during and after their journey into the IGM (see above).

In this context, it is instructive to estimate the cosmic mass density of dust grains by the type of outflows investigated in this paper. Aguirre (1999b) has considered this in more detail from a somewhat different perspective, but comes to rather similar conclusions. Let

us assume that superwinds associated with the formation of galactic spheroids propelled dust and gas-phase metals into the ICM and IGM, with an amount proportional to the mass in the present-day stars in such systems. We further assume that the mass fractions of the metals locked into grains in the ICM and IGM are $f_{g,icm}$ and $f_{g,igm}$ respectively. These assumptions imply:

$$\Omega_{dust,igm} = f_{g,igm}(1 - f_{g,icm})^{-1}\Omega_{spheroids}\Omega_{icm}Z_{icm}\Omega_{stars,cl}^{-1} \tag{12}$$

Following FHP and Renzini (1997), we take $Z_{icm} = 6.7 \times 10^{-3}$ (1/3 solar metallicity), $\Omega_{spheroids} = 0.0026\ h_{70}^{-1}$, $\Omega_{icm} = 0.0026\ h_{70}^{-1.5}$, and $\Omega_{stars,cl} = 0.00043\ h_{70}^{-1}$. This implies $\Omega_{dust,igm} = 1.0\times\ 10^{-4}\ f_{g,igm}(1 - f_{g,icm})^{-1}h_{70}^{-1.5}$. For a normal Galactic dust/metals ratio ($f_g \sim 0.5$), the implied value for $\Omega_{dust,igm}$ is twice as large as the value needed to explain the Type Ia supernova-dimming (Aguirre 1999a). Given the higher densities (and thus, faster grain sputtering times) in the ICM compared to the IGM, we might expect that $f_{g,icm} < f_{g,igm}$. More importantly, it is also possible that $f_{g,igm} << 0.5$ due to the destruction of dust in superwinds and/or the IGM (but see Aguirre 1999b for an optimistic assessment). While the above estimate for $\Omega_{dust,igm}$ should therefore probably be regarded as an absolute upper bound, it is an intriguingly large one from a cosmological perspective.

Finally, we note that since intergalactic dust will emit as well as absorb, its amount is constrained by the cosmic background measured by $COBE$ (Ferrara et al 1999). Indeed, Aguirre & Haiman (2000) argue that a significant fraction of the detected cosmic far-IR and sub-mm background must have an intergalactic origin if this dust is abundant enough to strongly affect the Type Ia supernova Hubble Diagram.

4.6. Relationship to "Associated Absorption" in AGN

Over the past few years, it has become increasingly clear that a young stellar population is present in the circumnuclear region of a significant fraction of type 2 Seyfert galaxies (e.g. Heckman et al 1995,1997; Gonzalez-Delgado et al 1998b; Schmitt et al 1999; Oliva et al. 1999). Most recently, a near-UV spectroscopic survey of a complete sample of the brightest type-2 Seyfert nuclei by Gonzalez-Delgado, Heckman, & Leitherer (2000) finds direct evidence for hot, young stars in roughly half of the nuclei. In this paper we have established that starbursts drive outflows of cool or warm gas with total column densities of a few $\times$ 10^{21} cm^{-2}, velocities of a few hundred km s^{-1}, and covering factors along the line-of-sight of typically 50%. The implication then is that this absorbing material should be detectable in those Seyfert nuclei that also contain a circumnuclear starburst.

In the standard "unified" scenario, type 1 and type 2 Seyfert nuclei are drawn from the same parent population, with the former viewed from a direction near the polar axis of an optically and geometrically-thick "obscuring torus" and the latter from a direction near the equatorial plane of the torus (e.g. Antonucci 1993 and references therein). Thus, in type 1 Seyferts, any starburst-driven outflow could be observed in absorption against the bright nuclear continuum source. While the total column density of the outflowing gas should be similar to the flows studied in this paper, the gas would be exposed to the intense ionizing continuum from the central nucleus, and therefore would be significantly more highly-ionized.

This can be quantified as follows. The ionization state of photoionized gas is determined by the ionization parameter:

$$U = Q/4\pi r^2 nc \qquad (13)$$

where Q is the production rate of ionizing photons and n is the electron density in the photoionized material located a distance r from the source. The radial density gradients observed in starburst-driven outflows are consistent with predictions for clouds subjected to the ram pressure associated with the superwind (Heckman, Armus, & Miley 1990):

$$2n(r)kT \sim P(r) = \dot{p}/\Omega_w r^2 \qquad (14)$$

where $\dot{p}$ is the rate at which the starburst feeds momentum into the superwind. For photoionized gas, $T \sim 10^4$ K (e.g Osterbrock 1989), so equations 13 and 14 together imply that the magnitude of U is set by $Q/\dot{p}$, and that U will be independent of r (neglecting radiative transfer effects). We adopt a generic Leitherer & Heckman (1995) starburst model (Salpeter IMF extending up to 100 $M_\odot$ and a starburst lifetime of a few $\times$ 10^7 years), include sources of ionization due to both a starburst (Q_*) and the type 1 Seyfert nucleus (Q_{sy1}). For a starburst and type 1 Seyfert nucleus of the same bolometric luminosity, Q_{sy1}/Q_* would be a factor of several. We then obtain the following estimate for U:

$$U = 2.6 \times 10^{-3}(\Omega_w/4\pi)(1 + Q_{sy1}/Q_*) \qquad (15)$$

The predicted properties of the absorbing material then overlap significantly with the "associated absorbers" seen in UV spectra of type 1 Seyfert nuclei (e.g. Crenshaw et al 1999; Kraemer et al 1999): an incidence rate of roughly 50%, a high line-of-sight covering fraction, outflow velocities of 10^2 to 10^3 km s^{-1}, and inferred ionization parameters of $\sim 10^{-2}$. Crenshaw et al (1999) find an essentially one-to-one correspondence between the presence of UV absorption-lines and soft X-ray absorption by hotter and more highly ionized material (the "warm absorber"). We speculate that the hotter and more tenuous phases of the starburst superwind could contribute to the warm absorber.

We emphasize that we are not proposing that all of the "associated absorption" seen in type 1 Seyfert nuclei is produced by gas in a starburst-driven outflow. In some cases, rapid variability or the presence of absorption out of highly-excited lower levels imply densities that are orders-of-magnitude higher than would be tenable for material in a starburst-driven outflow (Crenshaw et al 1999 and references therein). However, it appears that the absorbing material in type 1 Seyfert nuclei can span a broad range in physical and dynamical conditions (Kriss et al 2000). Given important roles for starbursts in the Seyfert phenomenon and for superwinds in the starburst phenomenon, significant absorption due to the superwind material seems unavoidable in some Seyfert nuclei.

5. Conclusions

We have discussed the results of moderate-resolution ($R =$ a few thousand) spectroscopy of the $NaI\lambda\lambda5890,5896$ (NaD) absorption-line in a sample of 32 far-IR-selected starburst galaxies. These galaxies were selected from either the far-IR-warm sample of Armus, Heckman, & Miley (1989) or the edge-on sample of Lehnert & Heckman (1995), and together span a range from 10^{10} to few $\times 10^{12}$ L$_\odot$ in IR luminosity. We found that the stellar contribution to the NaD absorption-line is negligible ($<10\%$) in some objects, but significant ($\sim 70\%$) in others. We have thus divided our sample into 18 interstellar-dominated ("ISD") objects ($< 30\%$ stellar contribution) and 14 strong-stellar-contamination ("SSC") objects ($> 40\%$ stellar contribution).

The NaD line lies within 70 km s^{-1} of v_{sys} in all the SSC objects (consistent with a predominantly stellar origin). The NaD lines in the SSC nuclei are about 0.2 dex narrower than expected for dynamics of the old stellar population in the bulges of normal galaxies of similar disk rotation speed and Hubble type. Thus, dynamically "cold" material (red supergiants and/or interstellar gas) in the inner part of the starburst makes a significant contribution to the observed NaD line in these nuclei.

The kinematics of NaD line are markedly different in the ISD objects. The NaD line is blueshifted by $\Delta v > 100$ km s^{-1} relative to the galaxy systemic velocity in 12 of the 18 cases (the "outflow sources"), and the outflow can be mapped over a region of a few-to-ten kpc in size. In contrast, no objects in our sample showed a net *redshift* in NaD of more than 100 km s^{-1}. The outflow sources are galaxies systematically viewed more nearly face-on than the other galaxies in our sample: 69% of the galaxies with a ratio of semi-major to semi-minor axes $a/b \leq 2.0$ show NaD outflows, while this is true for only 6% of the flatter (more highly inclined) galaxies. This is consistent with the absorbing material being accelerated out along the galaxy minor axis by a bipolar superwind. The absorbing

material typically spans the velocity range from near the galaxy systemic velocity (v_{sys}) to a maximum blueshift of 300 to 700 km s^{-1}. We therefore suggest that the outflowing superwind ablates the absorbing gas from ambient clouds at $\sim v_{sys}$, and then accelerates it up to a terminal velocity similar to the wind speed. We found no correlation between the widths of the Hα emission-line and the NaD absorption-line subsamples. Evidently, the dynamics of the more tenuous absorbing gas is largely decoupled from that of the dense (high emission-measure) gas that provides most of the nuclear line-emission.

The ratio of the equivalent widths of the two members of the NaD doublet (R) ranges from 1.1 to 1.7 in the ISD sample, implying that the doublet is optically-thick. However, R does not correlate with the residual relative intensity at the "bottom" of the stronger $\lambda5890$ line profile (I_{5890}), which ranges from 0.14 (nearly black) to 0.7. Thus, the optically-thick gas does not fully cover the emitting stars (covering factor ~ 1 - I_{5890}). The observed equivalent width of the NaD line is then set by the product of velocity dispersion and covering factor for the absorbing gas, and we showed that the latter quantity is the dominant one. Using two variants of the classic doublet-ratio technique, we estimated that the NaI column densities are $logN_{NaI} = 13.5$ to 14 cm^{-2}. This is roughly consistent with column densities measured in a few cases for KI using the optically-thin $\lambda\lambda7665,7699$ Å doublet (assuming a solar NaI/KI ratio). The total gas columns are uncertain, but the empirical correlation between N_{NaI} and N_H in the ISM of the Milky Way implies $N_H \sim$ few $\times 10^{21}$ cm^{-2}.

We found a strong correlation in the ISD sample between the reddening of the observed stellar continuum and the depth of the NaD absorption-line, and a significant but weaker correlation of the line-depth with the reddening of the Balmer emission-lines. Evidently, the gas responsible for the NaD absorption is very dusty. The typical implied reddening is $E(B-V) \sim 0.3$ to 1 magnitudes over regions several-to-ten kpc in size. For a normal dust-to-gas ratio, the corresponding column densities are $N_H \sim$ few $\times 10^{21}$ cm^{-2} (in agreement with the above estimate).

The inferred column densities and measured outflow velocities and sizes imply that the typical mass and kinetic energy associated with the absorbing gas is of-order 10^9 M$_\odot$ and 10^{56} erg, respectively. The estimated outflow rates of mass and energy are typically 10 to 100 M$_\odot$ per year and 10^{41} to 10^{42} erg s^{-1}. The mass outflow rates are comparable to the estimated star-formation rate, and much larger than the rate at which massive stars are returning mass to the ISM. Thus, powerful starbursts can eject as much gas as is being converted into stars, and most of this gas is ambient material that has been "mass-loaded" into the hot gas returned directly by supernovae and stellar winds. The energy outflow rates in the absorption-line gas are of-order 10^{-1} of the rate at which massive stars supply

mechanical energy. Most of the energy returned by massive stars probably resides in the kinetic and thermal energy of the much hotter X-ray-emitting gas. We showed that the overall properties of the absorbing gas in the outflow sources can be easily reproduced in the context of simple analytic estimates for the properties of interstellar clouds accelerated by the ram pressure of the hot high-speed wind seen via its X-ray emission. Detailed hydrodynamical simulations of galactic winds, while still missing some essential physics, also predict the observed properties of the cool absorbing gas.

We have discussed the implications of our results for the chemical evolution of galaxies and the intergalactic medium. The estimates derived for v_{term} using the NaD line in the outflow sources agree reasonably well with the outflow speeds implied for an adiabatic wind "fed" by hot gas whose temperature is measured by the observed X-ray-emitting gas. The typical implied values are 300 to 800 km s^{-1}, and are independent of the rotation speed of the "host galaxy" over the range $v_{rot} = 30$ to 300 km s^{-1}, confirming and extending the result in Martin (1999) based on X-ray data alone. This strongly suggests that the outflows selectively escape the potential wells of the less massive galaxies. We considered a simple model based on Lynden-Bell (1992) in which the fraction of starburst-produced metals that are retained by a galaxy experiencing an outflow is proportional to the galaxy potential-well depth for galaxies with $v_{esc} < v_{term}$, and asymtotes to full retention for the most massive galaxies ($v_{esc} > v_{term}$). For v_{term} in the range we measure, such a simple prescription can reproduce the observed mass-metallicity relation for elliptical galaxies and deposit the required amount of observed metals in the intra-cluster medium. If the ratio of ejected metals to stellar spheroid mass is the same globally as in clusters of galaxies, we predicted that the present-day mass-weighted metallicity of an intergalactic medium with $\Omega_{igm} = 0.015$ will be $\sim 1/6$ solar (see also Renzini 1997).

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

Finally, given the mounting evidence for a connection between starbursts and the Seyfert phenomenon, we have suggested that outflows like those studied here may account for some (but not all) aspects of the "associated absorption" seen in type 1 Seyfert nuclei.

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Table 1.   Sample

Galaxy (1)	v$_{sys}$ (2)		log L$_{IR}$ (3)	M$_{B_T}$ (4)	$\frac{a}{b}$ (5)	v$_{rot}$ (6)	Sample (7)	Run (8)
NGC 253	245	h,n	10.5	−19.8	4.1	202 h	AHM,LH	2
NGC 660	885	c	10.0	−17.7	2.6	175 h	AHM,LH	5
IIIZw035	8294	e	11.5	−19.5	2.0	87 h	LH	1
IRAS02021−2104	34630	e	12.0	−21.1	2.5	?	AHM	4
NGC 1134	3620	r	10.7	−21.2	2.9	211 r	LH	1
IRAS03514+1546	6662	h,n	11.1	−20.8	1.1	270:h	AHM	5,6
NGC1572	6142	r	11.2	−21.4	2.0	312 r	LH	1
NGC1614	4760	c	11.3	−20.8	1.8	210:c	AHM	4
IRAS04370−2416	4537	r	11.0	−20.0	2.5	172 r	LH	1
NGC 1808	1001	r	10.6	−20.1	1.7	160 r	LH	3,4
IRAS05447−2114	11977	e	11.0	−18.7	2.0	?	AHM,LH	5
NGC 2146	916	r	10.7	−19.3	1.8	272 h	AHM,LH	5
NGC 2966	2045	h,n	10.2	−19.2	2.6	124 r	LH	4
M 82	214	c	10.5	−18.5	2.6	50 h	AHM.LH	5,6
NGC 3094	2409	h,n	10.4	−19.5	1.4	150 h	AHM	5
IRAS10173+0828	14669	c	11.8	−19.1	2.5	140 c	AHM,LH	5
NGC 3256	2801	c	11.5	−21.3	1.8	170:c	AHM	3,4
IRAS10502−1843	16131	s	11.8	−19.0	1.2	?	AHM	4
IRAS10565+2448	12923	c	12.0	−20.7	1.3	300:c	AHM	5,6
IRAS11119+3257	56866	e	12.5	?	1.2	?	AHM	5
NGC 3628	843	h,n	10.2	−19.8	5.0	218 h	LH	3
NGC 3885	1938	r	10.3	−20.9	2.5	195 r	LH	4
NGC 4666	1511	r	10.9	−20.7	3.5	186 r	LH	3
NGC 4945	560	h,n	10.6	−19.8	5.2	172 h	LH	3
NGC 5104	5615	r	11.1	−20.2	2.8	231 r	LH	4
Mrk 273	11326	c,n	12.2	−21.0	2.0	260:c	AHM	5,6
Arp 220	5441	c	12.2	−20.7	1.3	330:c	AHM	5
NGC 6240	7339	c,n	11.7	−21.6	1.9	290:c	AHM,LH	3
IC 5179	3424	r	11.0	−20.9	2.1	194 r	LH	1
NGC 7541	2714	r	10.8	−20.3	2.8	221 r	LH	1
NGC 7552	1585	n	10.8	−20.2	1.2	230 h	LH	1
NGC 7582	1575	n	10.6	−20.2	2.4	180 r	LH	1

Note. Col. (2) — Galaxy systemic velocity (km s^{-1}) in the heliocentric frame. In order of preference, these are determined from: galaxy rotation curves (r), global CO 115 GHz emission-line profiles (c), nuclear stellar velocities (s), global $HI\lambda21cm$ emission-line profiles (h), and nuclear optical emission-line profiles (e). The rotation curve velocities (r) are taken from LH95 except for NGC2146 from Prada et al (1994). Items marked 'n' come from NED. Items marked 'e' or 's' are based on data obtained during the observing runs discussed in the present paper. Items marked 'c' are: NGC 660 (Elfhag et al 1996; Young et al 1995), NGC 1614 (Elfhag et al 1996; Young et al 1995; Aalto et al 1991; Sanders, Scoville, & Soifer 1991; Casoli et al 1991), M 82 (Lo et al 1987), IRAS10173+0828 (Planesas, Mirabel, & Sanders 1991), NGC 3256 (Aalto et al 1991; Casoli et al 1991; Mirabel et al 1990), IRAS10565+2448 (Downes & Solomon 1998), and Arp 220 (Young et al 1995; Solomon, Downes, & Radford 1992). Based on the intercomparison of independent measurements for a given galaxy, the typical uncertainties in v_{sys} range from 10 km s^{-1} for the nearby, relatively normal galaxies to as much as 100 km s^{-1} for the most distant systems (generally, highly disturbed mergers). Col. (3) — Total infrared luminosity from 8 to 100 microns, based on IRAS data and the definition of L_{IR} given in Sanders & Mirabel (1996). We assume throughout that $H_0 = 70$ km s^{-1} Mpc^{-1}. Col. (4) — Blue absolute magnitude for the galaxy, corrected for foreground (Galactic) extinction, but not for internal extinction. Taken from LH95 when available (adjusted to $H_0 = 70$ km s^{-1} Mpc^{-1}) or based on the data in NED or Armus, Heckman, & Miley (1987). Col. (5) — The ratio of the optical semi-major to semi-minor axes. These are taken (in order of preference) from LH95, the images published in Armus, Heckman, & Miley (1987; 1990), or NED. For the highly disturbed merging systems, we have measured this ratio at intermediate radii (excluding both faint tidal tails and the inner regions where dust obscuration is most significant). Col. (6) — The amplitude of the rotation speed of the galaxy. In order of preference, we have based these on rotation curves ("r" from LH95), global $HI\lambda21cm$ profiles corrected for inclination and turbulence ("h" - see LH95 for details), and global CO 115 GHz emission-line profiles using the half-width at 20% of the peak intensity and then correcting for inclination ("c" - using the same data as in Column 2). For M 82 we have replaced the value listed in LH95 by the more recent determination by Sofue (1998). The uncertainties in most cases are dominated by the inclination correction. We estimate the resulting uncertainties to be < 0.1 dex for all but the cases of mergers and strongly interacting galaxies, where the inclination corrections lead to an uncertainty of roughly 0.2 dex (denoted by :). Col. (7) — Sample from which the galaxy was drawn (Armus, Heckman, & Miley 1989; Lehnert & Heckman 1995). Col. (8) — Observing runs used in this paper (see Table 2).

Table 2.   Observing Runs

Run Num (1)	Date (2)	Obs (3)	Tel (4)	Spec (5)	Detector (6)	pixels (7)	Slit (8)	Res (9)
1	11/90	LCO	2.5m	ModSpec	TEK1024	0.68×1.2	2	3.4
2	10/92	CTIO	4m	Blue Air Schmidt	Reticon1	0.77×0.93	2	2.1
3	3/93	CTIO	4m	Folded Schmidt	TEK1024	0.79×0.60	2.2	1.8
						0.79×1.98	2.2	5.9
4	1/94	CTIO	4m	Folded Schmidt	TEK1024	0.82×0.6	2	1.8
5	1/94	KPNO	4m	RC Spec	T2KB	0.69×0.5	2	1.1
6	1/88	KPNO	4m	RC Spec	TI2	0.90×3.4	2	13.5

Note. — Col. (7) — Pixel size in arcsec by Å. Col. (8) — Slit width in arcsec. Col. (9) — Spectral resolution (FWHM) in Å for NaD.

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Table 3.   Measured Properties

Galaxy (1)	f$_\star$ (2)	v$_{NaD}$ (3)	Δv (4)	W (5)	EQW (6)	I$_{5890}$ (7)	R (8)	W$_{H\alpha}$ (9)
NGC253	50%	193	−52	150	6.0	0.04	1.1	280
NGC660	50%	878	−7	140	4.6	0.22	1.2	190
IIZw035	50%	8365	69	100	2.5	0.37	1.4	310
IRAS02021−2104	<20%	34692	56	340	8.1	0.28	1.5	420
NGC1134	70%	3620	0	320	4.4	0.57	1.2	220
IRAS03514+1546	30%	6461	−197	430	4.4	0.60	1.1	170
NGC1572	30%	6011	−128	360	4.3	0.65	1.2	330
NGC1614	<10%	4636	−122	420	8.3	0.35	1.2	300
IRAS04370−2416	40%	4525	−12	200	2.4	0.67	1.3	170
NGC1808	20%	1013	12	300	9.2	0.18	1.1	260
IRAS05447−2114	<30%	12072	91	200	4.2	0.47	1.2	290
NGC2146	30%	930	14	140	4.7	0.17	1.2	120
NGC2966	50%	2043	−2	190	3.8	0.45	1.2	210
M 82	<20%	204	−10	170	5.8	0.18	1.2	100
NGC3094	50%	2394	−15	190	3.9	0.48	1.3	120
IRAS10173+0828	<30%	14708	37	150	4.3	0.44	1.2	200
NGC3256	20%	2489	−309	550	5.5	0.59	1.6	210
IRAS10502−1843	<20%	16022	−103	240	6.8	0.31	1.2	310
IRAS10565+2448	<20%	12717	−197	500	8.5	0.34	1.3	210
IRAS11119+3257	<10%	55755	−934	170	6.1	0.14	1.2	1500
		55189	−1410	80	1.8	0.45	...	
NGC3628	70%	812	−31	170	4.5	0.29	1.2	120
NGC3885	70%	1962	24	200	4.1	0.46	1.2	300
NGC4666	70%	1521	10	150	4.3	0.25	1.2	200
NGC4945	50%	622	62	180	5.5	0.33	1.1	390
NGC5104	50%	5603	−12	240	5.3	0.41	1.1	470
Mrk273	30%	11145	−174	560	4.6	0.68	1.2	520
Arp 220	30%	5422	−19	500	6.5	0.45	1.4	610
NGC6240	20%	7049	−283	600	10.3	0.31	1.6	890
IC5179	40%	3431	7	130	4.5	0.28	1.2	180
NGC7541	50%	2695	−19	160	3.8	0.42	1.2	260
NGC7552	30%	1323	−261	480	4.3	0.70	1.1	140
NGC7582	30%	1344	−230	510	4.7	0.65	1.7	190

Note. Col. (2) — The estimated contribution to the observed NaD line by cool stars (the remainder is interstellar in origin). See text for details. Galaxies with $f_* \geq 40\%$ are members of the strong-stellar-contamination sample (SSC), while those with $f_* \leq 30\%$ are members of the interstellar-dominated (ISD) sample. Based on the agreement between f_* determined by the two independent techniques discussed in the text, the uncertainty is typically $\pm 10\%$. Col. (3) — Heliocentric velocity of the NaD absorption-line (km s^{-1}) measured by fitting the profile with a pair of Gaussians constrained to have the separation in wavelength appropriate for the red-shifted NaD doublet. Based on comparison of independent measurements of this quantity in the cases for which we have multiple spectra, we estimate that the typical measurement uncertainty is $\pm$ 20 km s^{-1}. Col. (4) — The velocity difference between the NaD absorption-line and the galaxy systemic velocity in the galaxy rest-frame: $\Delta v = (v_{NaD} - v_{sys})/(1 + v_{sys}/c)$. The relevant quantities are given in Col.2 of Table 1 and Col. 3 of this Table. A typical uncertainty in this velocity difference is $\pm$ 20 km s^{-1}, for the relatively bright nearby galaxies with well-determined values for v_{sys} up to $\pm$ 100 km s^{-1} for the most distant and far-IR-luminous galaxies (highly disturbed mergers with uncertain v_{sys}). Col. (5) — The full-width at half-maximum of each of the two Gaussians fit to the doublet (km s^{-1}). W was constrained to be the same for the two doublet members. The listed value has had the instrumental contribution to the measured value removed by assuming the intrinsic and instrumental widths add in quadrature: $W = [W_{obs}^2 - W_{instr}^2]^{1/2}$. Based on comparison of independent measurements of this quantity in the cases for which we have multiple spectra, we estimate that the typical measurement uncertainty is $\pm$ 20 km s^{-1}. Col. (6) — The rest-frame equivalent width (Å) for the NaD doublet. Based on comparison of independent measurements of this quantity in the cases for which we have multiple spectra, we estimate that the typical measurement uncertainty is $\pm$ 0.2 Å. Col. (7) — The normalized residual intensity at the center of the NaD $\lambda5890$ line profile ($I_{5890} = 0$ corresponds to a totally black line center). This has been corrected for the effect of the spectral resolution assuming Gaussian profiles: $(1-I_{5890}) = (W_{obs}/W)(1 - I_{5890,obs})$. Based on comparison of independent measurements of this quantity in the cases for which we have multiple spectra, we estimate that the typical measurement uncertainty is $\pm$ 0.02. Col. (8) — The ratio of the equivalent widths of the $NaD\lambda\lambda5890,5896$ transitions. A ratio $R = 2$ (1) corresponds to an optical depth of 0 (infinity). Based on comparison of independent measurements of this quantity in the cases for which we have multiple spectra, we estimate that the typical measurement uncertainty is $\pm$ 0.1. Col. (9) — The full-width at half-maximum of a Gaussian fit to the nuclear $H\alpha$ emission-line. These are taken from AHM, LH95, or our own unpublished spectra. The listed value has had the instrumental contribution to the measured value removed by assuming the intrinsic and instrumental widths add in quadrature. Typical uncertainties are $\pm$ 20 km s^{-1}.

Table 4.   Miscellaneous Properties of "ISD" Sub-Sample

Galaxy (1)	$\frac{H\alpha}{H\beta}$ (2)	$\frac{C65}{C48}$ (3)	Size (4)	v$_{term}$ (5)	v$_{rot}$ (6)
IRAS02021–2104	...	1.77	...	...	...
IRAS03514+1546	7.6	1.21	4.4	410	270:
NGC1572	...	...	2.4x3.2	310	312
NGC1614	7.4	1.32	3.2x3.2	330	210:
IRAS04370–2416	5.4	0.86	...	...	172
NGC 1808	8.0	1.39	3.7	700*	160
IRAS05447–2114	...	...	...	...	...
NGC 2146	10.0	1.39	...	...	272
M 82	8.4	1.44	...	...	50
IRAS10173+0828	...	1.61	...	...	140
NGC 3256	5.3	0.94	5.6x1.8	580	170:
IRAS10502–1843	...	...	7.7	220	...
IRAS10565+2448	9.7	1.14	8.5	450	300:
IRAS11119+3257	7.3	1.89	<6	1450	...
Mrk 273	8.7	1.02	3	450	260:
Arp 220	21	1.23	...	...	330:
NGC 6240	13.6	1.98	9	580	290:
NGC 7552	9.8	...	1.2x1.2	500	230
NGC 7582	8.2	...	1.0x1.0	490	180

Note. Col. (2) — The ratio of the nuclear Hα and Hβ emission-line fluxes. These have been corrected for the effects of underlying stellar absorption-lines (assuming a stellar equivalent width of 1.5 Å) and for foreground Galactic extinction (using a standard Galactic extinction curve and the measured Galactic HI column density. The data come from AHM, Veilluex et al (1995), data from runs 3 or 6 (Table 2), Vaceli et al (1997), or Dahari & DeRobertis (1988). Typical uncertainties are $\pm5\%$. Unreddened ionized gas would have a flux ratio of 2.86 for standard Case B conditions. Col. (3) — The ratio of the flux densities (F_λ) in the nuclear continuum near the wavelengths of Hα and Hβ. The values have been corrected for foreground Galactic extinction (see above). The data come from AHM, Veilluex et al (1995), or our runs 3 or 6 (Table 2). Typical uncertainties are $\pm5\%$. Note that an unreddened starburst corresponding to constant star-formation for 30 Myr would have an intrinsic color in these units of 0.5. Col. (4) — The projected size (in kpc) of the region along the spectrograph slit exhibiting strongly blueshifted (by > 100 km/s) NaD absorption. In NGC1572, NGC1614, NGC3256, NGC7552, and NGC7582 we have measured this along two position angles. Col. (5) — An estimate of the terminal velocity implied by the NaD absorption-line profile ($v_{term} = \Delta v + 0.5$ W). See Table 3. Col. (6) — The rotation speed of the starburst galaxy. See Table 1.

Fig. 1.— a) through d) Normalized spectra of the nuclear NaD absorption-line profile in the 32 galaxies in our sample. The region displayed is typically 2 by 4 arcsec in size centered on the region of peak brightness in the red continuum. Each displayed spectrum covers an observed range of 60 Å (~ 3000 km s^{-1}). Note the weak foreground Galactic NaD absorption at 5890,5896 Å in NGC660, NGC2146, and NGC4945.

Fig. 2.— Histogram of the difference between the mean radial velocity of the NaD line and the galaxy systemic velocity corrected to the galaxy rest-frame - see Table 3. The ISD (interstellar-dominated) lines are indicated by vertical hashing and the SSC (strong-stellar contamination) lines by horizontal hashing. The majority of the ISD lines are blueshifted by at least 100 km s^{-1}, while the SSC lines are all close to v_{sys}. Uncertainties in Δv range from ± 20 to 100 km s^{-1} - see text and Table 3. A typical uncertainty is represented by the plotted error-bar.

Fig. 3.— Histogram of the full-width at half-maximum of each of the two members of the NaD doublet, corrected for the effects of instrumental resolution and in the galaxy rest-frame. See Table 3. The ISD (interstellar-dominated) lines are indicated by vertical hashing and the SSC (strong-stellar contamination) lines by horizontal hashing. The ISD lines are much broader than the SSC lines. Typical uncertainties in W are ± 20 km s^{-1}, as indicated by the plotted error-bar.

Fig. 4.— Plot of the full-width at half-maximum (W) *vs.* the blueshift of the NaD doublet (Δv) for the sources showing nuclear outflows ($\Delta v \leq 100$ km s^{-1}). This Figure omits IRAS11119+3257, which has a blueshift of $\sim 10^3$ km s^{-1}. The diagonal line shows the relation $W = 2\,\Delta v$, expected in the case that gas is injected into the outflow at $v \sim v_{sys}$, and accelerated up to a terminal velocity $v_{term} \sim \Delta v + 0.5W$. Uncertainties in Δv range from ± 20 to 100 km s^{-1}, and typical uncertainties in W are ± 20 km s^{-1} (as indicated by the plotted error-bar).

Fig. 5.— Plot of the galaxy rotation speed (Table 1) *vs.* the full-width at half maximum of the NaD line (Table 3). The ISD (interstellar-dominated) lines are indicated by solid dots and the SSC (strong-stellar contamination) lines by hollow dots. The empirical relations between bulge stellar velocity dispersion and disk rotation speed found by Whittle (1992) for normal Sa (Sc) spiral galaxies are indicated by the lower (upper) diagonal line. The ISD lines are nearly all broader than these relations, while the SSC lines are nearly all narrower. Typical uncertainties are ± 20 km s^{-1} for W and range from < 0.1 dex to 0.2 dex for v_{rot} (dominated by the uncertain inclination correction in highly disturbed systems). Typical uncertainties are indicated by the plotted error-bar.

Fig. 6.— Plot of the galaxy rotation speed (Tables 1 and 4) *vs.* the inferred terminal

velocity of the outflow ($v_{term} = \Delta v + 0.5W$; see Table 4) for the sources showing outflows in NaD line ($\Delta v \leq$ -100 km s^{-1}). The diagonal line shows the relation $v_{term} = 2v_{rot}$. The terminal velocity shows no dependence on the rotation speed. Uncertainties in v_{term} range from $\pm$20 to 100 km s^{-1}, and from < 0.1 dex to 0.2 dex for v_{rot} (dominated by the uncertain inclination correction in highly disturbed systems). The typical uncertainties are indicated by the plotted error-bar.

Fig. 7.— Plot of the normalized residual intensity at the center of the λ5890 transition (I_{5890}) vs. the ratio of the equivalent widths of the λ5890 and λ5896 members of the NaD doublet (R), for the ISD (interstellar-dominated) NaD lines. See Table 3. $R = 1$ (2) corresponds to the limit of optically-thick (-thin) conditions. There is no correlation, implying that I_{5890} is determined primarily by covering factor rather than optical depth. Typical uncertainties are $\pm$ 0.02 in I_{5890} and $\pm$ 0.1 in R, as shown by the plotted error-bar.

Fig. 8.— Plot of the normalized residual intensity at the center of the λ5890 transition (I_{5890}) vs. the rest-frame equivalent width of the NaD doublet for the ISD (interstellar-dominated) lines. There is a significant correlation, implying that the equivalent width depends on the covering fraction of the optically-thick absorbing gas. Typical uncertainties are $\pm$ 0.02 in I_{5890} and $\pm$ 0.2 Å in EQW_{NaD}, and are shown by the plotted error-bar.

Fig. 9.— Plot of the full-width-at-half-maximum vs. the rest-frame equivalent width of the NaD doublet for the ISD (interstellar-dominated) lines. There is no correlation, implying that the equivalent width does not depend on the velocity dispersion of the optically-thick absorbing gas. Typical uncertainties are $\pm$ 20 km s^{-1} for W and $\pm$ 0.2 Å in EQW_{NaD}, as shown by the plotted error-bar.

Fig. 10.— a) Plot of the normalized residual intensity at the center of the λ5890 transition (I_{5890}) vs. the log of the color of the optical continuum (the ratio of F_λ at rest wavelengths of 6560 and 4860 Å). Points plotted as solid dots are the nuclei of the ISD (interstellar-dominated) sample members (Table 4). Other points are off-nuclear locations in M82, NGC3256, NGC6240, Mrk273, IRAS03514+1546, and IR10565+2448. The deeper the NaD line (higher covering factor), the more-reddened the background starlight. The correlation is obeyed by both the nuclear and off-nuclear regions. An unreddened starburst population should have $log(C_{65}/C_{48}) = $ -0.3. For a standard Galactic reddening curve, the implied A_V ranges up to roughly 4 magnitudes for the most-reddened sight-lines. Typical uncertainties for the nuclear (extra-nuclear) data are indicated by the error-bar in the lower-left (upper-right) of the plot. b) As in a), except that I_{5890} is plotted vs. the log of the Balmer decrement (Hα/Hβ flux ratio). Again, the more-reddened sight-lines correspond to the deepest NaD line profiles (highest covering factors). The log of the intrinsic Hα/Hβ flux ratio is 0.46, and

the implied values of A_V range up to ~ 5 magnitudes for the most-reddened sight-lines.

Fig. 11.— Logarithm of the gas number density (in units of cm^{-3}) in the hydrodynamic simulation described in the text, at four different epochs. The figure shows dense cool gas, either entrained into the flow at the walls of the cavity or remnants of the fragmented superbubble shell, being swept up and carried out of the galaxy by the wind. As material is locally in pressure equilibrium, the densest material visible is also the coolest, and might be considered analogous to the dense cool gas responsible for the optical absorption lines. The four clumps or clouds shown have average velocities (over the 1.5 Myr period shown) of 177 km s^{-1} (cloud A), 540 km s^{-1} (cloud B), 348 km s^{-1} (cloud C) and 858 km s^{-1} (cloud D) respectively.

Fig. 12.— As in Figure 6, except that we have added galaxies in which we have estimated wind outflow velocities from the observed temperature of the hot X-ray-emitting gas via the relation from Chevalier & Clegg (1985): $v_{term} \sim (5kT_X/\mu)^{1/2}$. The X-ray temperatures are taken from the references listed in the text. The data points based on the NaD profile are indicated by solid dots and the points based on the X-ray data are indicated by hollow dots. Note that the two data sets are consistent with each other, imply that the outflow speed is independent of the host galaxy potential well depth, and thus suggest that outflows will preferentially escape from the least massive galaxies. The two diagonal lines indicate the galaxy escape velocity under the assumption that $v_{esc} = 2\ v_{rot}$ and $v_{esc} = 3\ v_{rot}$ respectively (see equation 9 in the text). Typical uncertainties in the X-ray (NaD) estimates of v_{term} are shown by the error-bar on the bottom right (upper center).

NGC 253

NGC 660

III ZW 35

IRAS02021-2104

NGC 1134

IRAS03514+1546

NGC 1572

NGC 1614

Wavelength (angstroms)

Figure showing spectra of: IRAS04370-2416, NGC 1808, IRAS05447-2114, NGC 2146, NGC 2966, M 82, NGC 3094, IRAS10173+0828. All plots show Flux vs Wavelength (angstroms).

NGC 3256

IRAS10502+0828

IRAS10565+2448

IRAS11119+3257

NGC 3628

NGC 3885

NGC 4666

NGC 4945

Wavelength (angstroms)